**Final Report**

**on the**

# WORKSHOP ON THE SCIENTIFIC EXPLORATION OF SIMULATION PHENOMENA

**Sponsored by**

## the Army Model and Simulation Office

**and**

## the Defense Modeling and Simulation Office

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# EXECUTIVE SUMMARY

The Army Model and Simulation Office and the Defense Modeling and Simulation Office sponsored a workshop on scientifically exploring simulation phenomena in the late Spring of 2002. These sponsors invited 15 leaders in modeling and simulation from academia, industry and the U.S. Government to participate. They asked these participants to

- Determine if fundamental knowledge of the nature of simulation could exist,
- Assess whether a scientific approach to the study of simulation could improve that knowledge, and
- Recommend further steps (including performing research) to improve our knowledge of simulation fundamentals and, through that knowledge, improve current simulation workforce quality as a whole.

The workshop began with presentations from the participants that summarized their individual positions on the workshop topic. Working sessions constituted the bulk of the workshop in which the participants considered past scientific work on simulation, simulation observables and phenomena, hypotheses about simulation behavior, and possible experiments to improve our knowledge of simulation fundamentals. In the course of the working sessions, the participants explored the issues of simulation as a science, the nature of simulation fundamentals, past applicable work, the means to improve workforce quality, and the means to improve our knowledge of simulation fundamentals.

Despite considerable debate, the participants could not agree that a scientific approach to understanding the phenomenology underlying simulation would provide any substantial benefits over other less disciplined approaches. Their positions broke roughly into four, nonexclusive, arguments:

Simulation is technology but not science (although, perhaps, an important tool of science). Applying the scientific method to understanding simulation may yield interesting but not necessarily useful results for the time being.

Simulation consists of observable phenomena that the application of the scientific method can explain. The resulting explanations can provide the fundamental knowledge needed to advance simulation technology. Scientific study of simulation will certainly produce the core knowledge necessary to advance it as an engineering discipline.

Simulation is a technology too underdeveloped to sustain the productive application of rigorous scientific method. It needs many more casual exploratory observations from which scientific knowledge may later evolve.

Simulation is better considered as an engineering discipline. Taking an engineering approach to its study will produce more immediately useful results than trying to explain it scientifically.

Most of the participants felt strongly about their positions on this particular issue so no reconciliation seemed likely within the workshop's timeframe.

Over the course of several sessions, the participants identified many components of the knowledge unique to simulation. A set of processes in the simulation development chain best describes these components:

- Describing simulation representational characteristics;
- Mapping user needs into specific simulation capabilities;
- Abstracting models from referent information;
- Designing and building simulations from models;
- Interfacing the simulation with people and other systems;
- Determining if a simulation can meet user needs; and
- Preparing and using simulation to achieve user objectives.

The participants also believe that simulationists need the knowledge to handle the problems associated with constructing and operating any complex information system including aspects of software engineering, system engineering and program management.

The participants recommended several important areas of fundamental simulation research:

- Factors contributing to making simulations too hard;
- Criteria for choosing specific over general simulation approaches;
- Dealing with limited referents;
- Relationships between simulation fidelity and interoperability with other components;
- Inherent limitations of simulations of complex adaptive systems;
- Applications and limitations of visualization techniques;
- Effectiveness of abstraction techniques to achieve a particular purpose;
- Dependencies between simulation representation and implementation;
- Specifying simulation conceptual models; and
- Building comprehensible simulations.

In the last session, the participants recommended several near-term (i.e., within 1-2 years) actions that could improve the fundamental knowledge of simulation throughout the workforce. These recommendations encompass both building that fundamental knowledge and distributing it within the community:

- Conduct lessons learned workshops;
- Conduct a simulation competition;
- Compile a glossary of simulation terms;
- Construct a taxonomy of existing simulation literature;
- Formulate a recommended reading list for modeling and simulation;

- Consider instituting a reviews of modeling and simulation journal; and
- Compile and publish a modeling and simulation monograph series.

The first two of these recommendations address the lack of data that hampers the scientific exploration of simulation phenomena. The next three structure existing information on simulation to make it more accessible to practitioners. The last two recommendations create new knowledge resources for simulationists.

Speaking from a military applications perspective, Mr. Lunceford, Director of AMSO, observed that simulation technology has been stalled for the last three to five years. The phenomena that we can simulate today are no different than those that we could represent five years ago. We do not move forward because we allow people to cycle through the same ideas over and over again. The current system has no rigor and that hinders our progress in advancing the technology and, thus, its practices. The results of this workshop provide substantive material and realistic recommendations for breaking this technology log jam. Over the long term, scientific knowledge of simulation phenomena may evolve from these recommendations.

# INTRODUCTION - A SCIENCE OF SIMULATION? AND, WHY?

S. Y. Harmon

To any traditional scientist, the mention of a "science" of simulation at best appears misinformed and at worst grates on the scientific sensibility worse than fingernails dragging across a chalkboard. Many have misappropriated the term science, even to the point of blaspheming its lofty ideals. Is this not just such a case? But, any true scientist must consider every proposition, regardless of how absurd, scientifically.

**The hypothesis: A science of simulation could exist.**

The scientific definitions of science from various reputable sources show an amazing consistency considering the past liberal applications of the term to numerous nonscientific activities. They suggest that a science has but a few essential properties:

1. Science is a study.
2. It deals with the natural or physical world.
3. That study takes place through experimentation and development of theoretical explanation.
4. Its theoretical explanation (stated in terms of hypotheses, models, laws and principles) arises from and is confirmed by observation and experiment.

Testing the nature of simulation against each of these properties produces the following findings.

1. *Can simulation by studied?* Clearly, one could study, in the broadest sense, simulation. Many stately bodies of higher education offer courses and even entire curricula purporting to teach simulation. These observations lead to the conclusion that the study of simulation could exist in some form. That conclusion meets the first criterion of its being a science.

2. *Is simulation a part of the natural or physical world?* Certainly many simulations deal explicitly with the natural or physical world but are simulations actually part of that world themselves? That people construct all simulations sets them apart from the natural (as opposed to the man made) world. But wait, the Academic Press Dictionary of Science and Technology defines the physical world as synonymous with the material world. That world contains physical objects rather than emotions or the spiritual world. Simulations, the objects in the simulation world, do not generally contain emotions nor do they represent the spiritual world (at least as far as I know). Further, the development of simulations does not necessarily need reference to emotional or spiritual objects (although some program managers would argue this point). Therefore, simulations must be part of the physical world and so do meet the second criterion to necessary to succumb to scientific study.

3. *Can simulation be subject to experimentation that can lead to theoretical explanations?* Experimentation, involves a procedure carried out under controlled

conditions in order to discover, demonstrate, or test some fact, theory or general truth. This definition implies that a system subject to experimentation must

- Exhibit observable behavior, and
- Respond to controls of its behavior.

Most of the artifacts of simulations (e.g., designs, software, computers, results) are observable. I do not believe that we could construct simulations without many artifacts that would facilitate observation. This suggests that both simulations and their development are indeed observable.

People are inextricably involved in simulation development and often in their execution. Where people are not involved, computers perform most operations. Both of these elements are controllable. The field of psychology has repeatedly demonstrated controlled experiments involving people and computer science has repeatedly demonstrated controlled experiments involving computers. The success of these demonstrations shows that controlled experiments could be formulated and executed upon simulations to examine their behavior and the behavior of the processes involved in their creation**.** Admittedly, simulation project managers might complain against the controllability of the simulation development process but we, like most others, will ignore those pleas. Therefore, study of simulations could realistically involve meaningful experimentation. Some would even argue that meaningful experiments have already been performed on simulations. The ability to develop theoretical explanations of the experimental results clearly exists since many people have proposed theoretical explanations of various aspects of simulation without the benefit of either experiments or sound observations (a distinctly nonscientific thing to do). Therefore, simulation satisfies the third criterion to be subject to science.

(4) *Can experiment confirm simulation theory?* The final criterion remains untested and, therefore, inconclusive for simulation. This observation presents the major challenge in realizing the science of simulation. No clear physical barriers appear to exist to prevent the systematic study of simulation suggested by this criterion. However, only trying to execute this study can prove or disprove this criterion ... we won't know till we try.

So, the jury remains out on this criterion. Actually, the court has not yet been called into session. The final answer to whether a science of simulation could exist awaits someone brave enough to begin performing a systematic study of simulations and the processes for realizing them. No doubt, many physical and cultural hazards face any such individual. Perhaps, these will deter many. Hopefully, human curiosity will prevail and someone will gallantly ignore the naysayers and press forward to realize the science of simulation.

Finally, why study simulation scientifically? What value does knowledge derived from scientific study possess over knowledge derived from any other form of study? To me (unarguably a science zealot), science reaches for the surest truth, truth that applies broadly and persists over time. Science creates the most powerful form of knowledge. The assurance that real science provides founds much of the engineering and medical practice that has created the world we know and enjoy today. Scientific study has even permeated the justice system to some extent (e.g., genetic evidence) and I am confident that it will continue to do so. Over the few thousand years of its development, science

has evolved into a very robust and consistent source of knowledge unsurpassed by all other sources. This type of knowledge about simulation would surely supply tangible benefits beyond our meager imaginations as it has in so many other fields. Furthermore, science generates the knowledge that we can confidently teach to improve the capabilities of all practitioners in the field. These promises make a science of simulation worth pursuing.

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The origins of this article lie in the email discussion among Dell Lunceford, Bill Waite, Richard Fujimoto, Ernie Page and Scott Harmon provided in Appendix 2.

This article appeared as a guest editorial in SCS Simulation magazine, volume 1, number 1.

# WORKSHOP AGENDA

## Tuesday, 4 June 2002

| | | |
|---|---|---|
| 0800-0815 | Introduction | |
| 0815-0830 | Welcome | |
| 0830-0915 | Founder's Keynote | Dell Lunceford |
| 0915-1000 | Sponsor's Keynote | Sue Numrich |
| 1000-1030 | Break | |
| 1030-1055 | Towards a Science of Modeling | David Nicol |
| 1055-1120 | Toward Simulation on a Scientific Basis | David Gross |
| 1120-1145 | Philosophy, Science and Simulation | Scott Harmon |
| 1145-1210 | Walking Back the Cat | Bill Whelan |
| 1210-1235 | Thoughts on Science and Military Simulation | Ernie Page |
| 1235-1330 | Lunch | |
| 1330-1355 | The Art and Science of Simulation | Bill Swartout |
| 1355-1420 | Moving from the Art of M&S to the Science of M&S | Randy Shumaker |
| 1420-1445 | Science or Engineering - Modeling and Simulating as a Distinctive Technical Discipline | Bill Waite |
| 1445-1510 | A Discrete Event Computational Basis for Simulation Science | Bernie Zeigler |
| 1510-1535 | Simulating Humans | Marc Raibert |
| 1535-1600 | Break | |
| 1600-1625 | The Possibility of Simulation Science | Dale Pace |
| 1625-1650 | Dealing with Complexity | Paul Davis |
| 1650-1715 | Science, Simulation and Intelligence | Dennis McBride |
| 1715-1730 | Review & Adjustment of Workshop Goals | All |

## Wednesday, 5 June 2002

| | | |
|---|---|---|
| 0800-1000 | Working Session 1: If and Why a Science of Simulation? | Dell Lunceford |
| 1000-1015 | Break | |
| 1015-1215 | Working Session 2: What Has Been Done Before? | Bernie Zeigler |
| 1215-1315 | Lunch | |
| 1315-1515 | Working Session 3: What Are the Phenomena of Simulation? | Bill Swartout |
| 1515-1530 | Break | |
| 1530-1730 | Working Session 4: What Testable Hypotheses Could Exist? | David Gross |

## Thursday, 6 June 2002

| | | |
|---|---|---|
| 0800-1000 | Working Session 5: What Observations/ Experiments Could Be Made/Done? | Bill Whelan |
| 1000-1015 | Break | |
| 1015-1215 | Working Session 6: What Should Be Done Next? | Sue Numrich |

# POSITION PAPER ABSTRACTS

## Dealing with Complexity in a Science of Modeling and Simulation

Paul Davis
The Rand Corporation
Santa Monica, CA

One of the biggest challenges continues to be greatly enhancing the ability of a person or small team, working with a model built by others (or long ago), to comprehend and deal with massive complexity and uncertainty. We have many related techniques, which include hierarchical decomposition, structured programming, object-oriented modeling and programming, graphical depiction of system behavior, visual modeling and programing, and so on. In some respects, agent-based modeling can make sense of very complex systems, although it requires a different notion of "understanding" than some would yearn for.

Thinking of my own work, I like to believe that multiresolution, multiperspective modeling (MRMPM) and exploratory analysis will be major contributors. Both, however are still in their infancy.

## Toward Simulation on a Scientific Basis

David C. Gross & Bruce T. Fairchild
The Boeing Company
Huntsville, AL

The potential for a simulation science can be approached from several vantage points. For example, one might be considered with the issue of “turf”, what is the domain of inquiry for a simulation science? This might be phrased as, “is there enough there to sustain a field of an extended scientific inquiry?” Or, one might be concerned with what might be termed the “pure” question of simulation science: do there exist observable phenomena uniquely related to simulation? Finally, one might consider the question of how a scientific basis for simulation would benefit simulations actually being built.

This position paper argues the following answers arising from the foregoing questions. First, that the domain of inquiry properly belonging to simulation is small, at least compared with other fields of science. Second, that the set of observable phenomena best bounded as simulation include model resolution, error, precision, and sensitivity. Finally, that since simulation is actually used as a technique for gaining knowledge, like experiment design, placing it on a firm scientific basis is crucial for the continued expansion of its application.

## Philosophy, Science and Simulation

S. Y. Harmon
Zetetix
Oak Park, CA

All of science builds models to explain observations of nature and validates those models through further observations and experiments, preferably independent of their observers. As with all models, scientific models always abstract some aspect of nature and are necessarily incomplete or inaccurate over some domain. Scientists and philosophers have explored the character and limitations of modeling for as long as science has existed as a form of human study. All of our current scientific knowledge stands upon the issues addressed by this philosophy of science (e.g., causality and the flow of time).

Some have turned the models encompassed by science into computer simulations. Exercising these simulations has enabled much of the world that we take for granted (e.g., weather prediction, space flight, computers, safe air travel). Yet, few, if any, have attempted to apply scientific method to understanding the basic nature of simulations. Clearly, the behavior of simulations resembles the things they simulate but it also differs, sometimes in seemingly unpredictable ways. A potentially productive area of exploration is the correspondence between simulation and those things they represent.

Simple extensions of the philosophy of science teaches us that simulations share the characteristics and limitations of the models that they employ and these factors understandably contribute to the inaccuracies displayed in simulation behavior. But, they are not alone. To understand why, one must understand the nature of causality itself. The behavior of simulations is not inherently constrained by the same causal mechanisms that decide the behavior of the simulands. These causality differences can arise from execution performance as well as interoperability issues. No one has yet scientifically characterized the contributions of these phenomena, abstraction, performance and interoperability, to simulation behavior. Fortunately, the widespread availability of simulation resources makes the experiments to answer these questions reasonably easy and cost effective. This aspect of simulation phenomena is surely a good starting point for the science of simulation.

## A Science of Simulation?

David M. Nicol
Dartmouth College
Hanover, NH

Abstraction is the heart of modeling. A given system admits to a variety of abstractions. Some may be considered to be complimentary views with different emphases on different aspects, some may be related hierarchically. Abstractions that are related hierarchically are attractive for computational reasons. A hope exists that as one executes a simulation model definable by such a hierarchy, that one can dynamically shift up and down the structure, adding detail and specificity when and where it is needed.

There have been some successes in hierarchical simulation. I'd like to focus on one that is a bit afield from typical discrete-event simulation, but which illustrates very well the points I wish to make. The technique I'd like to highlight is multigrid solution numerical of certain types of differential equations. The equations of interest typically describe physical quantities in a physical domain; as such there is a spatial intuitiveness to the grids. The basic idea is this : a computational technique called relaxation is used to improve a potential solution. That is, given a tentative assignment of numerical values to the physical quantities one can both assess the accuracy of the solution (by means of computing some error measure), and can attempt to improve the solution by applying some mathematical operator to it. Equations that govern this operator frequently have the property that if you apply the operator over and over and over again, eventually you get a solution that does not change by repeated application, and that solution is correct. Now the larger the set of values to be computed, the more of these iterations are needed to converge to a solution, and (obviously) the more computational work is needed at each iteration. The fundamental idea of multigrid is to create a hierarchy of grids with different coarseness (e.g., spacing between grid points) and to move iterations between different levels. Suppose that G1, G2, ... , Gk are k different grid levels which are hierarchical in the sense that they all describe the same physical domain, and are nested in the sense that G1 has more points than G2, which has more points than G3, and so on. A multigrid technique will apply an iteration to G1, the "project" the solution there to G2 and apply an iteration, then project the solution there to G3 and apply an iteration, and so on. The solution computed at grid Gk is combined with the old solution at the next coarsest grid, which then is combined with the solution and the grid below that, and so on.

There is strong mathematical intuition driving multigrid, and a large literature exists for it now. In the space of twenty years it has gone from a research concept to being widely used in industrial contexts. Having said all that, it is only an approximate technique, and the contexts in which one can say anything truly formal about bounding the error or assuring convergence are few and far between. This last facet is my main point.

For all the interest in hierarchical modeling we must not lose sight of two important things. First, that an ability to formally prove the relationship between solutions at different abstraction levels is highly dependent on the specific problem being considered. Furthermore, I believe that in every case where such proofs exist, those proofs rely on mathematical and idiosyncratic properties of the systems being modeled. I see very little hope for an effective general approach to bounding error between hierarchical levels, and even less hope for any system whose fundamental behavior is not described by tractable (typically continuous and differentiable) equations. Second, despite these difficulties, the modeling and simulation community develops and uses hierarchical abstraction strategies, and will continue to do so. Given this, the challenge I see is to develop a science of model engineering. My use of the word ``engineering'' is to capture the sense of methodology and mathematics, and to capture the confidence that the methodology followed will yield the desired result.

Unfortunately my position is not especially constructive. I'm not prepared to offer deep insights into just how to approach a methodology that tends to yield accuracy in

hierarchical models with formal proofs of this. I am convinced though that formalism will not accomplish what is at heart an engineering problem.

## The Possibility of Simulation Science

Dale K. Pace
JHU Applied Physics Laboratory
Laurel, MD

The Sim Science Workshop addresses four questions: 1) Is sim science possible? 2) What can contribute to sim science? 3) How can we improve that contribution? and 4) What impact can Sim Science have on the world? Sim Science currently lacks three characteristics normally associated with a science (recognized "scientists, core body of discipline knowledge, and standard methodologies). Improvements in simulation development and use from increased employment of best practices and systematic endeavors are more likely than establishment of sim science as a science. There are four things that can be done to move toward establishment of sim science as a science: a) determine sim science boundaries (e.g., are analysis and software engineering part of sim science, or vice versa), b) codify core knowledge required of sim science practitioners, c) establish credentials for scientists in sim science (not just journeymen), and 4) establish *and enforce* sim science best practices. Academia must take the lead in this movement, with encouragement from government and industry sim users. Simulation advances will have a positive impact on the world, even if they are just the result of sim process improvements without development of sim science as a real science.

## Thoughts on Science and Military Simulation

Ernest Page
Army Model and Simulation Office
Arlington, VA

One of the questions we are being asked to consider is "could there be a science of simulation?" That is, could (should) simulation be viewed as a science in the same way that biology, chemistry and physics are viewed as sciences? In this paper, I'll begin to address that issue. But before engaging in that discussion, I briefly examine a related question currently occupying the interest of the military simulation community: "is there (should there be) a *profession* for M&S?" I go on to consider the difference between modeling being an art or science, and the issues of science, computing and politics. I then suggest a few areas within which certain aspects of the scientific method might be employed for the betterment of the practice of simulation within the military community.

In this article, I wax-not-so-eloquently on the relationship between science and simulation. I describe a few areas within my community—the military simulation community—where the scientific method might be gainfully applied. I'm sure that there are few, if any, original ideas or insights offered here. I also couldn't say whether other communities suffer from the same ills. I suspect not, but I'll gladly let them speak for themselves. (Editor's note: This abstract was hastily cobbled together from a much

longer and much more elegantly presented full paper that, sadly, did not have an abstract. My apologies to the author. SYH)

## Simulating Humans

Marc Raibert
Boston Dynamics, Inc.
Boston, MA

At Boston Dynamics we do three kinds of human simulation: Physics-based human simulation for virtual prototyping, visual simulation for training and mission planning, and humanoid robot simulation for developing robot control and behavior. For each of these kinds of human simulation there are key technical challenges that will drive future development. In physics-based human simulations, the challenge is to provide validated control systems that act like real people. Control allows the simulated humans to behave like real people, and validation enables simulations to predict behavior in novel circumstances. In visual simulation for training, one challenge is to make the simulators *SME-friendly*. Another key challenge is to provide characters that are intelligent enough to respond convincingly in interactive systems. Such intelligent characters are needed to provide believable advisaries and teammates for a range of training applications. In humanoid robot simulation, a key challenge is to make simulators easy enough to use so they provide a realistic way to augment physical experiments.

Physics-based human simulation for virtual prototyping, visual simulation for training and mission planning, and humanoid robot simulation for developing robot control and behavior. For each of these kinds of human simulation there are key technical challenges that will drive future development. In physics-based human simulations, the challenge is to provide validated control systems that act like real people. Control allows the simulated humans to behave like real people, and validation enables simulations to predict behavior in novel circumstances. In visual simulation for training, a key challenge is to provide characters that are intelligent enough to respond convincingly in interactive systems. Such intelligent characters are needed to provide believable advisaries and team mates for a range of training applications. In humanoid robot simulation, a key challenge is to make simulators easy enough to use so they provide a realistic way to augment physical experiments.

Validation normally means that a simulator has been tested so that it behaves the same the physical system. For example at Boston Dynamics we validated a human simulation of a person carrying various backpacks by showing that the timecourse of various parameters measured from the human simulation match comparable measurements made on real human soldiers. We varied the weight, load placement, and harness characteristics and looked at ground loading, kinematics, and other features of the behavior. Then we adjusted the simulator to better match the human performance. The real goal of validation is not to confirm that the simulation reproduces the actual measurements of the person. Rather, it is to convince ourselves that the simulator has predictive value, and that it will give correct data for conditions that have never been tested. The more the conditions being predicted differ from those tested, the more valuable the simulator would be.

This paper outlines three kinds of human simulation: realtime visual simulation for training and mission planning, physics-based dynamic simulation for virtual prototyping, and humanoid robot simulation for developing advanced robots. The second dynamic simulator is the Digital Biomechanics Lab, a tool for *Virtual Prototyping* of equipment used by humans. The core of the Digital Biomechanics Lab is a dynamic human simulator that is being validated against live human performance, and that uses human anthropometry as the basis of the body models. The SDR-3X Humanoid Simulator was jointly developed by Boston Dynamics and Sony Corporation. It is being used to develop the robot mechanism, create innovative movements, and develop new movement control strategies for locomotion and expression. This paper describes both simulations and how they were built using a common set of simulation infrastructure.

## Moving Simulation from an Art to a Science

Randall Shumaker
UCF Institute for Simulation and Training
Orlando, FL

The question we were asked to address was whether there is or could be a science of simulation. A superficial answer is that if you have to ask the question, then there isn't. While simulation may not have reached the status of clearly recognized science, it is at least an identifiable technical specialty, and more probably an emerging science. My conclusion is that there is probably not enough science or even engineering in simulation yet to declare it a separate discipline. There is evidence to suggest that there could and really should be such a science. The lack of a disciplined and principled approach to development of simulations is costly in many ways and is a major impediment to progress in many fields. Whether simulation will ever be considered an entirely separate discipline is unclear, but the resolution of this question isn't particularly germane to creating the scientific underpinnings of the endeavor.

## Does Simulation Need a Reality Check?

William Swartout
USC Institute for Creative Technologies
Marina del Rey, CA

Simulation and science share a common root in that both are concerned with constructing predictive models of some world of interest and then running the model to see what will happen in a variety of situations. But how should that model be constructed? There are many approaches. Sometimes, a so-called "deep" model is constructed, in which the structure of the model mimics reality as we understand it. At other times, people focus on constructing a surface model, where the concern is to produce correct outputs, but the structure of the model need not reflect the world being modeled. At the Institute for Creative Technologies, we have worked with people from the military simulation community and from the entertainment industry. Both communities construct simulators ---- the military simulates reality for training and analytic purposes, while the entertainment community simulates reality through movies and video games to entertain

and occasionally to teach. We have found that the military simulation community and entertainment community approach the simulation of reality in very different ways. Generally speaking, the military simulation community attempts to duplicate reality literally by reproducing real elements in a simulation. The entertainment community, on the other hand, creates the appearance of reality by bringing together a number of elements that suggest reality, but that may not be drawn from it. In this talk, I will examine these two approaches, gives examples of how the entertainment industry approaches the simulation of reality, discuss some of the advantages and tradeoffs associated with each approach, and outline when each might be most appropriate.

## "Science .AND. Simulation…?"

William Waite
The AEgis Technologies Group, Inc.
Huntsville, AL 35806

There are several forms of relationship between 'science' and 'simulation'. The set of such relationships most relevant to the present debate concern the degree to which simulation is a kind of science and the degree to which, therefore, simulation may be successfully be pursued by scientific means. The lexical and semantic homework that is necessary for such an analytical investigation to proceed successfully is somewhat daunting. Nevertheless, there is merit in defining terms and parsing statements carefully so as establish a sound basis of discourse upon which credible and persistent results may be established. A second perspective altogether, however, is to consider a more synthetic approach based on 'intention'. What it is that we intend to do with our newfound appreciation of the relationships between science and simulation is likely to suggest how we ought to proceed and what intermediate determinations are worth making. The subject paper addresses investigating the relationship of simulation and science from both perspectives alternatively; and it provides a few concrete findings and recommendations derived from the latter, consistent with the former. Our pragmatic approach yields the conclusion that: the formal relationship of simulation and science is irrelevant - except by way of being suggestive - so long as simulation is recognized to be associated with a specific body of knowledge that discriminates it form other disciplines and that can systematically be developed and used to practical advantage.

## Walking Back the Cat

William Whelan
Concepts and Technology Group
Tehachapi, CA

The science of modeling and simulation is one of the newer interdisciplinary sciences, whose development has been accelerated over the past fifty years. An older definition of this science is recalled and examined along with a personal look back at some of the defense study areas where this science has made significant contributions.

Another look to the past suggests that selected previously developed and used models and simulations might be adapted to study current problems areas such as terrorism and the use of operations flexibility. These seclected models include a submarine trailing model and a basketball simulation.

The operational flexibility approach to operations planning and execution is discussed along with the need for appropriate models and simulations to explore this approach.

## A Discrete Event Computational Basis for Simulation Science

Bernard P. Zeigler
Arizona Center for Integrative Modeling and Simulation
The University of Arizona/Arizona State University
Tucson, AZ

System theory, and its mathematical instantiations, provides a rigorous framework for M&S but it lacks computational and conceptual infrastructures. Object orientation (OO) is a strong computational basis for M&S. OO is being given commonly accepted conceptual interfaces through such the Unified Modeling Language (UML) for general software development. However, UML is inadequate when applied to M&S since it fails to come to grips with elements that are intrinsic to M&S, continuous and discrete dynamics, model composability, and abstraction-related families of models, efficient simulation infrastructure, etc. I take the position that a more encompasing M&S framework is needed to address these requirements. Here I will present the outlines of such framework that draws upon an existing

M&S framework, systems theory and UML but goes further to provide a computational basis for the M&S intrinsic elements just mentioned. I demonstrate that DEVS (Discrete Event Systems Specification) provides such a computational basis and go on to consider some of the implications for simulation science including reengineering of the mathematical underpinnings for M&S.

# POSITION PAPERS

# Dealing with Complexity in a Science of Modeling and Simulation

Paul K. Davis
RAND and the RAND Graduate School
July, 2002

## INTRODUCTION

This is a very informal paper prepared for a workshop on simulation science. It has been neither reviewed nor carefully edited. The first part of the paper highlights certain issues that I believe *must* be dealt with effectively if modeling and simulation is to address complexity. It is not a survey of complexity issues, nor of the relevant literature, but merely a highlighting of some particular topics that my colleagues and I have worked on, topics which seem to me of central importance and may be of interest to workshop attendees. The second part of the paper records my thoughts on some of the themes of the workshop, notably about whether simulation should be seen as a "science" and what that might mean.

## PART ONE: ENABLERS FOR DEALING WITH COMPLEXITY

### Background

Dealing well with complex adaptive systems (CAS) is a profound challenge for modeling and simulation. Although much progress has been made over the last few decades, it is not clear that the corner has yet been turned. We know some of the principles for doing so, of course, including the principle that CAS typically are characterized by "nearly decomposable hierarchies," a phrase used by Herbert Simon in his early work on the subject. They may also be networked and, depending on what aspect of the system one is interested in, hierarchy or networking may loom larger. One of my focuses here is on the hierarchical aspects. My second focus relates to dealing with uncertainty, not just garden-variety uncertainty on the margin, but massive uncertainty - as commonly characterizes problems of strategy and policy.

### Multi-Resolution, Multiperspective Modeling (MRMPM)

To represent nearly decomposable hierarchies in modeling and simulation, we must deal well with multiple levels of abstraction (roughly, levels of resolution), each of which has its legitimacy and its own "laws." We also know that different perspectives or representations are needed for different purposes. The result, then, is a need for multi-resolution, multiperspective modeling (MRMPM). It includes multiresolution modeling, which I earlier called variable-resolution modeling until people convinced me that some were interpreting that to imply a continuous rheostat. MRMPM overlaps with but is not identical to what others, such as Paul Fishwick, call multimodeling. On the other hand, what I mean by MRMPM is decidedly *not* merely a matter of generating output displays at different levels of detail, with the underlying model being at high resolution. Again, the intention in MRMPM is that each level of detail treated is described by its own model. To be sure, we want to be able to relate the models that apply at different levels

of detail, and ideally to have an integrated description, but we should not think of high resolution as "good" and low resolution as "inferior."

A fair amount of research has been done on MRMPM over the last decade, but it is still a cutting-edge subject. See Davis and Bigelow (1998)[1], which includes material of earlier work and Davis and Bigelow (forthcoming)[2]. Some of the issues are discussed also in National Research Council (1998)[3].

**Adaptive Systems and Agents**

A second essential feature of M&S dealing with CAS is the need for what is the functionality provided by what is today called agent-based modeling. Traditional simulations remain fatally flawed by their failure to represent adaptation well. We should not get hung up, however, on whether someone is using SWARM or SEAS or some other anointed language of the agent-based modeling community. To do so would be to make the same mistake of people in the 1980s who seemed to believe that LISP was required in an artificial intelligence model. What matters is that the models include entities that make decisions and exhibit behaviors, which can change as a function of circumstances and even evolve. Personally, I recommend that people seeking a nontechnical introduction read John Holland's book Hidden Order, which conveys a sense of the fundamentals well.

Agent-based modeling, by the way, now has a history of about 20 years, depending on how one counts. To my knowledge, the first substantial agent-based modeling in military work was the RAND Strategy Assessment System (RSAS), which we developed in the mid-1980s (see, e.g., Davis, 1988[4]). The Santa Fe Institute, of course, developed many of the CAS-related ideas and techniques that have subsequently become well known. Current relevant work includes that of Andy Ilachinski at the Center for Naval Analyses (see his "Isaac" web site) and work of Aerospace and RAND using the SEAS model.

**Exploratory Analysis and Assessment**

An essential part of serving the needs of higher level decisionmaking with modeling, simulation, and analysis is what I call *exploratory analysis*, which is designed to deal with problems characterized by massive uncertainty - as is common when dealing with CAS, and has been dramatically evident in past conflicts over the ages. The philosophy of exploratory analysis is diametrically opposite to that which has dominated military analysis in years past. Instead of collecting "authoritative data" and treating it as though it were also valid, and then using "authoritative models" as though they were accurately predictive, exploratory analysis uses models and simulation to chart the *broad* landscape and identify subjects worthy of more detailed attention, whether through M&S or experimentation. Its forte is in supporting the development of strategies that are flexible, adaptive, and robust, rather than optimal for some artificially well defined circumstance.

A great deal of work has now been done at RAND on exploratory analysis, which dates back to early work on "multiscenario analysis." For early work, see Davis (1988)[5] and, for very early notions on the subject before the capability existed to pursue them, Davis and Winnefeld (1983)[6]. My colleagues and I believe that exploratory analysis is of *fundamental* importance. And, because of technological and theoretical advances (including MRMPM), it is also quite feasible. My collaborators and I have applied it in

theater- and multi-theater work using the JICM model, in several mission-level analyses involving force projection in the presence of anti-access tactics, and in careful study of how the effectiveness of long-range precision fires varies with terrain, enemy maneuver tactics, and aspects of command and control. See Davis, Bigelow, and McEver (2001)[7] for a collection of some relevant reprints. See Davis (2002)[8] for a primer on capabilities-based planning and how it depends on exploratory analysis.

RAND colleagues have applied a closely related method called "exploratory modeling" to weapon-allocation analysis, to policy problems related to global warming, and other non-military subjects. One of them, Steven Bankes, has also developed new tools for both generating scenarios and studying their outcomes in exploratory modeling. For his early and influential paper, see Bankes (1993)[9]. See Bankes (2002)[10] for more recent work.

### Representing Decisions and Behaviors.

Finally, let me mention one more enabler, which is the modeling of decision making more as it actually occurs, than as it might be imagined to occur by game theorists. This is a subject of considerable research currently, by workers using a variety of methods that include neural nets, Bayesian nets, influence nets, and other techniques. My colleagues and I at RAND have used and are again using a rather different approach. See Davis (2002)[11], which discusses *synthetic cognitive modeling* of adversaries.

## PART TWO: OBSERVATIONS ON SIMULATION AS SCIENCE

This part of the paper is wholly different and attempts to respond to issues asked about for the workshop. There is a relationship between the two parts, however, in that *if* modeling and simulation are to be a science, then I believe the topics of Part One must be considered core elements.

### Should Modeling and Simulation Be Seen as a Science?

Personally, I see modeling and simulation as a natural professional specialty, and as a broadly taught skill used by scientists, engineers, and analysts among others--a skill that should be rooted in system science and other disciplines. I see it as something that "ought" to be teachable in 2-4 semester courses, if those occur on top of basic mathematical and computer skills through first year calculus.

I do not see any particular need for new departments of modeling and simulation. We have PhDs in operations research, the physical sciences, biophysics, applied mathematics, and engineering. People in all of these domains use M&S. My suspicion is that a pure PhD program in M&S would generate people lacking "real" modeling skills in the same way that many computer-science graduates lack such skills unless they were undergraduate scientists, engineers, or applied mathematicians.

A counter-argument is that the field will not get the respect it deserves until it develops more of a separate identity. That may be true, but why not accomplish this within existing departments? Why should OR PhDs still spend so much time studying queing and optimization? Why should computer scientists spend so much time working on operating-system theory? My examples may be wrong, but I think that room could be

found. On the other hand, new departments have historically been created when new fields simply could not gain the prestige and resources needed by working within existing departments. If that is the situation that applies here, then forming separate departments may be the best approach. In short, I am agnositic.

**But Simulation, by Itself, Does Not Seem to Be a Good "Science"**

Perhaps I am overly dominated by my own background, but to me simulation is merely a special kind of model - one that attempts to describe the time dependent behavior of a system. Intuitively, at least, I am hostile to the concept of simulation science in the narrow, because what is needed in the several communities served is a mix of simulations and other types of models developed with the benefit of principles and good practices. Whether the "right" model for a given purpose is a simulation, a steady-state equation, an interactive war game, a seminar war game, or something else depends on the circumstances. Further, when I have seen lists of what would be uniquely in the realm of simulation science, the subjects appear to me to be a mixture of engineering and craft, but not science. In contrast, general systems theory, which is arguably a basis for thinking about simulation systematically, applies much more generally than to simulation per se.

**What Might Be Underlying Principles of Modeling and Simulation Science?**

Here I will merely make some quick comments in response to questions that arose for and during the workshop.

Despite the importance ascribed to hypothesis testing in books on the philosophy of science, overfocusing on it can be overdone and can become pedantic.

Nonetheless, we have basic hypotheses such as that simulation can be understood in terms of general systems theory. If that is not true, then what is left out (aside from software engineering?).

Two principles from elsewhere in science clearly apply to M&S science. These are reproducibility and falsifiability.

*Reproducibility*. If a group of analysts do a study using M&S and reach some conclusion, then another group of analysts can redo the study and either corroborate the conclusions, disprove it (e.g., by finding fatal flaws in a key program), limit its validity by showing how results depend on assumptions, and so on. Reproducibility, then, is not transferring the computer code so that it can be run on another machine (although that is a special case of interest when results are confounded by the problems of complex adaptive systems). Instead, it is about peer review, counter modeling, and counter analyzing (where one uses different assumptions within the same models). This is very much in the spirit of science.

This issue has been debated for years in the operations research community, where many believe firmly that OR has adopted and adapted principles of the scientific method--even though OR folks typically consider OR to be more a discipline than a science.

*Falsifiability*. If one says that a given simulation is a good training system, then "falsification" might consist of showing that the skills learned by using the simulation are inappropriate for cases of considerable interest. For example, a deterministic simulation

may "teach" that the world is predictable, whereas good training might teach the need to adapt. Or, to use an example in analysis, the claim that a model is "good" for some type of analysis can be disproven by presenting significant instances in which the model gives poor results. A simple example of this is that models based on Lanchester or Bonder-Farrel attrition models can fail catastrophically to describe results of battles in which an attacker is able to concentrate force and exploit its concentration faster than the defender can conduct the counter-maneuver operations that are implicitly assumed in force-on-force calculations. What is "falisfified," however, is not the model as a whole, but the application of the model in certain kinds of circumstances.

**If It Were Deemed a Science, Could Simulation Be Studied Systematically?**

Of course it can. It has been studied for some years in a small number of schools in the United States and Europe. It has also been studied in some our major research labs and elsewhere. People have learned all sorts of things that go far beyond mere "lore." For example, the development of the high level architecture depended upon some rather sophisticated stuff, which can be regarded as applied mathematics, computer science or whatever, but can just as well be consider simulation science or, perhaps better, simulation engineering. The folks at USC (see Bill SwartoutÕs paper) are learning how to use "immersive" techniques to build training simulations that deal with soft subjects are obviously drawing on the behavioral sciences, so, again, I see it as fine engineering, whether or not it's science in the narrow. For someone studying the elegant concepts involved in establishing super-high-fidelity representation of humans, it seems to me perfectly legitimate to see the study as a kind of simulation science. But if others want to see it as a combination of applied mathematics and so on, ok.

An analogy here is that biophysics is now a field, but for years it was rather an orientation and, for years, an uncomfortable interdisciplinary field with no single home.

## ACKNOWLEDGEMENT

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# Toward Simulation on a Scientific Basis

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## BOUNDING SIMULATION

When considering the question of a science of simulation, it is necessary to define boundaries on just what we mean by these terms. We need to know what is in the domain of inquiry and what is not to productively form and evaluate the question of whether any part of simulation is suitable for scientific study. One way to begin is to consider the definition of the term simulation. The Online M&S Glossary [1] presents a definition of simulation as:

> Simulation: A method for implementing a model over time.

It further presents the definition for, the obviously required term, model, as

> Model: A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process. [1]

These definitions tell us is that a simulation is special kind of system, namely a representation of other systems (not to exclude the possibility that a simulation could simulate itself). The definitions also suggest (but do not require) than simulations are made artifacts, i.e., they are the products of some cognitive activity and do not occur "naturally". As such, the domain of inquiry for simulation must include all of the issues regarding the construction of simulations in addition to the contents of the models themselves. Finally, artifacts are made for a purpose, namely to be used. Therefore, the domain of inquiry for simulation must include how the artifact is to be used.

There are a number of ways to elaborate the bounds of a given field, but one helpful way is to form a *taxonomy*. The Online M&S Glossary [1] defines taxonomy as a classification system providing the basis for classifying objects for identification, retrieval and research purposes. Figure 1 illustrates the simulation taxonomy we have developed and used.

This taxonomy decomposes simulations into five main areas:

- Simuland: what is to be simulated
- Credibility: how people other than the developers regard the simulation
- Purpose: why the simulation is developed and how is it used
- Technique: how are models in the simulation implemented
- Programmatics: how simulation projects are conceived and managed.

Consideration of this figure will reveal that simulations have much in common with other systems, particularly software intensive systems. Figure 1 shows simulation as an amalgam of components of many other disciplines. Consider, for example, the issues associated with building a modern word processor and how many of those issues overlap with the issues in simulation as advanced by the taxonomy of Figure 1.

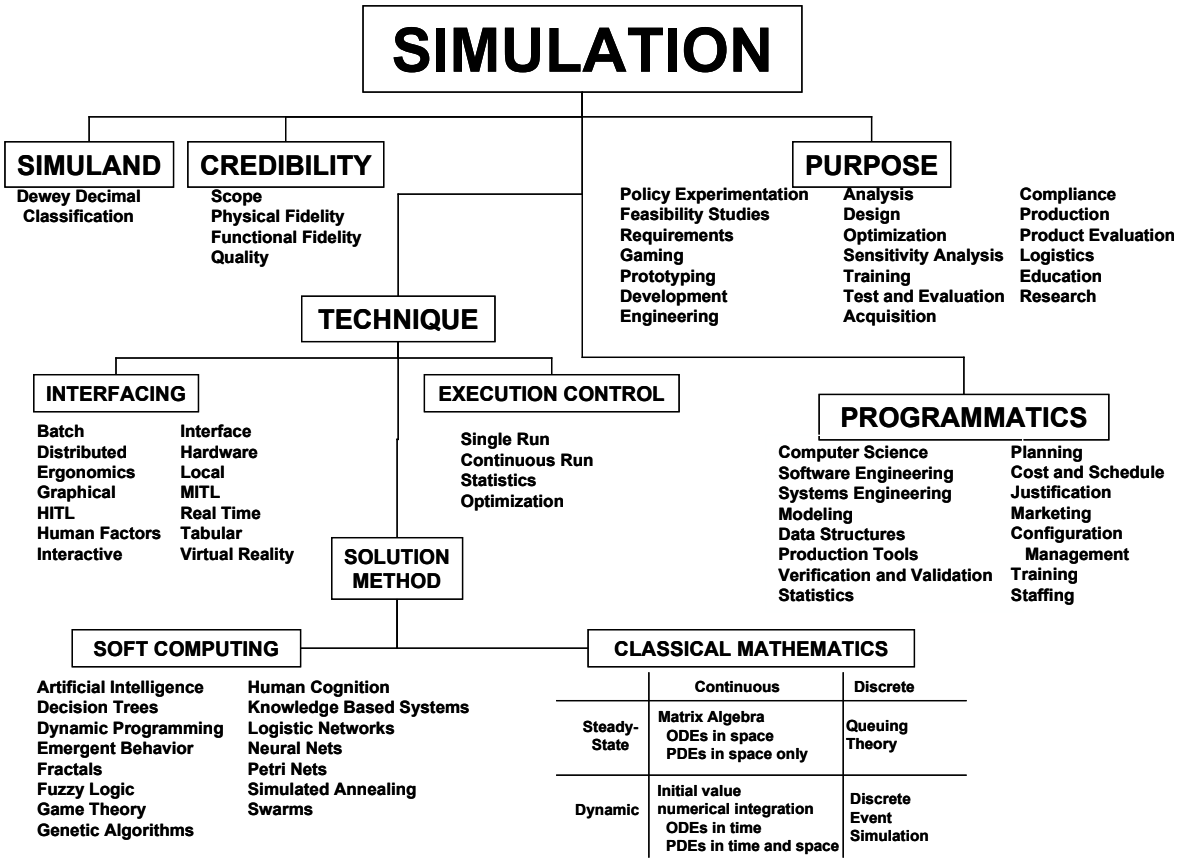


**Figure 1.** Taxonomy of the Simulation Domain

A prime contention of our position is that if there is a science of simulation, then some portion of the taxonomy in Figure 1 should be the best and proper field of inquiry of simulation as opposed to other fields.

## THE NATURE OF SIMULATION

Armed with a basic understanding of simulation, our thoughts turn naturally to the question of simulation as science. So, what is science?

> Science: The observation, identification, description, experimental investigation, and theoretical explanation of natural phenomena. [2]

Science includes:

- Observation
- Deductive & Inductive reasoning
- Experimentation
- Conclusion
- Communication [3]

The workshop's call for participation is a hymn of praise for the value science has brought to humanity, and we certainly agree that science has produced great value. In that context, the workshop's central question of "is there a science of simulation?" can be heard as "is there a science of simulation (and therefore some value) or not (in which case simulation has no value)?" That form of the question is so extreme as to provoke a "yes" answer whether or not simulation is actually a topic suitable for scientific inquiry. There are other sources of value besides science as noted by Greenberg & Hough's list of major value systems [3]. We intend no judgment here on the relative merits of these different value systems, just to note there are sources of value other than science, and not all topics are suitable for scientific inquiry.

> SCIENCE - A system of logic in which the truth about the natural world is sought based on factual, unbiased, repeatable observations and experiments, through the use of testable hypotheses. A hypothesis is presumed true until proven false. Evidence is sought to falsify it; all facts must be considered.
>
> LAW - The process or pursuit of justice based on legal rules of evidence. An accusation is legally presumed to be false until proven true. Evidence is sought to prove it; only legally admissible facts can be considered.
>
> PHILOSOPHY - A search for truth through an internally consistent system of logical reasoning (which may or may not include factual observation). Such a system can be based on any premise or agreed upon set of rules or descriptors of a situation or point of view.
>
> SOCIOLOGY - The analysis and description of sets of behavior patterns that have evolved in populations as "social norms", i.e. the usual, accepted ways of doing things, with and against which all behaviors are compared and judged.
>
> POLITICS - The pursuit of understanding and/or influencing the policies of institutions and/or governments. Upon erecting an internally consistent premise, an entire prescription for institutional and social behavior can be devised (e.g. federal democracy, fascism, communism, etc.). The premises are based on sets of assumed sociological and socioeconomic "truths".
>
> THEOLOGY - The interpretation of religious truths expressed in bodies of written and/or spoken histories and/or mythologies, generally accepted by proponents of a religion as revelations of the relationship of mankind to the universe and the meaning of life, especially applicable to things that are scientifically unknowable.

Therefore, simulation may have value, even if it is not a topic suitable for scientific inquiry. To further this argument, consider two additional value systems that Greenberg and Hough [3] did not note: engineering and mathematics.

The separation of science and engineering may not be surprising, as many think of engineering as applied science. Change in the material environment is the explicit purpose of engineering, and not, as is the case with science, the understanding of nature; accordingly its solutions are not right or wrong, verifiable or falsifiable, but more or less effective from different points of view [4]. Utility is the measure of merit for engineering, and engineering borders closest on science when it is developing *technology* (the application of science to industrial or commercial objectives).

The separation of mathematics from science may surprise some, but mathematics (except in the relatively trivial fields of counting) does not proceed from observation of the natural world. Instead, it proceeds from the construction of an internally consistent notation and analysis techniques developing from an axiomatic foundation. It is more important in mathematics that the axioms be useful, rather than description of nature.

Any casual consideration of the state of simulation practice today certainly indicates that simulation is much more a technology than a science. There are few if scientific hypotheses about the behavior of simulation related phenomena, and correspondingly few programs of rigorous experimentation in simulation, except at the extreme edges of simulation such as algorithms for random number generation. There are very few formal, peer-reviewed journals reporting on scientific investigation of simulation phenomena. Simulation conferences as they exist are largely a demonstration of how simulation technology has been applied to a problem. As regards academia, the very few simulation related degrees are in engineering colleges.

It may be that simulation is best viewed not as a science or technology but as an enabling technique, like mathematics. Some technologists have noted that in some sense, all of science is about the construction and test of models, and the really new development in modeling and simulation is in its application for engineering in the synthesis of new designs, or equipping users to make the best use of the design. Figure 2 illustrates this view of simulation, in which it is the enabling technique that on the one hand ties theory to experiment for science, and heuristics to test for engineering.

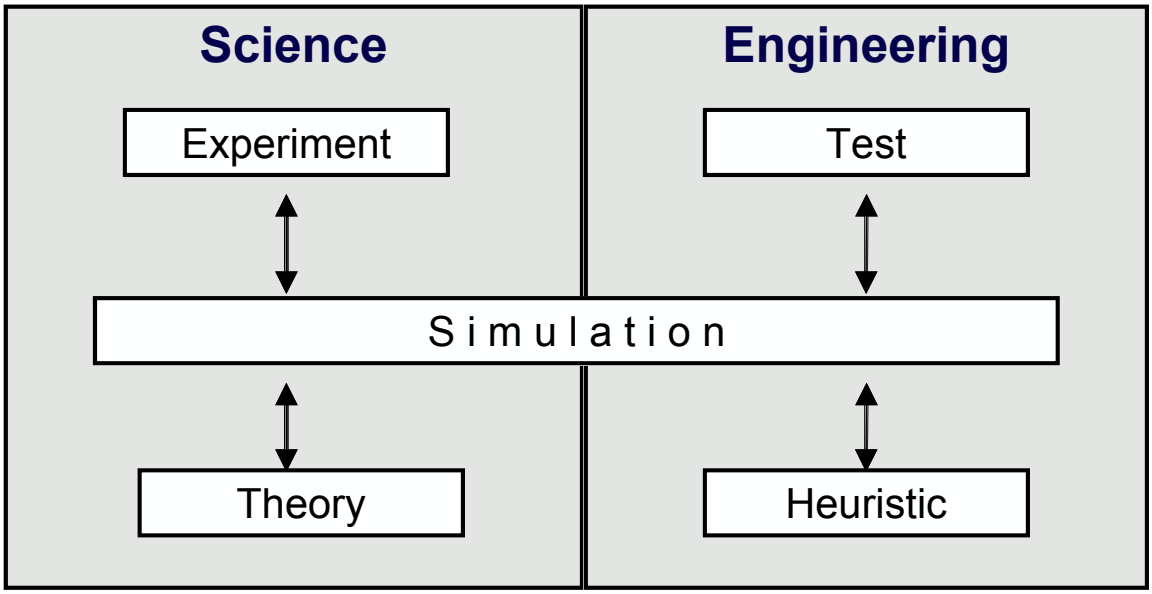


**Figure 2.** Simulation as an Enabler

A prime contention of our position is that simulation as practiced today and considered as a whole, is a technique, like unto mathematics, used by scientists and engineers to accomplish their goals.

## A SIMULATION FIELD OF SCIENTIFIC INQUIRY

Even so, there are aspects of simulation that are suitable to scientific study. The vast majority of these, such as observable characteristics of software, are not the sole (or even chief) province of simulation. Without meaning to belittle the challenges associated with developing and using simulations, these challenges are not for the most part much different that those associated with any large scale, software intensive system. Simulations are just a small part of the universe of such systems and would be simulation scientists can hardly lay claim to the privilege of denominating research on such challenges to be the domain of a simulation science.

What makes simulation different than other such systems is that in addition to all of the same challenges they face, a simulation also contains within it a model of another system. This system-within-a-system quality makes simulation a *meta*-problem. Further, the model of the system within is not just the de facto model, the model of everything known about the system under investigation (the simuland). That would simply be a model that included the simuland's referent. In any effective simulation, the system model is a carefully abstracted version of what it known. The process of abstraction, by which a simulation designer selects aspects of the system under investigation to include or discard, creates a measurable observable, unique to simulation, and suitable for scientific study, namely ***fidelity***.

> Fidelity: The degree to which a model or simulation reproduces the state and behavior of a real world object or the perception of a real world object, feature, condition, or chosen standard in a measurable or perceivable manner; a measure of the realism of a model or simulation; faithfulness [5].

Figure 3 presents a simple, if somewhat misleading, picture of fidelity. It is simple because it illustrates that a model's fidelity ranges from no relation to the referent to perfectly reflecting the referent. However, it is misleading in that it supposes that a model fidelity to the referent is a simple quantity, represent-able on a scale from 0 to 1. This is not true.

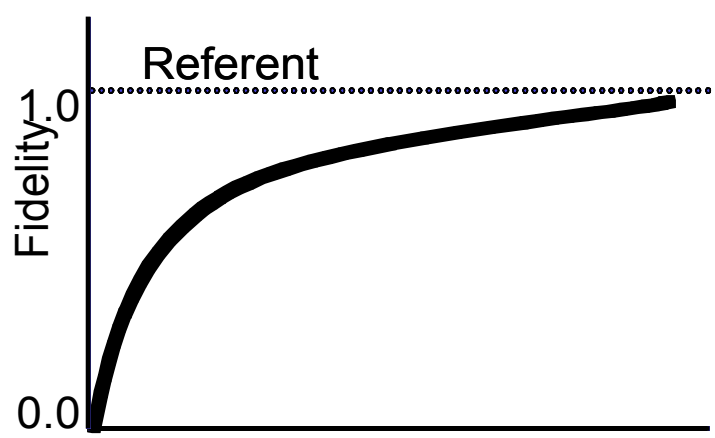


**Figure 3.** A Somewhat Misleading Illustration of Simulation Fidelity

Fidelity is actually a composite of a model's resolution, accuracy, sensitivity, precision, and capacity. Figure 4 shows fidelity as a multi-criteria composite, and shows how fidelity is integral to every aspect of developing a simulation.

The final prime contention of our position is that fidelity is the most significant aspect of simulation that both "belongs" to simulation

and is suitable for scientific study.

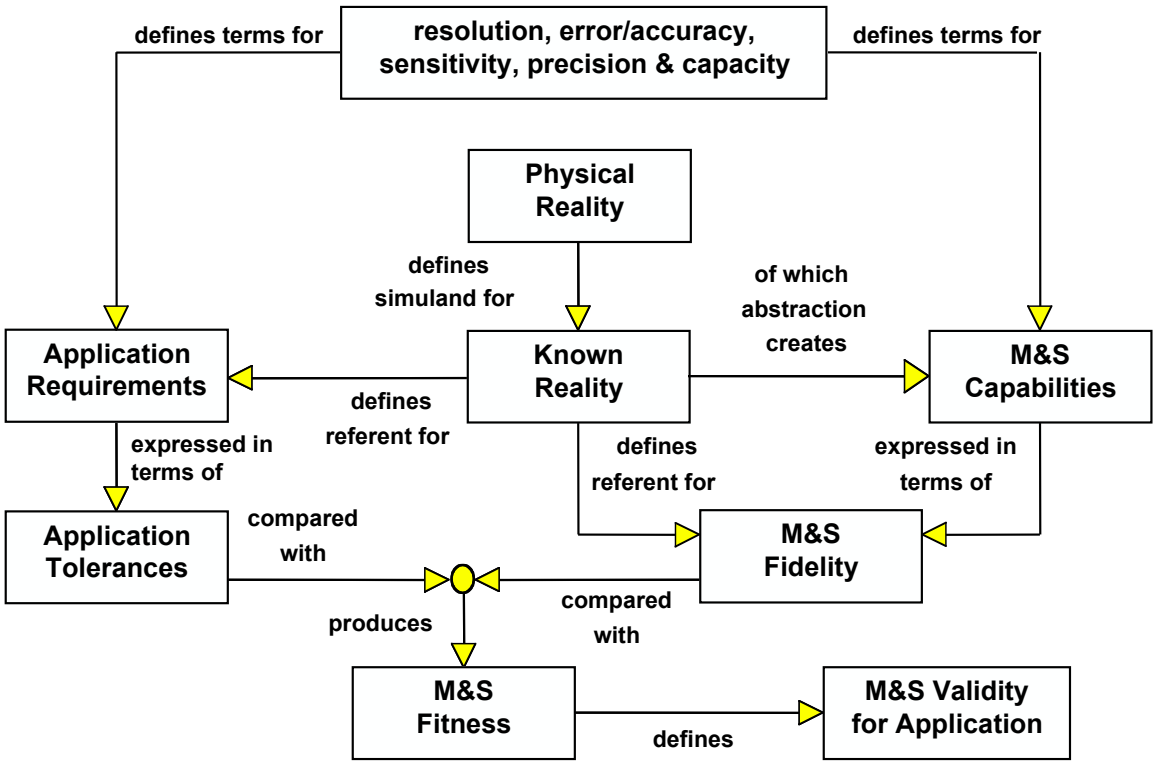


**Figure 4.** A Conceptual Framework Relating Fidelity to Issues of Simulation Design and Evaluation [6]

## TOWARD SIMULATION ON A SCIENTIFIC BASIS

Assuming for the moment that at least fidelity is a topic suitable for scientific study, why would that benefit simulation development efforts? In general, familiarity with science and adopting a more scientific frame of mind can benefit non-scientists in many ways (both personally and as citizens), including:

- Reducing the consequences of unfounded and incorrect biases.
- Increasing fairness of allowing opportunity for alternative outcomes even where biases are correct.
- Reducing cost of wrong decisions based on jumping to conclusions from inadequate information.
- Avoiding being fooled by those who profit from deceiving the ignorant or unwary.
- Allowing more competent assessment of science-based issues facing society that require political and social decisions.
- Improving the responsible use of the power of this knowledge. [3]

Specific to simulation, we suppose a number of benefits to a scientific foundation for simulations.

Objective Validation of Simulation Models: validation is the process of determining the degree to which a model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model [1]. However, at present this determination is a subjective assessment. A better scientific understanding of fidelity would first provide the means to measure the degree to which the simulation is a representation of the world. Second, a scientific study could propose and test hypotheses about the degree of fidelity required to succeed in a given application. Both of these developments would shift validation from a subjective basis to an objective basis.

Improved Reliability of Simulation–Based Decisions: a scientific study of fidelity would involve hypotheses about how abstraction choices affect the quality of the result data provided by a simulation. For example, one greatly desired simulation feature is prediction – however, only highly detailed, narrow scope simulations today provide any predictive value. A scientific basis for simulation would reveal how and why abstraction choices effect prediction.

Interoperability: developments like the High Level Architecture and Distributed Interactive Simulation have gone a long way toward solving the model intercommunication aspect of interoperable. They do not solve the problem of predicting a priori the full-scale semantic interoperation of simulation models. A scientific understanding of the nature of fidelity would provide the basis for predicting the semantic interoperability of models.

## CONCLUSION

There are aspects of simulation that are suitable for scientific study, although they are a relatively small part of the total problem of development and using simulations. However, there is a significant obstacle to any such scientific endeavor, namely unlike existing scientific fields, the available observations are very sparse. Most significant simulation problems (and hence the opportunity for large payback) are within very large simulation projects, but by their very nature such projects are uncommon. In addition, simulations of any scale are not readily available for analysis. Contrast simulation with a field like astronomy – in the beginning anyone wishing to scientifically study astronomy simply had to walk outside and look up. Of course, very quickly it was necessary to construct and use analytic tools, but the raw data was and is readily available to any budding astro-scientist. This is not so with regards to simulation. Like politicians, simulationists bury their mistakes.

Finally, we close with a caution about the difficulty of engaging in serious scientific study. Consider for example, Feynman's tale [7] about cargo cult science, in which people follow all the apparent precepts and forms of scientific investigation, but they're missing something essential. That something is that the scientist must give all of the information to help others to judge the value of the contribution; not just the information that leads to judgment in one particular direction or another. But such complete disclosure is unlikely in an environment such as exists today in the field of simulation, in which commercial interests greatly overshadow the benefits of a scientific foundation.

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# Philosophy, Science & Simulation

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## INTRODUCTION

In the past, the states of software and computing hardware technologies limited our abilities to develop simulations of complex phenomena. The relentless advance of these technologies has dissolved these barriers in many cases. Now, despite our considerable experience in building simulations for a wide variety of purposes, our shallow understanding of their fundamental nature limits our success. Most other engineering disciplines hit this same barrier, often with disastrous consequences. Only a concerted and scientifically disciplined effort to discover this knowledge can lead to our overcoming this barrier and, thus, to realizing the promise of powerful predictive representations of complex phenomena. Without the knowledge such an effort will supply, the progress simulation technology has seen over the past decade will slow, the costs of simulation development will rise precipitously, and their reliability will drop. We have started to see this trend even now. This requisite fundamental knowledge and its pursuit could be called the science of simulation. However, valid questions exist as to whether such a science could be possible.

The very nature of science has deep implications that philosophers have debated for hundreds of years. This paper offers a simplified and pragmatic view of science for the purpose of exploring the fundamental nature of simulation. This view defines science as the body of consistent knowledge that describes the natural phenomena underlying the behavior of Nature. This definition reduces the more philosophical question of "Does a science of simulation exist?" to "What scientific models could exist that could explain simulation phenomena?"

This paper considers the relationships between philosophy, science and simulation. It begins by exploring some aspects of the philosophy of science. It then uses this perspective to show how science and simulation fit together. This connection suggests possible areas of simulation that could yield to the explanatory powers of science. This paper concludes by recommending possible scientific experiments exploring the fundamental nature of simulation. These experiments, if performed and their results independently repeated, provide proof of the existence of a science of simulation.

## PHILOSOPHY & SCIENCE

Science studies Nature and, from that study, tries to discern the laws that describe Nature's behavior. Nature displays both state and behavior. State describes Nature's instantaneous appearance (i.e., those aspects that can be observed directly or inferred from direct observation) while behavior describes the change (or lack of change) of Nature's state over time. In general, we can only actually observe state and changes of state. We can then infer behavior from those observations performed over time. Finally, phenomena are the specific and actual mechanisms that change Nature's state over time (or prevent its state from changing over time) and, thus, underlie its behavior. We can

only observe the phenomena of Nature by observing how those mechanisms change its state. We cannot directly observe Nature's actual phenomena and can only infer their character from the state changes they cause.

Scientists strive for explanations of observed behavior and their underlying phenomena through their theoretical and empirical studies. In the course of doing this, they build phenomenological models to explain their observations of Nature and then validate those models through further observations and controlled experiments, preferably independent of their observers. These models explain observed behavior in terms of the dependencies between the states of Nature. These models become the scientific theories we see in the scientific literature.

Thus, all of scientific knowledge consists of a collection of models describing Nature. Scientists and philosophers have struggled with the character and limitations of modeling for as long as science has existed as a form of human study. Many eminent scientists have contributed to this discourse (e.g., Heraclitus, Parmenides, Plato, Galileo, Newton, Leibniz, Laplace, Kant, Maxwell, Boltzmann, Gibbs, Einstein, Von Neumann, Schroedinger, Bohr, Heisenberg, Dirac) [1]. All of our current scientific knowledge stands upon the issues addressed by this philosophy of science (e.g., causality and the flow of time).

Interestingly these models do not necessarily represent the ways that Nature really works. They just fit some subset of the observations of some aspect of Nature. This suggests that nothing that we know about Nature is necessarily absolutely true (i.e., in the sense of being the real reason that Nature behaves the ways she does). Our knowledge just agrees with our collected observations (hopefully). Galileo emphasized the importance between our observations and models (i.e., theories) of Nature when he said "Science can advance only so far as theories, themselves based upon experiment, are accepted or rejected according as they either agree with, or are contrary to, other experiments devised to check the theory [2]."

All models abstract Nature in their representations (i.e., no model provides a complete representation). Therefore, all models have limitations in their correspondence with the observations of nature. In other words, all scientific models are necessarily incomplete or inaccurate over some domain. Philosophers of science realized this property of models, their inherent abstraction of Nature's behavior and discussed its limitations extensively [3].

Scientists have traditionally employed two distinct modes for collecting information about Nature:

- Controlled experiments and
- Careful observations.

Scientists performing controlled experiments arrange circumstances so that a narrow aspect of Nature's behavior predominates the observable situation during the course of the experiment. They then watch and record Nature's states under these "controlled" conditions. Controlled experiments can give us reliable quantifiable knowledge of Nature but their conditions must be well understood or the results of experiments can be misleading. Many aspects of Nature do not lend themselves to human control (e.g., the

behavior of planetary and star systems). This leaves scientists with only the ability to observe their state changes over time. Careful observations can contribute as much good science as can controlled experiments. However, they often require significantly more effort to characterize the interacting phenomena of Nature. Often observation leads to theory that can then be tested through controlled experiments.

In general, observations/experiments test the limits of model validity. As Weidner and Sells say, "Theory and experiment both play essential roles in the development of physics. Experiment discloses the facts of Nature; theory makes sense out of them [4]." Figure 1 illustrates the marriage between theory and experiments where models embody theory. Experiment creates observations from which scientists can build models and models create predictions that the observations from experiments can verify.

Independence of the observer/experimenter is essential to science. This means that two independent observers performing the same observations or experiments must obtain the same results. No science comes solely from a single scientist's work. Others must independently reproduce that work, often many times, to ensure the integrity of its results.

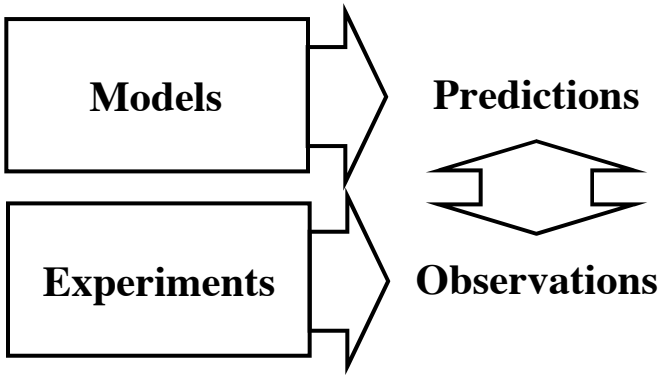


**Figure 1.** Coupling between Models and Experiments.

Common wisdom suggests that cause produces effect. In this case, a cause is the combination of initial conditions and the phenomena that must be present to precipitate an observed state change (or lack of change). Effect is a change in nature's state over a specific interval of time. This relationship is known as causality and philosophers of science have discussed it at length [1, 3, 5-7]. Causality represents one model that explains the phenomenon associated with the order and direction of time. But, the causality explanation has the same limitations of any model. In effect, the phenomena represented by causality both generate & constrain Nature's behavior.

## SCIENCE & SIMULATION

Many models describe the behavior of Nature (i.e., its change of state over time). When a device (not necessarily a computer) executes a model, it replicates the behavior of that part of Nature being modeled (in actual effect or an abstract representation of Nature). This execution of models to create observable behavior has been called simulation [8]. A simulation's execution device can take many forms including humans, computers and surrogate devices. Some models created by scientists become computer simulations. Exercising these simulations has enabled much of the world that we take know (e.g., weather prediction, space flight, microelectronics, safe air travel). Yet, few, if any, have attempted to apply scientific method to understanding the nature of simulations. Clearly,

the simulation behavior resembles the things they simulate but it also differs, sometimes in seemingly unpredictable ways. A potentially productive area of exploration is the correspondence between simulation and those things they represent, their simulands.

We can describe the entire world of modeling and simulation in terms of information and the flows of information. The information of modeling and simulation describes the objects that they represent. As in any other natural phenomenon, the interesting parts of modeling and simulation arise from the changes of state in that part of Nature. Fortunately, all information can be observed (i.e., because of its inextricable coupling with energy of various forms). Therefore, the phenomena related to information can describe the interesting parts of modeling and simulation, its behavior. This conclusion leads us to believe that a science of simulation could exist that explains the coupling between the different products/participating information.

Figure 2 depicts the information flows associated with a generic modeling and simulation effort. This information model of modeling and simulation begins with scientists observing some aspects of Nature and producing information about it as observations. Scientists then consider those observations and develop models of the underlying phenomena. They test those models through further observations or controlled experiments. These processes and information flows define the realm of science.

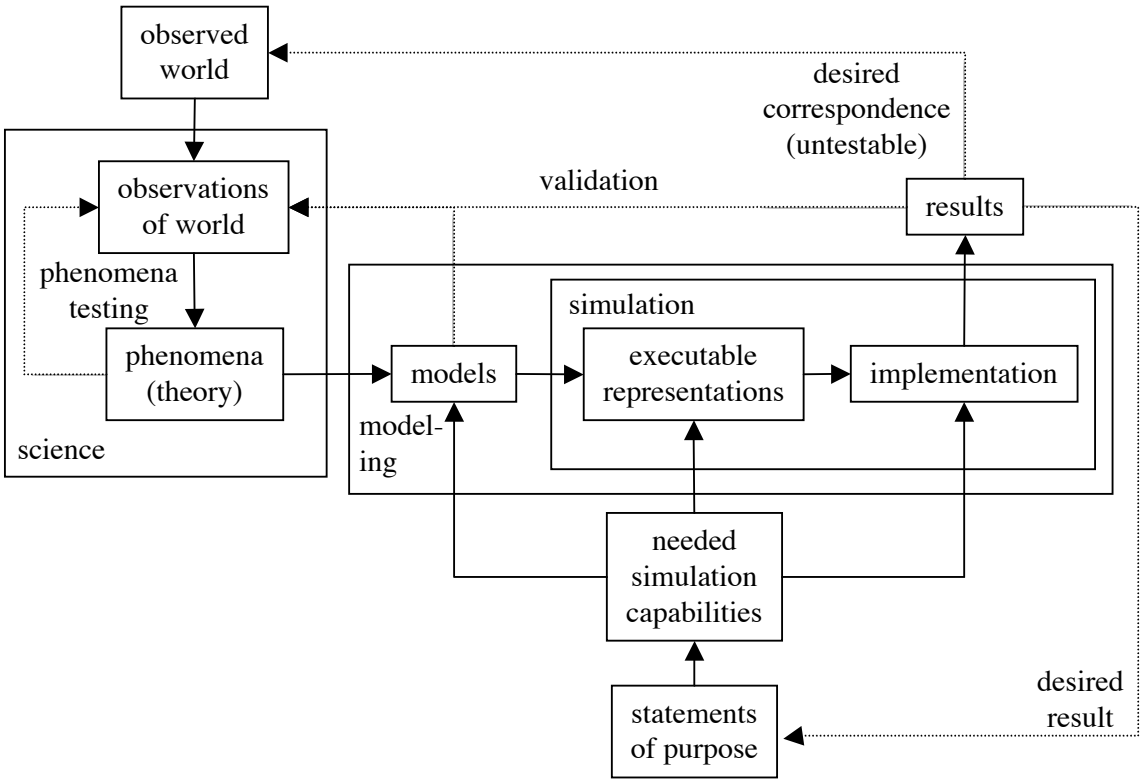


**Figure 2.** Illustration of an Information Model of Modeling and Simulation Processes.

Modelers take the information produced by scientists and often further abstract those to yet simpler models or, in some cases, assemble multiple models into even more complex

models. Simulationists create executable representations of those models and then implement those models in some execution environment, often one or more computers. They then execute those simulations to produce results that parallel the behavior of their natural counterparts, the simulands. They can compare those results against the actual observations of Nature to assess the validity of the simulated representation. These processes and their information flows define the realm of modeling and simulation.

This model has a few interesting properties. Primarily, the results should contribute to serve some user's purposes. As described above, a simulation must represent the behavior of some other object(s) in Nature. Ideally, its results will correspond closely enough with the behavior of the aspect of Nature that it represents to achieve the user's objectives. This correspondence can only be reasonably checked by comparing the simulation results with the observations of the natural behavior that it represents. In addition, the models underlying the simulation can only be checked against the original scientific models from which they were abstracted. Models, by themselves, cannot be executed so they cannot be compared against the observations, as can a simulation's results. This leads to the conclusion that model validation is a weak form of validation (since it cannot be checked against the actual observations). Therefore, results validation provides the strongest form of validation if and only if simulation results are checked against the actual observations of the natural behavior. All this creates some notion of simulation validity (i.e., how well the simulation reproduces the aspect of Nature's behavior that it represents).

As discussed, simulations will faithfully reproduce, to some extent, the behavior of that part of Nature that they represent in their output. But, occurrences of simulation behavior deviating from that part of Nature they represent are common. These deviations of simulation from simuland are a fundamental characteristic of all simulations. The phenomena that affect the correspondence between simulation and Nature include

- Abstraction effects and
- Causality differences.

The phenomena associated with model abstraction affect simulation correspondence. Since all models have correspondence limitations so must all of simulations that rely upon these models. This means that no simulation can create a representation of Nature better than the models from which it was derived. The term "fidelity" describes the representational capabilities of models and simulations [9]. The degree of correspondence between models and simulations and their simulands, called accuracy or error, is one component of fidelity.

The same phenomena that constrain Nature to certain behavior (e.g., the First Law of Thermodynamics, conservation of energy) do not constrain the simulations representing that Nature in the same way unless those simulations explicitly and accurately represent those phenomena in their models. Other phenomena, not necessarily associated with the represented phenomena (e.g., those associated with computer execution and communications), clearly also affect simulation execution and the behavior that simulations produce. These causality differences between simulations and their simuland include

- Interoperability issues and
- Performance issues.

Fortunately, we can observe the behavior of both Nature and simulation and compare them to assess the importance of their differences to assess the magnitude of these effects. This ability creates one opportunity for exploring one fundamental characteristic of simulation.

The interoperability issues represent one aspect of this opportunity and these are particular poignant for distributed and composable simulations. Differences in the fidelity of interacting simulations can cause correspondence deviations in two primary ways

- Functional dependencies and
- Manifold representations.

Several criteria have been derived, but not experimentally validated, that describe the relationships necessary to support a specified level of fidelity of the combined simulations in terms of these phenomena [10-13].

Performance issues can also cause correspondence problems but these effects are not as well understood as the interoperability issues. These create a plethora of opportunities for experiments.

## POSSIBLE EXPERIMENTS

The concepts presented in the previous sections suggest one avenue of experimentation. Table 1 outlines the nature of this experimental direction.

**Table 1.** Proposed Experiment to Examine the Fundamental Nature of Interacting Simulations.

| | |
|---|---|
| Objective | Identify the magnitude of the effects of interoperability and performance upon the correspondence between a simulation and its simuland. |
| Procedure | Execute simulations of well characterized phenomena and record their output, |
| | Vary the model fidelity and the properties of the computing environment (e.g., performance & interoperability conditions), and |
| | Observe how the correspondence between simulation and Nature differs with these changing simulation characteristics |

This experiment could add to our body of knowledge of simulation and improve our ability to construct simulations in at least three ways:

1. It will tell us how closely we must control the computing infrastructure to achieve a certain correspondence between simulation and nature;
2. It will help in the design of both computing environments and simulations; and
3. It will result in concrete relationships that could be taught in school thereby making simulation architecture less sensitive to individual attributes.

These experiments can easily be performed and the data analyzed. But they will only add

to real scientific knowledge if others can independently reproduce the experimental results they produce. Further, the identification of simulation as a class of information system and the model shown in Figure 2 suggest further opportunities for experimentation. All of this discussion paints a rich picture of the science still ahead of us that explores the phenomenological nature of simulation.

## CONCLUSIONS

Why study simulation scientifically? Science reaches for the surest truth, truth that applies broadly and persists over time. Science creates the most powerful form of knowledge known to humankind. The assurance that real science supplies founds much of the engineering and medical practice that has created the world we know and enjoy today. Scientific study has even permeated our justice system to some extent (e.g., genetic evidence) and, as legal trends show, will continue to do so. Over the few thousand years of its development, science has evolved into a very robust and consistent source of knowledge unsurpassed by all other sources. This type of knowledge about simulation would surely supply tangible benefits beyond our meager imaginations as it has in so many other fields. Furthermore, science generates the knowledge that we can confidently teach to improve and unify the capabilities and knowledge of all practitioners in the field. These promises make a science of simulation worth pursuing.

Any scientific study of any set of phenomena is a long journey. This paper has shown a clear path along which the journey to scientifically characterizing the fundamental nature of simulation can begin.

## ACKNOWLEDGMENTS

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# A Science of Simulation?

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The question posed to members of a workshop on "The Scientific Exploration of Simulation Phenomena" in June 2002 asked whether in fact a science of simulation existed or could be developed. All participants shared their perspectives on this issue. My sense of the discussion was that people involved in the development of simulations for the Department of Defense experience a plethora of problems involving models and programmers and projects of unimaginable scale. Their hope is that a "science" of simulation could lay a firm basis for addressing some of these problems.

My reaction to the problems expressed by the practitioners is that while the problems are terribly real, I didn't see that they necessarily were unique to simulation development. Lack of programmer training in application domain basics, issues of system complexity, issues of getting separately developed bodies of code working together---my thought was that these have to be the same kinds of problems that are faced elsewhere, such as development of a new national air-traffic control system, or the imagined systems for ballistic missile defense. These are problems of software and system engineering. If there is one thing that distinguishes a simulation from these other application domains, it is the possibility for uncontrolled growth in scale.

However, before I muse about a science of simulation I think I need to muse first on the use of the noun "science". At our workshop the dominant idea was that a scientific veneer could be lent to simulation system building and evaluation if one could devise hypotheses, run repeatable experiments, and possibly negate a hypothesis on the basis of the experimental outcome. While that activity is certainly a component of physical science and worthy of emulation, it is also critically important to realize that in physical sciences the hypotheses posed are statements about (presumably) immutable physical laws, e.g. the speed of light is independent of its frame of reference, or pressure and temperature in a gas are proportional. The power of experimentation is that it can provide understanding about fundamental underlying physical laws. However, an equally important aspect of physical science is theory to explain and predict the outcomes of experiments.

There is an adage which says that any discipline which needs to put the word "science" in its title, isn't. (As one with graduate degrees in "computer science", I would prefer the discipline be named "Computing".) There is insight in that adage. I would find a word other than "science" to describe the formally analytic aspects of disciplines such as "political science" and "social science". I would reserve the full sense of the "scientific approach" for areas grounded in immutable law, with the approach being applied to discover and apply that law.

With my prejudices now on full display it is fair to ask whether mathematics is a science as I have described it. I think the answer is yes. The immutable laws are laws of logic, and relationships that must exist as a result of those laws. One can certainly design

experiments whose results can refute hypotheses. Pushing the envelope, we can ask whether the discipline known as "computer science" is indeed a science. I think those areas which are largely mathematical (e.g. theory of computation, algorithms, formal languages) are, for the same reasons that mathematics is. Other areas of the discipline rely heavily on experimentation, e.g. performance evaluation. The underlying laws being explored are immutable, but are also idiosyncratic to the system under study. Nevertheless the methodology is used the same way and for largely the same reasons as in the physical sciences. However there are significant sub areas of computer science which I don't think admit to the direct and full application of the scientific approach. Software engineering is one of these, and is an area that overlaps significantly with the concerns of simulation practitioners. This is an area where methodological arguments dominate, over analysis and experimentation. The area is not bereft of experimentation, and that activity does give insight into human tendencies when developing or interacting with large bodies of code, but I don't see the experimentation resting on hard re-testable law in the same way as physical and mathematical sciences do.

This then brings me to my gut feeling about the feasibility of "simulation science". Can there be one? ---of course. The work on formalisms by researchers like Ziegler is clearly in the mathematical tradition. There is a large body of mathematical work on simulation output analysis which likewise fits my understanding of "science". Performance evaluation of simulation systems has a scientific basis. But all I'm saying here is that like computer science, simulation has sub areas that admit to a scientific approach, and areas that don't. And to the point, I don't think that the kinds of problems that Department of Defense practitioners are having designing, developing, and deploying large-scale simulations have solutions based on the scientifically analyzable sub areas of simulation.

I think that rather than ask whether there is a "Simulation Science", the better question asks how to develop a better "Simulation Engineering" discipline. The distinction is important I think in terms of managing expectations about outcomes. Mankind has been engineering solutions to problems long before we achieved fundamental understanding of why the solutions work. Bridges built on arches of stone were discovered and built long before force vector analysis explained why they work. That's the point we're at with large-scale software systems, but with a difference. We've built smaller scale systems and have gotten them to work, and now we want to build really big ones. The difference is that bridge design ultimately rests on physics, and software design rests on something a great deal more nebulous. If there are "laws" that affect our ability to develop reliable software systems of very large scale, they are "laws" about human nature, not logic, and not natural science. We can get things done, of course, without a full understanding of any foundational forces that might be at play. But I think we have to realize that for the foreseeable future, the best we can hope for are methodology-oriented engineering approaches to large-scale simulation design. Having said that, I think it is certainly possible to develop university programs that prepare students for working in simulation by designing a curriculum drawn from selected areas of systems engineering, mathematics, computer science, and operations research.

In summary, I'm trying to simultaneously express a number of sentiments. I appreciate the difficulty and magnitude of the problems faced by the Department of Defense in their simulation and modeling efforts. I understand the desire and motivation for putting

simulation on a rigorous basis, to try and deal with some of these overwhelming problems. However, I think the development of a comprehensive "Simulation Science" to solve these problems isn't possible given my conservative view of what constitutes science. I'm not just quibbling about words. Use of the word "science" creates certain expectations about what is possible within such a framework, expectations that I don't think can be met. Instead I would argue that those limitations be recognized and accepted up front, and turn the discussion towards a vein more likely to produce results, albeit incremental. We should view large-scale simulation development as essentially an engineering problem, in an area where the underlying principles aren't terribly well understood. We will build large simulations using methodologies (hopefully) based on our best some will work and some will fail. Without knowledge of underlying principles (if there are any) it will be critically important to analyze both successes and failures to understand what contributes to both. Finally, in order to maximize the chance of success, it will be important to train "simulation engineers" as best as possible, to enable us to achieve our goals and at the same time come to understand what methodologies work when used by highly trained professionals, and which ones do not.

# The Possibility of Simulation Science

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## INTRODUCTION

The Sim Science Workshop addresses four questions: 1) Is sim science possible? 2) What can contribute to sim science? 3) How can we improve that contribution? and 4) What impact can Sim Science have on the world? The discussion below addresses each of these four questions then adds some closing comments.

## IS SIM SCIENCE POSSIBLE?

In order to answer this question, we must know what science is. Over time, the definition of science has changed. In the ancient (classical) world, science was the state or fact of knowing. In the Middle Ages, science was used interchangeably with arts. Today, although some would like to restrict science to the branch of study that relates to the phenomena of the material universe and its laws, the term science has many shades of meaning because the term is applied to so many different areas. For example, science is associated with physics, chemistry, biology, information, computer, social customs and behavior, management, and even as an adjective with some kinds of fiction. "Science" usually involves some or all of the following traits: application of systematic process, observations, theories/hypotheses, repeatable experiments, explications of phenomena, predictions, potential for falsification, etc. We shall not try to develop a more precise or complete definition since it is hard to find one that accurately describes the full variety of disciplines that are accepted as science today.

A discipline that is accepted as a science usually has three attributes. First, the science has "scientists" associated with it who possess community-accepted credentials. For example, a PhD in physics normally qualifies one as the kind of scientist known as a physicist. Second, a science typically has a codified body of general knowledge about it which all who work in that discipline are expected to know. Third, a science normally has reasonably well defined methodologies for conducting experiments, performing research, or practicing/working in that discipline.

Now we can address the first question, Is sim science possible? From a definition perspective, the answer is Yes. The definition of "science" is vague enough and varied enough to allow legitimate use of the term "simulation science." *BUT* sim science lacks the three attributes typically associated with a science, and it is my judgment that the discipline of simulation is unlikely to acquire these three attributes within the next decade (or two). However, I expect the discipline of simulation to be improved within the next few years by more systematic approaches and by increased use of accepted "best practices," but that is not the same as the simulation discipline qualifying as a science.

So, *I answer the first question with, Sim science is possible, but not likely within the next generation of professionals* (20-30 years).

## WHAT ARE POSSIBLE CONTRIBUTIONS TO SIM SCIENCE?

*I identify four possible contributions that would move the discipline of simulation toward a science*. First, the boundaries of sim science need to be determined (defined). We need to say what is included in simulation (or what simulation is included in). For example, are software engineering, modeling, analysis, etc. part of sim science? Or is sim science part of one of them (such as analysis)? Until the boundaries of a discipline are basically clear (even if fuzzy at points), one cannot make much progress on transforming that discipline into a science. Second, basic sim science knowledge needs to be codified. Is the core knowledge that all simulation professionals should know contained in the several popular textbooks on computer simulation? Or is there more to it? Is that core knowledge well enough defined that one could prepare for sim science the equivalent of the various tests used to determine who has professional capabilities as an engineer, CPA, medical practitioner, lawyer, etc.? Third, credentials required of a simulation scientist need to be clearly defined so that anyone with those credentials will be recognized and accepted as a scientist qualified for the simulation discipline. Current credential endeavors for simulation professionals (by NTSA/SISO/et al) are oriented toward the journeyman level (or lower), not toward the scientist level. Such proposed credentials require little more than that one have had a course in modeling and simulation, touched a computer running a simulation at least once, or claim interest in simulation. Fourth, "best practices" for sim science need to be established and *enforced*. That means that any one in the simulation community who does not use such best practices has to be declared as *unprofessional* (as publicly as needed to get the best practices to become the normal way of behavior in the simulation community). This is probably the most significant contribution that can be made to sim science, and until it occurs, there will be little real progress in transforming the discipline of simulation into a science. However, doing this will create much hate and discontent as well as ruin a few careers – both of good simulationists and of irresponsible unprofessional characters.

## WHAT'S NEEDED FOR SIM SCIENCE PROGRESS?

*I will identify what I think can be the spark that will start the transformation of the discipline of simulation into a science*. It combines elements from several of the items mentioned above. That spark must come from the academic part of the simulation community. They have to define a coherent set of skills, along with a curriculum of courses and lesson plans to support such, that are needed for simulation competence at bachelor and graduate levels. It does not matter whether such skills are imparted in courses in a simulation department or elsewhere (aspiring physicists know what math skills are required and take most of their math courses from outside the physics department in order to obtain needed skills). The simulation user community in government and industry need to encourage and support identification of the coherent sets of simulation skills and development of the educational materials to facilitate attainment of those skills. Without this spark, I expect little real progress toward sim science.

## HOW WILL SIM SCIENCE HELP THE WORLD?

Simulation is a support function, like analysis and various other disciplines. As a support function, simulation can help things to be done better (decisions, designs, training, etc.). Improvements and advances in the discipline of simulation can lead to improvement in simulation development and use. In theory, those improvements in simulation might be as startling and significant in stimulating progress as introduction of the "scientific method" was a few centuries ago for many areas of intellectual activity. Personally I think such is unlikely since much of the progress from simulation capabilities in the past few decades has come from practice of the simulation discipline without it being a science. The "critical mass" needed for explosive movement toward science by the simulation discipline has not yet manifested itself in my perspective.

## THREE CLOSING COMMENTS

The delight of an essay is the freedom to express one's ideas, unfettered by restriction to what experiments and observations have demonstrated or logic can prove (as one should be in a serious study). The comments in this section allow me to revel in that freedom.

1) A current emphasis of mine is the importance of an explicit simulation conceptual model to support verification and validation (V&V) of simulation development and intelligent decisions about simulation use and modification. The importance of such is not novel and has long been recognized, but the M&S community does not demanded that such be a standard part of M&S development and use – the Missile Defense Agency (MDA) may become an exception by demanding such of the MDA M&S community. If inertia (politeness denies a more candid explanation) prevents this rational practice of insisting on explicit conceptual models for simulations, what realistic expectation is there for rapid movement toward sim *science*?

2) Simulation literature is relative sparse for a science. There are only a handful of entry-level textbooks, and few (if any) textbooks for advanced practitioners. Accepted sciences have many textbooks. Who is writing the textbooks needed for simulation to become a science, especially the advanced ones? Who is likely to publish such? Subsidy from industry or government will be required for development of such textbooks to be financially viable, but who will provide that?

3) Very well established disciplines have firm criteria that determine who is considered a "scientist" or practitioner of that discipline (PhD, PE, MD, etc.). Some disciplines (such as analysis) lack that kind of benchmark. Sim science is more like the latter set of disciplines than the former set, and as such may be more likely to remain a discipline than become a science.It is always possible to say more, but I think I have said enough, probably more than enough, for a white paper, and will now close.

# Thoughts on Science and Military Simulation

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## INTRODUCTION AND DISCLAIMER

This "position paper" has been developed for a workshop within which the relationship between simulation and science is to be examined. Whenever professional self-deprecation is called for—as it all-too-often is in my case—I sometimes appeal to a brilliant quote whose attribution I am unsure of: "*Any discipline that calls itself a science, is not one*." I am in possession of three degrees in Computer Science. So, while I would consider myself a modeling and simulation (M&S) professional, whether or not my discipline qualifies me to discuss the nature of *M&S as science* is clearly a judgment call.

Furthermore, while my graduate work in M&S could arguably be considered a *somewhat* scientific endeavor, my post-graduate career has been spent in service of the U. S. Federal Government—specifically the U. S. Department of Defense (DoD). Practicing science in a political arena is difficult … at best.

And further still, for the past several years, I have been serving in an M&S policy office for the Headquarters, Dept. of the Army. There isn't anything scientific about Powerpoint.

My dubious qualifications having been established, I will now unabashedly regale the intrepid reader with my thoughts on the nature of M&S as science.

## ON SCIENCE

I will leave to other workshop attendees more learned in the history and philosophy of science than myself to establish the overall framework for the SimScience debate. I frankly much prefer Michael Crichton to Karl Popper. I am more-or-less aware that science evolved from a discipline referred to as "natural philosophy" dating at least to the ancient Greeks, and that a "scientific revolution" is widely recognized as taking place in the 1500s–1600s through the works of Galileo, Bacon, Newton, Descartes and so forth. I have read that the term *scientist* was coined by William Whewell in 1834 [1]. I am aware that the nature and value of science itself is the subject of considerable debate—debate regarding the nature of inductive vs. deductive reasoning; debate on the value of hypotheses, experiment, and probabilistic inference. Each of the debates within the broader Philosophy of Science must be manifest in any discussion of the science of simulation. However, these do not seem surmountable within the confines of this article (not to mention the confines of my own intellect).

For purposes of this position paper, I will regard science as a *rigorous, repeatable, process through which knowledge is attained*. Certainly, knowledge is gained through means other than scientific inquiry. However, many believe (as do I) that the structure of

scientific method provides the most productive and reliable mechanism through which to attain knowledge—and hence the popular belief that *science is good!*

## ON SCIENCE AND SIMULATION

One of the questions we are being asked to consider is "could there be a science of simulation?" That is, could (should) simulation be viewed as a science in the same way that biology, chemistry and physics are viewed as sciences? In the sections that follow, I'll begin to address that issue. But before engaging in that discussion, I would like to briefly examine a related question currently occupying the interest of the military simulation community: "is there (should there be) a *profession* for M&S?"

## ON AN M&S PROFESSION

Does M&S constitute a "first class" profession, or is M&S more suitably treated as a technique that is applied *within* first-class professions?

Despite the fact that I consider myself an "M&S guy", I continue to vacillate on the idea of an "M&S profession." On the one hand, modeling is a notion/technique that pervades the human condition from playdough to Lincoln logs to Leggos to Barbie dolls to WARSIM… We are all modelers. Mankind is certainly far too big a group to establish a profession around. But, on the other hand, I believe the kinds of things that go along with a profession (a shared body of knowledge, code of ethics, etc.) would be nice to have in the community I work in. For example, how many folks who show up at the biannual Simulation Interoperability Workshops know what "common random numbers" are? Not that everyone needs to be able to derive the statistical notion of variance from first principles (and not that I could either), but an "M&S guy" maybe ought know a little bit about what variance is, and why variance needs to be minimized in simulation output and how common random numbers are used to do this. So, from that perspective, the notion of an "M&S profession" appeals to me greatly.

And as for the "S" part of M&S, a survey would quickly illustrate that simulation is practiced within nearly every scientific and engineering discipline. So that would mean that all scientists and engineers are necessarily simulationists. Again, that would seem to be too big a group to effectively manage as a single profession. And if simulation is the business of all science and engineering, then inevitably it must be dealt with at the (necessarily smaller) "domain" level (e.g. biologists, chemists, economists, engineers, etc., will own the bodies of knowledge and the codes of ethics, and so forth, associated with the practice of simulation).

If simulation is somehow smaller than all of science and engineering, *then* what should happen? Well, isn't simulation *really* just a problem-solving technique—numerically approximating system state at time $t$ in the absence of a closed-form solution for the system state at $t$? Do other problem-solving techniques have professional disciplines (sciences) attached? Probably some do, others don't. Is there a profession for linear programmers? Simulated annealers? Queuing theorists? Fuzzy mathematicians? Inductive provers? Differentiators? Integrators? Dividers and multipliers? Adders and subtractors? Or do these folks primarily view themselves as mathematicians, operations researchers, and so forth?

Like I said, I vacillate…

## ON MODELING, ART AND SCIENCE

There are those—myself included—who will tell you that modeling is *inherently* an art form. Does this imply that modeling cannot be viewed as a scientific endeavor? While I believe the artistic nature of modeling does limit our ability to turn it into an engineering discipline, I do not believe modeling is disqualified from the realm of science. Constructing a model sufficient to satisfy a collection of modeling objectives is the same art as designing an experiment to test an hypothesis. There is clearly an artistic quality to the practice of simulation, but so, too, is there an artistic quality to the practice of all science.

## ON SCIENCE, COMPUTING AND POLITICS

Science is largely about *repeatability*—especially experimental science. For knowledge to be accepted, the experiments leading to the acquisition of the knowledge must be repeatable. The scientific literature in biology, chemistry, medicine and so forth is filled with scholarly articles that describe the repetition of experiments originally reported by others. Computer science is notoriously unlike this. It is rare, if ever, that computer science journals contain articles that repeat the work of others. Any discipline that calls itself a science is not one.

Similarly, the halls of funding agencies in Washington D.C. echo with the mantra "reduce redundant expenditures!" If something has been done once, there is considerable resistance to spending dollars to do it again.

The influence of computer science and politics has (at least) two ramifications that merit brief discussion.

The first impact, driven by computer science, is most manifest in the literature of the military training simulation community. While the military analytical simulation community is dominated by operations researchers, the military training simulation community seems to be dominated by computer scientists. Since repeatability isn't valued (or understood) by computer scientists, there are relatively few case studies (experiments) reported. Most articles on training systems describe the architectural and design aspects of these systems rather than their use. Computer scientists love to tell each other about data structures I suppose. The literature in the military analytic community is reflective of the broader operations research community and is much better in terms of describing the use of systems in such a way that the use could be repeated by others.

The second impact, driven by politics, is an attrition in the number of models available to support analysis and training. There is a belief that we have too many models in the government. "Why build a combat model if we already have a combat model?" And so there is currently a push toward driving the number of models down to a fairly small collection of major, so-called "authoritative" systems (e.g. OneSAF, WARSIM, JWARS) that solve all needs. While it may be true that poor management has resulted in a proliferation of highly redundant models, the current paradigm shift seems to be an over-

correction—the balance between too many and not enough isn't clear. Models are, of course, opinions not facts. Having multiple opinions is arguably quite useful for systems analysis. The daily weather forecasts are the result of at least three separate models; why would one want to design a future force structure using only a single model? While fiscal reality dictates that we can only afford to build so many models, shouldn't we concern ourselves with building lots of inexpensive models rather than a few billion-dollar babies [2]?

## ON MAKING MILITARY SIMULTION MORE SCIENTIFIC

In the paragraphs that follow, I suggest a few areas within which certain aspects of the scientific method might be employed for the betterment of the practice of simulation within the military community. (Oooh, how's that for a lofty sentence?)

*Simulation Based Acquisition.* There is a push in DoD generally, and within the Army under a program known as Simulation Modeling for Acquisition, Requirements and Training (SMART), to maximize the use of M&S across the product life-cycle. It is believed that the application of M&S makes "better, faster, cheaper" a reality. We believe this, mostly, because we look around at the commercial world and we see companies that employ simulation to improve their bottom lines. That's reasonable. These companies at least provide an existence proof that M&S is effective. But it starts to fall apart a little from there. Does the government measure the bottom line the same way that commercial entities do? No. Does the government use simulation in the same way than commercial entities do? Absolutely not. The folks that modeled distribution methodologies for Starbucks, for example, were probably not told that they *had* to use RTI NG and federate with a high fidelity, but partially-finished, latte server. They were probably allowed to do whatever they needed to do in order to optimize distribution. If government business practice isn't the same as commercial business practice, should the government, therefore, expect to reap the benefits of M&S in the same way commercial entities do? Probably not. The government needs understand the application of M&S within the governmental context, and needs to collect the data necessary to achieve this understanding. The government should not expect to see the same results from simulation that General Motors or Boeing sees, unless the government organizes and operates like General Motors or Boeing.

*Science of battlefield modeling.* This is a pretty big topic, and others within the workshop will address it better than I can. But the topic deserves at least a small mention here. Despite decades of investigation, our combat models are still not very robust. Part of the problem is that there is not enough data from combat, but even where data exists our models do not fit actual outcomes very well [3]. The notion of "PKs" itself has also been severely criticized [4]. Clearly, with most combat models, you tell the analyst the answer that you want, and the analyst will get the model to give you that answer—with wholly justifiable values for the input parameters. Has science failed us here? Or are we just victims of the circumstance of inadequate data and highly nonlinear systems dynamics?

*Interoperability.* This is an interesting topic that has preoccupied the military simulation community for the past couple of decades. It began sensibly enough, with SIMNET, but how we arrived at our current paradigm is perhaps worth examining. SIMNET was

networked tank simulators. Interoperating homogeneous simulators within a common "synthetic environment" is a perfectly reasonable thing to do. You want two tank drivers to learn how to work together in combat? Give them an environment to practice in. SIMNET evolved into the Distributed Interactive Simulation (DIS) protocol. DIS was developed to enable the interoperation of somewhat-less-than-homogeneous simulators within a common synthetic environment. Still, it is quite sensible to have trainees in tank simulators interact with trainees in helicopter simulators. Then a funny thing happened. It was called the Aggregate Level Simulation Protocol (ALSP). ALSP was designed to allow the interoperation of *wargames*. Specifically, to allow an Army wargame to interoperate with a Navy wargame, an Air Force wargame and so forth. The stated reasoning behind the development of ALSP was twofold: (1) combat is (will be) a joint endeavor of all the military Services, therefore we need environments that represent each Service's capabilities; and (2) only Service *x* can represent Service *x*'s capabilities. The first reason is valid. The second one is a little suspect. It is probably true that the Army best knows how to represent the Army capabilities, doctrine, tactics, and so forth. And likewise for the Navy, Air Force and Marines. But it doesn't necessarily follow that you need each Service to build its own model and then network these models together! Certainly, one could posit the development of a *single* model that had subject matter expertise (SME) from each of the Services as development guidance.

The High Level Architecture (HLA) sprung from DIS and ALSP, and the paradigm of interoperating everything has been adopted whole-heartedly by a populace that believes in its merits. Some very thoughtful work has been done on the dark side of this paradigm [5], but a true calculus of interoperability remains to be developed. To me, the idea of lashing together two perfectly good simulations is not unlike the idea of jumping out of a perfectly good airplane.

*On the relationship between M&S and Test and Evaluation (T&E).* Except perhaps for very trivial systems, system testing can never be exhaustive, nor provide us with 100% confidence in future system performance. Therefore, testing must confront the problem of *quantifying uncertainty and risk*. For example, limitations associated with the number of shots that are taken in a live fire test produce risk and uncertainty. These limitations may be overcome (somewhat) in simulation where hundreds of thousands of rounds may be fired, however risk in this context is incurred due to the fact that a model is an approximation of a system. Finding the optimal balance between hardware-based and M&S-based testing requires a delicate balance of cost, schedule and risk—with the understanding that neither cost nor schedule are infinite and risk can never be completely eliminated. Some work has been done in this area [6], but much more is warranted.

*Rigor*. DoD M&S types—particularly in the training arena—just don't practice rigor very well. In 1687 Isaac Newton stood on the shoulders of giants. Today we seem to have a hard time standing on each other's toes [7]. In the DoD M&S training arena it is not uncommon to see papers published that have no literature surveys. Even worse, proposals are submitted *and funded* with equally poorly-established bases in prior art. We don't avail ourselves of peer review. We should.

## CONCLUSIONS

In this article, I have waxed-not-so-eloquently on the relationship between science and simulation. I have described a few areas within my community—the military simulation community—where the scientific method might be gainfully applied. I'm sure that there are few, if any, original ideas or insights offered here. I also couldn't say whether other communities suffer from the same ills. I suspect not, but I'll gladly let them speak for themselves.


## ACKNOWLEGMENTS

The ideas presented in this paper have evolved through many lively debates, discussions and almost-but-not-quite-fisticuffs with Dell Lunceford.


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# Simulating Humans

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## INTRODUCTION

While humanoid robots and live humans have many differences, their simulators can have many similarities. The dynamics of both humans and humanoids are described by similar sets of equations that model the physical behavior of tree-like articulated chains. Both types of simulators require control systems to produce human-like behavior and tasks. Both require efficient models of contact between the simulated body and the environment. And both kinds of simulators need a simulation infrastructure that manages the simulation process, simulation data, provides 2D and 3D visualization, and tools for graphical user interaction.

This paper describes dynamic simulators for humans and humanoids that take advantage of these similarities. One is the SDR-3X Humanoid Simulator for the Sony SDR-3X Humanoid Robot. The simulator was jointly developed by Boston Dynamics and Sony Corporation to develop the robot mechanism, create innovative movements, and develop new movement control strategies. The second simulator described here is the Digital Biomechanics Lab, a human simulator that uses dynamic simulation, human anthropometry and validation to provide a tool that can predict human behavior in new situations. It will be used for *Virtual Prototyping* of equipment designed for use by real people. Both simulators share a common software infrastructure and each leverages the development of the other.

## SDR-3X HUMANOID SIMULATOR

The Sony SDR-3X Humanoid Robot is a prototype entertainment robot being developed by Sony's Digital Creatures Laboratory, the same group that originally developed AIBO. The SDR-3X Humanoid Robot stands half a meter tall, weighs 5 kg, and has 24 actuated degrees of freedom. Each actuated degree of freedom is powered by a package consisting of an electric motor, gearing, and custom support circuitry. The robot has two 64-bit microprocessors; one used for motion control and the other for sensory and cognitive functions. The robot's sensors include a CCD camera for vision, two microphones for hearing, an

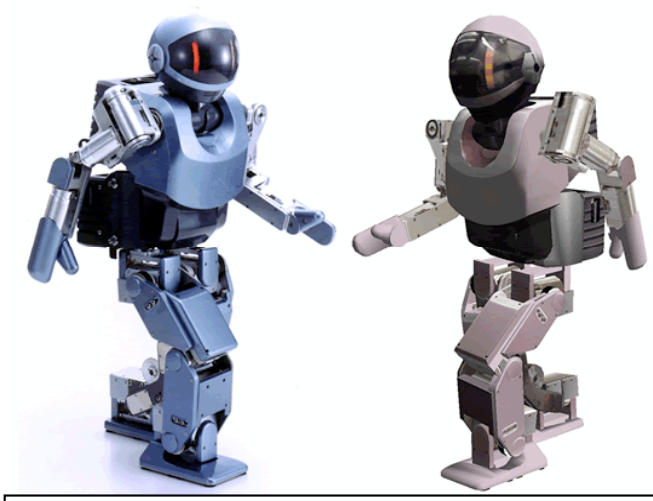

**Figure 1.** Photograph of Sony SDR-3x Humanoid Robot (left) and image from SDR (right)

orientation sensor, and touch sensors on the feet. The robot uses the Aperios real-time operating system and the Sony OPEN-R architecture.

SDR-3X walks at up to 0.25 meters per second using a ZMP-based control system. It can also sit down, lie down, get up from lying-down, kick a ball, and dance the ParaPara. For more information about the SDR-3X robot, see (Kuroki et al 2001) or visit http://www.world.sony.com/News/Press/200011/00-057E2/ .

The SDR-3X Humanoid Simulator is a dynamic simulator used to develop the robot design, create new behavior for the robot, and test control algorithms.

**Modeling SDR-3X**

To model the Sony SDR-3X robot for simulation we created three kinds of models: dynamic, geometric, and ground contact. We used CAD data from the robot design to estimate the dynamic properties of the robot, including the kinematics, mass, mass center, and moment of inertia tensor for each link. We also used the CAD data to create an articulated geometric model of the robot, for use in 3D real-time visualization. Figure 2 shows a screen shot of the simulator, including a 3D graphics rendering of the robot. Whereas the CAD data has hundreds of thousands of polygons defining the shape of each link and actuator, the 3D graphics required a model with just a few thousand polygons. Our modelers used the CAD data as a reference in order to build the lower-polygon visual models. They also used a set of photographs of the real robot to create textures that were applied to the surface of the 3D visualization.

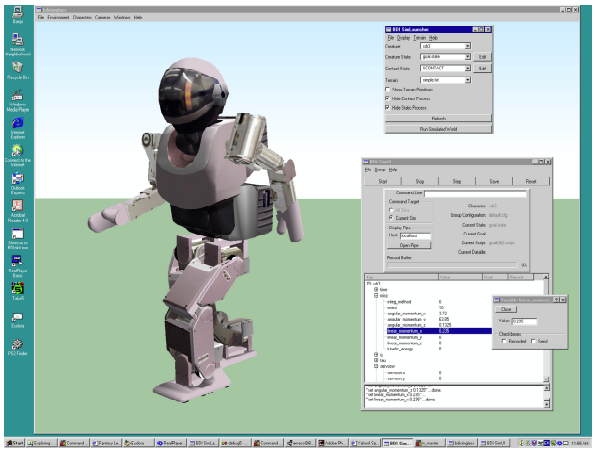

**Figure 2.** SDR Humanoid Simulator. It models the physics of the robot, as well as the actuators, sensors, ground contact and control. The simulator is used to analyze the mechanical design of the robot, and to develop advanced control and behavior.

We built a third model of the robot for calculating ground contact detection and contact forces. We created this contact model by taking the convex hull of each robot link.

The SDR-3X Humanoid Simulator also includes detailed models of the electric motors and gearing. These actuator models account for inertia, compliance and backlash in each actuator. Because these model include the dynamics of motors and their gearing, not just the kinematics, they require that an additional high-frequency state be added to the simulator for each actuator using the detailed model. The simulation is quite slow when they are enabled. The structure of the simulator allows the user to switch among actuator models, so simpler ones can be used for faster results.

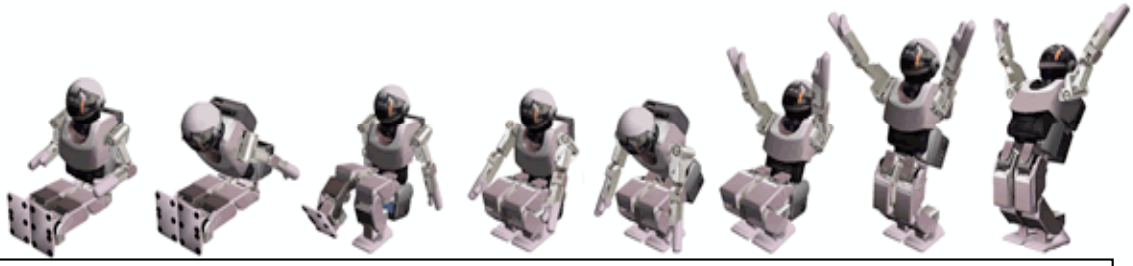

**Figure 3.** SDR Humanoid Simulator Getting Up from Sitting.

**Modeling Contact**

Ground contact forces for the SDR-3X Humanoid Simulator are calculated in two steps. First, contact between the robot and the ground is determined by searching for geometric intersections between the robot body and the support surface. The convex hull of each link is used in the calculation, to determine what parts of each link are in contact with the ground. A modified Lin-Canny algorithm is used for this purpose. Foot contact uses a more specialized calculation, employing hand-designed contact geometry. The support surface is modeled as a triangle mesh of polygons, with varying altitude at the vertices. Each ground triangle has separately programmed friction and compliance.

The second step in calculating ground contact force, once the geometry of contact is determined, is to calculate the forces at each contact point. The simulator uses spring/damper models with sliding friction at each contact point to determine forces. All ground forces acting on each link are resolved into a net force and torque acting on the link.

**User Interface**

The SDR-3X Humanoid Simulator has a graphical user interface (GUI) that lets the user control operation of the simulator. The GUI allows the user to start and stop simulations, load simulation parameters, specify which parameters and variables are recorded and saved, load goal data, and view behavior using the 3D graphics.

The GUI allows the user to view or modify any variable in the system. This level of access is both a blessing and a curse. The ability to access all parameters at simulation time, without having to write or modify code, is a blessing. However, the demands of managing several thousand variables and parameters can make operation of the simulator a skilled activity. To help relieve this curse, the GUI has facilities for organizing the parameters and variables into a heirarchy of user-defined groups, and to view or hide variables as required.

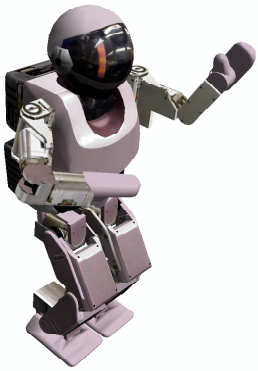

**Figure 4.** SDR Humanoid Simulator dancing the ParaPara.

The simulator has data handling facilities built in. It allows the user to load goal data, record and save data from any variable in the system, and view data both via standard 2D

data plots and via 3D computer graphics. We feel that both methods of viewing performance data are essential for this kind of research and development tool.

The SDR-3X Humanoid Simulator is designed for use by engineers and programmers who are knowledgeable about robotics, dynamics, computer science, and control. We wonder if consumers of entertainment robots will have the skills and interests needed to use simulation tools like this one. We expect the interest to be high if the simulator can help consumers program behavior they design themselves and download it into their robot. Skill levels will vary, so a challenge lies in crafting user interfaces, controllers, and simulation paradigms that are robust and powerful enough to support a broad range of users.

## DIGITAL BIOMECHANICS LAB

We now turn to a description of a dynamic simulator for actual humans. The human simulator we built, which we call the *Digital Biomechanics Lab*, uses the same underlying simulation infrastructure as the SDR-3X Humanoid Simulator, but the application is somewhat different. The purpose of the Digital Biomechanics Lab is to provide an advanced design and test tool for developing equipment that will be worn or used by humans. Examples of such equipment are load carriage systems (backpacks), safety helmets, and footwear.

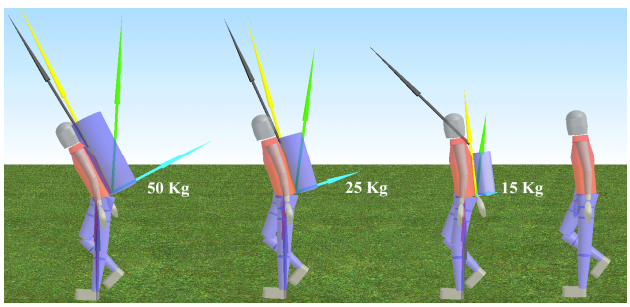


**Figure 5.** The Digital Biomechanics Lab uses physics-based models and control systems to simulate a human carrying backpack loads in the range 0 – 50 kg. Arrows indicate forces exchanged between the body and the backpack through shoulder straps, hip belt, and surface contact.

### Virtual Prototyping

The process of using a simulation in the design process is called *Virtual Prototyping*. Virtual prototyping allows users to test equipment and products in simulation, before fabricating the equipment, and without the cost and risk of testing on live people.

Suppose you are designing a backpack and want to see how it will work when the user climbs a stairway or dives to the ground. For physical testing, you would have to fabricate a physical prototype of the backpack, add instrumentation, hire human test subjects, justify the human safety of the experiments, then do the experiments. The process generally takes months or years. With virtual prototyping, you load CAD data of the backpack, use human anthropometry to specify the human body to simulate, select a *virtual obstacle course* appropriate to your problem, and run experiments on your desktop computer. Then collect and analyze simulated performance data. This process takes days or weeks. It is faster, less expensive, and far safer than physical testing. Rather than replace physical testing of prototypes, we expect virtual prototyping to augment it and make it more efficient. We

believe virtual prototyping with human simulation will develop into a large application area, once the technology has matured.

**Figure 6.** Data are recorded from humans performing tasks using motion capture technology. The performer works in a studio while 8 specialized cameras track retroreflective markers.

## Anthropometry

One difference between the SDR-3X Humanoid Simulator and Digital Biomechanics Lab is the need for human anthropometry. The Digital Biomechanics Lab lets the user load data from a human anthropometry database to define the size and shape of the human being simulated. These adjustments are important for virtual prototyping, because the designer may want to know how the product will work for a range of users, or test different size products on different size simulated humans.

The Digital Biomechanics Lab imports anthropometry from a database of 5000 American men (1988 ANSUR). The link lengths and approximate link shapes of the body parts are derived from a database of human anthropometry. Mass properties are derived using the segmental volume of the link shapes and density information from Dempster (1955.) A graphical user interface (GUI) allows the user to sort the database on any anthropometric measure and to select and build any individual human model. Depending on the experiment, the Digital Biomechanics Lab uses human models with 15-18 links, and about 35 degrees of freedom.

We are interested in supporting other databases, such as those for women and non Americans. The current databases are not perfectly suited to dynamic simulation in that they focus on geometric measurements of the body, without providing information about mass properties or strength. New human databases currently being developed (eg. by Hashimoto in Japan) will provide such information.

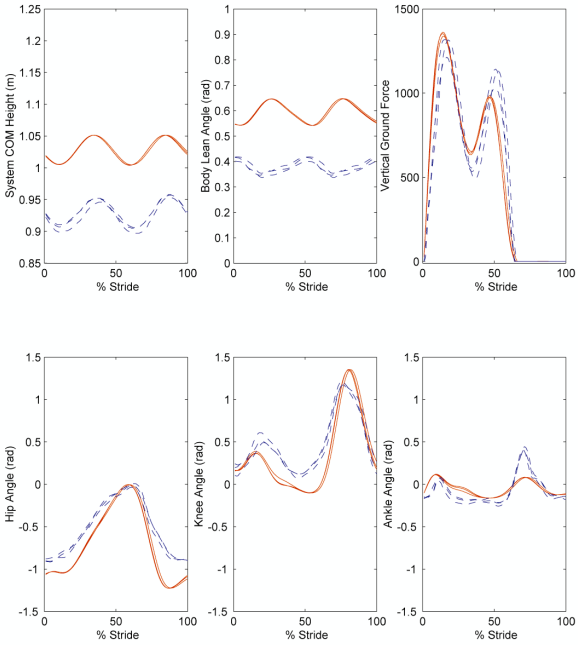


**Figure 7.** Time sequence comparing live (top) and simulated (bottom) humans performing a load carriage task (the backpack is not shown.) Live data was gathered using cinematography and digitization systems at USARIEM. Simulated data was gathered using the physics-based model in the DBL. Both live and simulated data are used to animate a computer graphic model of a human for visual comparison.

## Control

Perhaps the most important feature of The Digital Biomechanics Lab is the control. We believe the key to virtual prototyping is the ability of the simulated humans to perform realistic tasks. Equipment can be tested only when it is used to perform tasks representative of actual use. Then the designer can check the dynamic loading, interferences with other equipment, limitations on range of motion, and other attributes that result when human, equipment, and task are combined.

Our approach to providing Digital Biomechanics Lab with control has two parts. One part is to use control algorithms like those used for robots, adapting them for human behavior as necessary. Sometimes this is quite difficult because humans are so much more complex than most robots and because human behavior is more diverse and varied. A second part of the our approach to providing control is to use data recorded from live humans as an element of the control. Human motion data, once recorded, provides many of the subtleties and coordination needed to perform tasks.

The control system used for walking is an extension of the work of Pratt (2000.) It uses a state machine based approach to divide the walking cycle for each leg into five phases including support, toe-off, swing, straighten, and load. Roughly speaking, the hip is used to control body attitude during stance, the ankle is used to control velocity during stance by manipulating the center of pressure location relative to the foot, the hip, knee, and ankle coordinate to create a thrust phase. Joint torques are computed using servomechanisms to follow desired joint trajectories within each state, and to adjust contact forces. Motion data from live humans provides desired joint trajectories.

A summary of this approach is that we record behavior from a human performing the task, identify the key events in the recorded behavior, develop a state machine that switches on the key events, and apply control within each state. The control typically includes a motion part, derived from the recorded motion, and a force control part, designed to support, propel, and balance the body.

We have used this approach to simulate walking, running crawling, rolling over, diving to the ground, and getting up from the ground quickly to run. We plan to extend the behavior to include climbing, jumping, and other

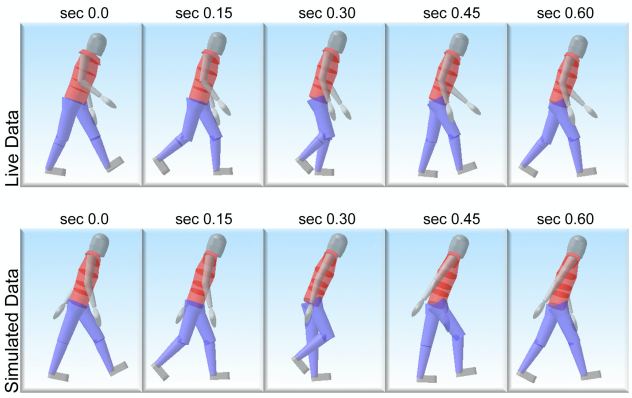


**Figure 8.** Data comparing live subjects to human simulations. Eleven live subjects performed walking experiments with a specially designed, 34Kg backpack. The center of mass of the backpack was varied to nine locations. Test subjects were asked to walk at constant speed (1.4 m/s). Subjects were filmed and digitized to provide joint angle data, and a force platform was used to gather ground reaction forces. Oxygen consumption was measured to estimate energy consumption.

behavior required to run a virutal obstacle course.

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Figure 7: Time sequence comparing live (top) and simulated (bottom) humans performing a load carriage task (the backpack is not shown.) Live data was gathered using cinematography and digitization systems at USARIEM. Simulated data was gathered using the physics-based model in the DBL. Both live and simulated data are used to animate a computer graphic model of a human for visual comparison.

### Validation

Another important aspect of the Digital Biomechanics Lab is validation. Validation is the process of showing that the simulated human will produce behavior that is similar to that of actual humans, when doing similar activities under similar conditions. Validation is important for virtual prototyping because only a validated model can produce test results that are predictive of live testing.

We are working with a team of researchers at the US Army Research Institute of Environmental Medicine (USARIEM) to develop a validated human simulation that can be used as part of the design and evaluation process of future backpack systems. To validate the human simulation, we compare data from human simulation with data from live subjects. Data used for comparison include joint angle data, posture data, and ground reaction force data. Results from one validation experiment are shown in Figure 8.

We are excited by the validation results produced so far. But validation is a tricky business. A model validated for one set of operating parameters and tasks, may not produce correct results when used with another set of operating parameters and tasks. That suggests two things. Validation should include sensitivity analysis and users must exercise judgement in how they apply virtual prototyping tools.

## CLOSING REMARKS

This paper summarizes two dynamic simulators, one for a humanoid robot and one for humans. Because the SDR-3X Humanoid Robot and humans are similar with respect to overall kinematic structure and general behavior, it was straight forward to build one set of simulation software and infrastructure that worked for both.

Moving forward, however, we expect the needs for each to vary: Humanoid simulators need to be made robust and easy to use if they are to be accepted and used by non specialists. Human simulators must be validated and predict complex human behavior and use validated anthropometry if they are to be useful for virtual prototyping. We expect to see rapid progress in both of these directions.

**ACKNOWLEDGMENTS**

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# Moving Simulation from an Art to a Science

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The question we were asked to address was whether there is or could be a science of simulation. A superficial answer is that if you have to ask the question, then there isn't. While simulation may not have reached the status of clearly recognized science, it is at least an identifiable technical specialty, and more probably an emerging science. Part of the problem is semantic. Having been party to many exchanges on this and related questions I can safely say that one of the biggest problems in even carrying on an intelligent conversation on the subject is that while we may use exactly the same words, there is no common understand of their meaning. In the case of modeling and simulation the range of underlying techniques, intended purposes, levels of abstraction, and application domains is so broad as to make consensus on universal definition almost impossible. I can't think of any technical or scientific domain that doesn't have practitioners who are labeled "computational - <insert your domain here>". All of these specialists are M&S practitioners within some technical area of interest, but very few have training both in the computational aspects and the specialty that is being modeled. I found out only a few weeks ago that there are computational neuro-biologists, and I suspect, but have not confirmed that there are computational exobiologists. For practical purposes almost anyone can declare himself or herself to be a "simulationist" with little fear of being challenged to show credentials or perhaps more significantly, to exhibit a defined set of skills.

Since all sciences employ M&S, not to mention the M&S work done in support of all kinds of engineering, manufacturing, marketing, and training is it just another methodology employed by "real" scientists and not a discipline in itself? Scientists develop abstract models within their area of study employing representations that range in formality from precise mathematical descriptions to natural language narratives with little formalism. It is doubtful that the field of simulation can claim too much in the way of unique contribution to this part of the equation right now, although such contributions can be imagined. There is a particular need for this in the soft sciences. When models move from an abstraction on paper to a concrete implementation executable on a computer they of necessity acquire a more formal form. This in no way implies they become more formal; in fact important information is lost in the process and various artifacts introduced. The transformation process, the techniques, tools, and principles that are applied, seem to constitute an identifiable technology of simulation. This simulation technology, or perhaps simulation art is often not uniformly nor effectively applied in many cases. People create models and build simulations with varying degrees of success all the time. While many wonderful scientific and technological advances have been made using these creations, it cannot be claimed that this is due to the systematic application of a principled process based on an underlying science. The ability to build something doesn't imply that the science is known, but even pure art forms such music and painting have bodies of theory that have derived from studying

practice. Chemistry came from alchemy. Even though alchemists never made gold from lead they did create an impressive body of empirical knowledge that had practical value and lead to systematic study. From this emerged the science of chemistry. From this standpoint then, there could be, and really should be a science of M&S, even if we haven't yet defined it.

Across the various specialties to which M&S contributes there are clearly common underlying approaches, techniques and principles that are (or should be) employed regardless of application domain. Many of these could be argued to be just good system and software development practices. Some others are more peculiar to M&S, relating to moving from mathematical formulations of a model within a specific domain to executable software, with due regard for issues such as accuracy, fidelity, validation and verification. Beyond this, and not too far along yet, are means for composing, scaling, and changing granularity, and of making predictions about the performance that might be expected from the results of such manipulation. Similarly there are implementation issues involving reuse, re-hosting, federations, networking, parallelization, that may also be peculiar to, or at least of special interest in M&S.

If we accept that there are issues that transcend specific applications, the next question is whether or not these elements of a proposed science are sufficient to constitute a separately named scientific specialty rather than just being a special case of computer science, system engineering, or mathematics. Even a casual search for literature on the subject produces a very large number of potential sources of information. I found more than 3800 on Amazon.com alone. The great majority of these are focused on such things as software packages, narrow problems, issues in specific technical domains or they don't really address what practitioners mean by simulation despite the book's title. In short, the science and technology of simulation won't be found there. There are, however, a few significant and weighty volumes that attempt to collect the body of knowledge in simulation. Among these are Zeigler's [1] more theory-oriented text and Banks' [2] state-of-the-practice volume. While both of these address broad issues it can be argued that only a subset of their content uniquely addresses a science and technology of simulation that transcends that which is modeled and simulated. The bulk of the science and technology described derives from other already-named disciplines. Whether that which remains is sufficient to constitute declaring a new field is currently a matter of opinion. What is clear is that much remains to be understood and described in this domain.

Simulation certainly has the promise of becoming a unique, but narrower than currently defined scientific discipline with application to many other endeavors. It can be argued that it isn't quite there yet though. Some empirical evidence exists that others support the emergence of simulation as an identifiable discipline; academic programs, specialized professional groups, and certification programs. At least five universities have significant and distinct modeling and simulation programs; University of Arizona, the Naval Postgraduate School (NPS), Old Dominion University, Georgia Tech, and the University of Central Florida (UCF). Two of these (UCF and NPS) and perhaps others offer graduate degrees through the PhD in M&S. In both of these instances, one third (for UCF, 9 of 27 credits) of the core course requirements are unique to the M&S program, while the rest are taught within existing departments. At UCF, six departments

and the Institute for Simulation and Training are involved. A number of other universities offer certificates in M&S as a probable prelude to offering degree programs.

If there is at least an identifiable art and technology of M&S regardless of whether these should constitute a unique discipline, then it is fair to ask what sort of science could be expected to emerge. There are several fundamental problems in simulation that could benefit from improved basic understanding; composition, abstraction, and scaling. Understanding how to combine component simulations to produce larger systems and accurately predicting the performance of such a combination is a much-desired capability in the world of simulation. There is no current body of simulation theory that addresses this issue, although comparable issues have been considered in other domains. The world of computer security has long been interested in understanding how to build secure systems and how to ensure that compositions of such systems will retain desired properties [3]. A theory of composition for mathematical models of physical systems and the simulations derived from them would be a worthy research effort for the science of M&S. Similarly, systematic methods for changing model granularity from fine to courser while retaining some specified fidelity would be welcome. A purely mathematical approach would be ideal, however tools for automating or assisting in this process would also be welcome. The problem of discovering abstractions was addressed some time ago by artificial intelligence researchers [4, 5] with some modest success, and efforts continue in various domains [6, 7]. Research toward such automated abstraction would be highly appropriate for a simulation scientist to conduct.

My conclusion is that there is probably not enough science or even engineering in simulation yet to declare it a separate discipline. There is evidence to suggest that there could and really should be such a science. The lack of a disciplined and principled approach to development of simulations is costly in many ways and is a major impediment to progress in many fields. Whether simulation will ever be considered an entirely separate discipline is unclear, but the resolution of this question isn't particularly germane to creating the scientific underpinnings of the endeavor.

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# Does Simulation Need a Reality Check?

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## INTRODUCTION

How can one best simulate reality? The military simulation community and the entertainment community take two very different approaches in answering this question. Generally, military simulation takes what might be called the literal approach to simulation. In this approach, one tries to create in the simulator an exact replica of the object being simulated. Thus, in the literal approach, a simulated helicopter cockpit would have all the switches, knobs, gauges and controls that one would find in a real helicopter. Often this is done by using in the simulator the same flight-qualified hardware that would be used in an actual helicopter. Similarly, the terrain databases that provide the out-the-window view for the simulator covers a large area represented at a uniform level of detail.

We see some important limitations to this approach. Using hardware from an actual vehicle in a simulator may significantly increase its cost while at the same time reduces its portability and ability to be reconfigured. If large areas of terrain are represented at a uniform level of detail, the graphical depiction of any particular part may not be very compelling due to processing limitations, even with today's powerful graphics engines.

In films, television and video games, the entertainment community also attempts to simulate reality--but using a very different methodology. Rather than trying to literally simulate everything, Hollywood begins by defining the ultimate objective. From their point of view these are criteria such as "What experiences should the audience have?" and "How should it feel." Once these goals are understood, they can guide how much effort is put into creating different aspects of the simulation. Some parts may be only roughly sketched, others represented very close to reality, while in some cases the simulation may be hyper-real, exaggerating reality for effect. For example, explosions in film and television are deliberately extended several times their normal clock time through a process called double-cutting. Another example: in the new movie, “Gladiator” only the lowest part of the Coliseum was actually built. The upper tiers and the thousands of screaming Roman participants were all done with CGI. If done skillfully, the audience is not aware of the different levels of simulation used.

In this paper we will describe some of the techniques used by Hollywood to simulate reality selectively, and we will raise some questions: (1) When is it appropriate to use these techniques in military simulations and how could they contribute or detract from pedagogical goals and (2) Can training be equal or even more effective in a less real environment, where the participant can more easily suspend disbelief?

## CASE STUDY: Differentiating Real and Almost Real

In personal communication with the authors, Alesya Paschal of STRICOM recounted an experience she had during the development of a simulator for the UH-1 helicopter. For

the most part, the simulator cockpit was constructed using actual components from the UH-1. However, the contractor was unable to obtain the actual Air Speed Indicator used in the UH-1 (shown in Figure 1) due to availability. Instead, a commercially available indicator (shown in Figure 2) was used. The major differences are that the markings for the simulator indicator are equally spaced, while those on the indicator in the real helicopter have unequal spacing between 0 to 40 knots. On the real aircraft, the marking for 10 knots is very close to zero, but much more widely spaced on the indicator used in the simulator.

**Figure 1,** Air Speed Indicator from Actual UH-1

**Figure 2.** Air Speed Indicator from Simulator

When experienced pilots were debriefed after using the simulator, they stated that the indicator used in the simulator was *exactly* the same as the one they were accustomed to in the actual aircraft. They were quite surprised when they were shown photographs of the two obviously different gauges. One pilot told Alesya Paschal that the reason he did not notice the difference was that the major differences between the gauges are with their markings for slow speeds and he rarely went that slowly.

The lesson we take away from this case is that even very experienced users of a piece of equipment may have difficulty distinguishing between a real object and something that is close to the real thing, particularly if the major differences occur in areas that are usually not operationally relevant.

## VERISIMILITUDE VS. REALITY

Whereas military simulations try to create realistic simulations by using actual components from real equipment, the entertainment industry attempts to create verisimilitude, or the appearance of reality, by weaving together a number of different elements, some of which may be real, while others may be completely synthetic. The key difference between the two approaches is that one attempts to *duplicate reality* to the highest fidelity possible, while the other attempts to *create an apparent reality*.

To create verisimilitude, the entertainment industry begins by asking some questions:

- What is the critical situation or story element that the user/viewer/participant should experience?
- How can we direct attention toward this element (and away from the irrelevant ones)?

The answers to these questions help direct effort and guide the process of creating verisimilitude. Depending on how the questions are answered, different degrees of reality may be required:

1. **Sketched reality.** If an element is not critical to the story or experience, it may be possible to just sketch it, leaving out much of the detail.
2. **Apparent reality.** If an element is central to the story it needs to appear as convincing as possible.
3. **Hyper-reality.** If an element is critical, but in real life it may escape notice or occur so quickly that it lacks impact, it may be necessary to exaggerate reality to create the appropriate impact.

In the next section we give examples of how these different approaches to reality are used in the entertainment industry and when each is useful.

## DEGREES OF REALITY: Examples

### Sketched Reality

A *cloze* is a "test of reading comprehension in which the test taker is asked to supply words that have been systematically deleted from the text" [American Heritage Dictionary]. People can successfully take such tests because they use the surrounding context to fill in the blank. The ability of people to supply missing details isn't limited to text. If one draws an almost complete circle on a blackboard, most people will call it a circle, even though it is in fact an arc.

Hollywood uses this trait and people's imaginations to fill in gaps similarly. For example, in the famous shoot-out in the office tower in the movie "Matrix" only the ground level was actually built. The remaining part of the impressive multi-story atrium was a painting. Another famous example can be found in Disneyland or Disney World, where the upper stories of the building on Main Street are built at a reduced scale.

By relying on the mind's ability to fill out missing details (as with painted upper stories) or correct erroneous information (as with upper stories at a reduced scale) it is possible to create perceptions that are effective and convincing, but at a much lower cost than would be required if all the details were constructed.

### Apparent Reality

When greater fidelity is required to create a convincing environment, there still may be a number of possible ways to do it, each with its own set of tradeoffs. For example, consider the familiar movie scene of a couple driving down a road in a car.

The most straightforward, but also most difficult way to film such a scene is to use what is called a *tow shot*. The cameras are mounted on a truck or other vehicle that tows the

actor's car down the street. This approach can provide very realistic results, but it can be difficult to execute. The street needs to be cleared of traffic. If one of the actors blows a line, the whole parade needs to be moved back up the street before the shot can be started again. These complications make such shots expensive and cumbersome.

Another approach is the *process shot*. In this approach, the car is mounted on rockers and placed in front of a rear projection screen. While the scene is filmed a moving street scene is projected on the screen, so even though the car is stationary it appears to be moving. To make the motion of the car more convincing, grips may bounce the car while it is filmed to simulate going over a bumpy road. To be convincing, this shot must be done carefully. For example, at night the car must be illuminated with light that has the same color and direction as the light that illuminated the street scene when it was filmed. This approach also requires a considerable investment in equipment. The advantage of this approach is that the logistics are much easier. It is not necessary to close a city street, and re-taking a shot is simple. .

A third approach, sometimes called the *poor man's process shot,* provides many of the benefits of the process shot, but with almost no investment in equipment. The one restriction is that this shot must be set at night.

The car is set up on rockers as before, but because the scene is at night, there is no need for a rear projection system — it's supposed to be dark in the background, after all. As the scene is filmed, grips carry lights past the car to cast reflections on it and simulate driving at night down a lighted street. This shot can be extremely effective and very inexpensive.

These three different approaches to creating apparent reality represent different tradeoffs. The tow shot is similar to the approach used in military simulations: it incorporates real elements to create verisimilitude, but it is also the most expensive and cumbersome. The other two approaches move increasingly farther away from directly incorporating reality into simulations, with correspondingly reduced cost. But the latter approaches (particularly the poor man's process shot) are applicable in more limited circumstances. The lesson we take away from this is that by thinking carefully about the context in which a simulation will take place, it may be possible to significantly reduce its cost.

**Hyper-reality**

Sometimes it is necessary to exaggerate an event because a direct filming of the real event lacks the impact of actually experiencing the real event. One example of this is an explosion. In reality, it occurs very quickly and then is over. But it also has a major impact because it assaults all the senses (particularly if one is too close). In a direct filming of an explosion, one can see and hear the blast, but duplicating the chest-shaking thump is difficult. To compensate, filmmakers make the experience more intense by exaggerating the reality. One way to do this is to use slow motion so that the explosion lasts for a longer time than it does in reality. The audience has a longer time to see and hear the impact of the explosion and it intensifies the experience.

Another approach is to use a technique called *double-cutting,* which involves filming a critical scene (like an explosion or car wreck) from several different viewpoints simultaneously using multiple cameras. When the film is edited, the cuts from multiple

cameras are used and spliced together in sequence, with some temporal overlap between the end of one cut and the beginning of the next. In this way, a viewer sees the same explosion from multiple points of view, and because the cuts are overlapped, the event lasts longer than it would in reality, increasing its intensity.

Movie soundtracks provide a number of examples of reality that has been altered or exaggerated for effect. In fact, in most major feature films, very little of the sound that was recorded when the film was shot ever makes it into the final cut. Instead, the soundtracks of most films are carefully constructed from sound effects, music and voices dubbed in after the fact. One example of this comes from the opening titles of the famous TV series *Hawaii Five O*. In one of the shots of the montage, a jet airliner lands on a runway. As it touches down, the tires squeal. This provides a nice punctuation for the landing. However, when a real jetliner lands, it is not possible to hear the tires squeak because the noise from the engines completely drowns it out. Nevertheless, the squealing-tires-on-landing effect, which started in *Hawaii Five O,* is now almost a sonic cliché. One rarely sees an airplane land in the movies today without hearing the tires squeak.

Another example of Hyper-reality is evidenced in the movie "Terminator II." Everyone who saw the movie remembers the famous scene where the kid on his motorbike is being chased by the bad Terminator in an 18 wheeler. The scene takes place in the concrete channel they call the L.A. River. Arnold, the good Terminator is on his motorcycle on the rim of the channel, and sees what is happening. He guns his hog, races along the rim and then leaps the fence and lands perfectly in the channel, placing himself between the boy and the bad Terminator. It is an exciting shot, and an impossible stunt. No one could do it, not even a Terminator.
How was it done? In one of the first uses of digital manipulation, director James Cameron had Arnold and the bike slowly lowered by wire into the channel. Then all the wires and apparatus to do this were digitally erased. When speeded up and enhanced with digital sparks and other effects, the impossible became possible. And no one in the audience complained that it was phony.

## NON-REALITY: A Conjecture

The greatest words in literature are "Once Upon a Time" (or "a long time ago in a Galaxy far, far away.") Once the reader accepts this, he or she suspends disbelief.

Although military simulations generally try to be as realistic as possible, some of the most effective stories and films have been made about worlds that are completely made up. Film history is replete with works such as *Toy Story* and *Star Wars* (all of them) that take place in worlds that are imaginary. The fact that the story takes place in a fictional world is a great strength, because once the audience accepts that the world is fictional, they suspend disbelief and it is no longer necessary or expected that the world will duplicate our own. On the other hand, if a story is supposed to be set in the real world, then much more attention must be paid to getting all the details right.

What is most important, however, is that even though these stories may be set in imaginary places, it is still possible to learn from the stories and transfer these lessons back to the real world. Indeed, through out history, people have written allegorical

stories set in unreal situations that are intended to teach lessons. An interesting question to explore is whether or not it would be possible to create military simulations that were set in unreal worlds, and use them to achieve pedagogical goals. Taking such an approach might make it possible to create effective simulations at a low cost.

## SUMMARY

The point of this paper is to point out that for the entertainment industry, the most compelling experiences are not created by directly mimicking reality, but instead by using a wide variety of techniques that may be only loosely coupled to the underlying reality to be conveyed and potentially altering reality depending on the message that is to be delivered. The process of designing such an experience consists of answering a number of questions:

1) What are the objectives? What should the audience learn? How should they feel?
2) What techniques are available for achieving the desired objectives? Are they obtainable?
3) Are they affordable in terms of time and dollars? What is the acceptable trade-off that will do the job effectively?

In our view, military simulations could benefit from such an approach. Rather than using terrain data that renders thousands of square miles at the same level of resolution, consider first what the pedagogical goals are for a simulation system. Does all of the data need to be present? Is some more important than others? It may be possible to render the scene selectively, and draw attention to just the most relevant parts. While the specific techniques that we have outlined here may not be directly applicable to military simulations, we believe the general approach of altering reality to create a compelling experience will help us create simulations that are more effective and less costly.

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# "Science .AND. Simulation…?"

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## INTRODUCTION

"I may not know much about Science *or* Simulation, but I know what I THINK!"

### Truth in Adversity

The thoughts presented in this paper are predicated largely on my personal view of the nature of modeling and simulation. My perspective is not by any means unique or particularly privileged, but it is, I think, a useful and interesting one from which to consider the fundamental relationships between science and simulation.

Having been trained in a scientific discipline (e.g. Physics), I have worked in what passes as the M&S industry for more than 25 years, have developed simulations of various types (continuous-system, discrete-event, real-time hardware-in-the-loop, virtual man-in-the-loop, etc), and have used them for a variety of purposes (system concept definition, engineering analysis, design and evaluation, training, and system operations and maintenance). A variety of technologies, more-or-less peculiar to modeling and simulation are familiar to me (conceptual modeling, simulation system architectures, verification, validation, and accreditation, simulation-based studies and analysis, etc.). My perspective on M&S has ranged from being a novice practitioner, surviving by my wits and significant on-the-job training, through journeyman status, to management of a small business dedicated solely to the delivery of modeling and simulation products and services.

Whether these experiences actually qualify me to speak on the subject is, of course, debatable. The comments that follow are naturally biased by this peculiar perspective. In addition, the positions taken here are no doubt self-serving in respect to my current roles and responsibilities – namely to care passionately about the evolving development of the modeling and simulation profession, industry and marketplace. Nevertheless, I can do no more than to try to tell the truth by calling 'em as I see 'em, and trust you, the reader, to arrive at a balanced judgment based on this and its associated offerings, together with your own experiences and sound judgment.

### What's the Question?

In a way, the question we are asked to address is not wholly well-formed. Are we, for example, to consider whether simulation is itself a science? …whether it has or can have or should have a scientific basis? … or whether it can be pursued by scientific methods? The discussion space being relative large – namely anything within the Venn intersection of 'simulation' and 'science' somewhat without regard to type or directionality of relationship – I have elected to step to the edge (if not outside) of the box and address

rather the fact and implications of the existence of simulation science and/or technology. This is certainly a 'cheap trick' in context of the workshop, but one that nevertheless allows me both to focus my observations on an aspect of simulation (e.g. technology) that is necessarily relevant, and to derive conclusions and action-oriented recommendations whose soundness is not sensitive to the results of the more formal debate on 'what-is-the-relationship-of-simulation-to-science'.

## DISCUSSION

Hereafter, we will pursue primarily consideration of the implications of modeling and simulation's being a distinctive technical discipline, and only secondarily the simulation-to-science nexus.

### Definitions

There is something in us that is averse to starting such an exposition as this with definitions of terms – perhaps it recalls to us our pedantic instructors or smacks of Platonic formalism, or insults us by telling us what we already know. Nevertheless, semantics does matter, and notwithstanding there are very many (sometimes different and conflicting) 'authoritative definitions' around, and after all: "We know what we're talking about!", we don't. So to be precise if only for the duration of this paper, we take the noun 'model' to mean: "a representation of something" [1]. Similarly, the noun 'simulation' is: "a method for implementing a model over time e.g. for determining the value of one or more dependent variables of a model with respect to one or more designated independent variables." … *also*… "such a representation", e.g. an instance artifact. The verb form of 'simulation' is: "implementing or using such a method…."

Note that these definitions are extremely broad in their denotative range. A model is, effectively *any* representation of something and a simulation is *any* method for implementing a model over time. The selection of definitions with such broad range of applicability is intentional. It challenges us to analyze modeling and simulation in the most comprehensive way possible, and it ensures that any conclusions we draw are as widely relevant and therefore as powerful as may be. In addition, by providing such ecumenical definitions we may be deterred from our usual habits of thinking only in terms of instances with which we are particularly familiar and so from drawing either false or unnecessarily limited conclusions.

### Scope of Analysis

One implication of the very broad definitions we have established is that they are *de facto* relevant across wide domains of objects and processes related to modeling and simulation. There are several such classes of object and process that pertain to M&S and that, by serving as the dimensions of the subject, help to establish what is properly in our scope of interest.

For instance, one dimension across which modeling and simulation may be understood is that of the elements of the M&S asset development process. Here, of course, simulation-the-verb generates simulation(s)-the-noun. This dimension is closely correlated in its various manifestations to the technical information held by M&S practitioners and the technical competencies exhibited by them in their simulation system development

behaviors. Similarly, the object entities that are thereby produced – types of simulations, their parts, their composites, and their various complementary accoutrements – themselves suggest a dimension for analysis of the field. We move back to process again for behaviors of simulation practitioners in using simulation assets. Finally, but likely not exhaustively, there are meta processes – the set of behaviors that are not of first order respecting the 'doing' of modeling and simulation but instead are the necessary second order activities whereby modeling and simulation are allowed to be done. These meta-processes are nevertheless part of the scope of our concern, including as they do all the competencies that relate to enterprise-echelon operations (beyond the cottage-industry M&S practitioner level) and relating as intimately as they do to such technically sensitive issues as standards and collectively appreciated expertise. Altogether, these types of processes and entities serve to illustrate the space over which the debate of simulation and science (or at least technology) must range.

**More Definitions**

Going from bad to worse, establishing an operational definition of science is, unexpectedly perhaps, even more difficult. There are myriad writers, such as Whitehead, Einstein, Kahn, Bronowski and Feynmann, whose explication of the philosophy of science might be expected to put us on solid ground here. But review of their works, and of standard lexical reference texts is not so decisive as might be hoped.

Definitions of science are observed to relate variably to 'that which is known', e.g. "knowledge acquired by study" as well as 'the fact of knowing', e.g. "possession of information, … acquaintance with or mastery of [that which is known]."

Definitions allude to composites or compartments of knowledge or learning as composing a scientific domain or designated discipline, e.g. "The domain known - A particular branch-of-knowledge or study; a recognized department-of-learning..."

Some definitional frames address connectedness of knowledge within the frame as the qualifying criterion or attribute, and emphasize the rationality of that connectedness, e.g. "Relationships among that known - A branch of study which is concerned either with a connected body of demonstrated truths or with observed facts systematically classified and more or less colligated by being brought under general laws, …"

Others emphasize the operational attributes of the domain of interest with respect to auto-generational capability, e.g. "… and which includes trustworthy methods for the discovery of new truth within [the subject] domain…"

This methodological theme is profound insofar as it is widely believed that the "scientific method" is in fact the defining attribute of science itself – namely that science is that body of knowledge that is developed and evolved by application of the scientific method. Unfortunately, debate from Bacon back to Plato and Aristotle and forward to Bohr and the modern cosmologists provide an inconveniently diverse picture of scientific method. What is soundly indicative of science, however, from almost every perspective, is the discovery of independently corroborable truth about some substantive referent believed to exist independent of the science (or the scientist) itself. The significance of such an independent referent-basis-of-truth to which a 'science of simulation' might apply is reprised again later.

As is documented, the qualification of one or another field of endeavor as a science is rather liberally accepted [1]: "The many conflicting systems proposed in recent times for the classification of the sciences, and the need frequently arising (apart from any formal classification) for a common designation applicable to a group of sciences that are related by similarity of subject or method, have given currency to a large number of expressions in which the word science is qualified by an adj." … although, there are some old fogies who hold to a stricter standard. "In modern use, [science is] often treated as synonymous with 'Natural and Physical Science', and thus restricted to those branches of study that relate to the phenomena of the material universe and their laws, sometimes with implied exclusion of pure mathematics. This is now the dominant sense in ordinary use."

**Simulation as Technology**

In any case, it seems that the existence of some objective referent about which truths can be systematically found and publicly confirmed seems to be at the heart of any 'science'. Physics, biology, psychology, and even linguistics seem to qualify as referring respectively to the physical, biological, mental, and natural language universes. Simulation seems like the odd man out having as its referent not an objective reality but instead a universe of lexical constructs developed for the convenience or the practitioner.

THEREFORE…

Taking a rather less optimistic position, and considering simulation as a kind of technology provides us with a somewhat lower qualifying criteria, but still, as we shall indicate below, a quite sufficient basis for pursuing the core issues of the evolution of a profession, industry, and marketplace.

Technology is variably defined as:

- The scientific study of the practical or industrial arts
- Practical arts collectively
- A particular practical or industrial art

Simulation as a practice and as defined above, certainly qualifies as a technology. And it is just this basis of a demonstrable, perceptible, persistent, and significant existence of simulation *as a technology,* that can be both taught and learned, that we assert is the critical attribute whereby profession, industry and marketplace can and should be evolved.

Whatever … There is a perspective from which it just doesn't matter whether simulation is science or not as long as it can be recognized as a distinctive, discriminable, and non-redundant technology in relation to other technological domains. This is the perspective that we take in re-considering the questions at the motivational heart of this Workshop. Namely:

- Could there be a science of simulation? Alternatively, *is* there a technology of simulation?
- What is our state of understanding that might contribute to such a science / technology?

- What do we need to do to improve that understanding?
- What difference will it (a science of simulation or the recognition of a fundamental technology of simulation) make to the world?

**Intention**

As indicated earlier, our position is that of the technologically-oriented entrepreneur. Our intention is to understand and to influence simulation by quite practical means. Whether the perspective of simulation as a science or simulation as a technology is optimal, we are fundamentally concerned with having an *effect*! In the first case, we may want to understand the degree to which simulation is a kind of science and the degree to which, therefore, simulation may be successfully be pursued by scientific means. Alternatively, and more constructively perhaps, we want to know: What is the degree to which simulation is a domain of technology and what is the degree, therefore to which a profession, industry, and marketplace based on that technology can be expected (or more positively, caused) to mature? Simply, what's it take to be *doing* simulation well in the real-world?

In the next few paragraphs, we consider from each of several perspectives: What matters? – what is significant about the existence of simulation technology? Then we address: So what? – What are the action-oriented imperatives that follow from the state of simulation technology regarding accelerating the evolution of the field to the collective advantage?

**Body of Knowledge**

*The Body-of-Knowledge (BOK) of modeling and simulation matters.* A significant consideration in relating M&S to either science or technology – and the paramount issue in establishing the identity of modeling and simulation as a distinctive field – is the specification of information that constitutes the body of knowledge of modeling and simulation. All sciences presume the possession of information - *knowledge* acquired by study; *acquaintance with or mastery* of [that which is known]... Technology presumes the competent and artful application of such knowledge.

The challenge is in discriminating and denoting explicitly and convincingly that body of knowledge that correlates fundamentally to modeling and simulation and relates only peripherally with other related domains.

The debate over whether there is a discriminable body of knowledge upon which modeling and simulation can be predicated and if so what precisely it is, is challenging, but not essentially impossible. In pursuing this debate, however, it is essential not to succumb to the line of reasoning that because such-and-such a fact is relevant to mathematics or systems engineering it therefore cannot be in the body of knowledge of simulation. This false argument – expecting unique membership of knowledge in the field - is true of every recognizable field as well and therefore is puerile. For instance, physics depends upon math, but physics is no less a science for that dependency. The admissibility of existence of a body of knowledge is therefore more complex than is commonly appreciated, and must consider relative consanguinity of knowledge and sets of knowledge used in specific ways within a domain.

Forestalling the complete explication of the body of knowledge of M&S for the time being, we offer only a few instances of information that seem to be 'close to the center-of-mass' of the M&S BOK. *Conceptual modeling* – establishing the representational schema from some form of existing or prospective reality that may be implemented into a simulation artifact - is at the heart of modeling and simulation. Together with the technology art and craft of use of representational schemas whereby abstraction and subsequent notation of conceptual models is achieved, conceptual modeling is what 'representation', and therefore modeling and simulation, is all about. In a similar vein, the attributes of simulation products most salient to its core are *fidelity and detail of representation* – again intimately related to the definition of simulation itself. Further, the implementation features of *architectural design* and associated developmental concerns such as developmental composition, while shared across all systems engineering disciplines, nevertheless have a special 'flavor' when applied to simulation development processes and their consequent artifacts. Finally the area of *verification, validation and accreditation* are wholly devoted to establishing the degree to which representational capability of M&S assets is appropriate for their intended uses, is *ipso facto* fundamental to modeling and simulation.

By way of action-oriented guidance, therefore: *Invest in identification and specification of the M&S Body-of-Knowledge*. Include particularly the discrimination of elements of the body of knowledge that relate to the processes (including meta processes) and entities that are so obviously a part of the field: elements of asset development, types of simulation artifact and parts of the artifact, kinds of uses, of modeling and simulation, and the overall conduct of M&S practice.

**Recognition**

*Recognition matters*. Having modeling and simulation be acknowledged as a particular branch of knowledge addressed in a recognized department of learning is significant. Taken from the second element of the definition of science introduced above, the features of recognition of the branch of knowledge and the existence of an associated department of learning are crucially important. Given, for purposes of discussion the existence of a body-of-knowledge, the perception, appreciation, and general acknowledgement of this BOK and its associated encapsulations is the basis of the social acceptance of modeling and simulation as a distinctive technology, profession, and industry, rather than only as some minor enabling aspect of one or another or even several existing fields.

It is critically important that simulation be widely and authoritatively perceived as a discriminable 'branch of knowledge' – that the body-of-knowledge identified above be accepted broadly and implicitly by the widest possible constituency. Publicizing and campaigning for acceptance of the identification of modeling and simulation as a credible and significant branch of knowledge, while not a particularly attractive or immediately rewarding task, may well be necessary to the achievement of recognition of the profession, industry, and marketplace.

Similarly, establishing the demonstrable existence of a department of learning whose subject matter is modeling and simulation is likely necessary. Given the degree (pun intended) to which university organizational units and instructional curricula are considered to effectively define such departments of learning, it seems obvious that the

establishment of organizational units and degree programs is also a necessary investment in the evolution of the M&S industry. By way of action-oriented recommendation, therefore: *Establish effective recognition of the domain known by conducting a campaign to cultivate acknowledgement of modeling and simulation as a particular branch of knowledge or study, and as a recognized department of learning*.

Changing perception is always a 'non-trivial' challenge. In fact, this change may already be underway or may be best left to itself to emerge eventually. However, if there is any expectation of the M&S industry emerging sooner rather than later, investing in influence whereby these perceptual objectives may be met is imperative.

**Relationships**

*Relationships matter*. Both the relationships *within* the M&S BOK and the associated professional practice, as well the relationships *between* simulation and other domains or fields, are important.

Science is characterized by clearly appreciated relationships among that which is known. Simulation (or any other science or technology) is a branch of study which is concerned either with "a connected body of demonstrated truths or with observed facts systematically classified and more or less colligated by being brought under general laws."

Clarity of appreciation of the relationships between simulation and other fields is necessary to avoid unnecessary debate about proprietary custody of knowledge by one field or the other (to put it negatively) and to accentuate the constructively supportive relationships among fields (to put it positively). Typical of such related domains are: program management, product evolution, systems engineering, software engineering, computer engineering, etc.

By way of action-oriented recommendation, therefore: *Establish standard taxonomic relationships within the Body of Knowledge and between the M&S BOK and those of other significantly related fields*.

'Getting a grip' on these relationships is of utmost importance as it is the basis of effective collaboration within and beyond M&S field of endeavor.

**Evolution**

*Consistent evolution matters*. A field that has no basis of systematic, progressive growth in scope and power is neither a science nor a viable technology.

Science is characterized by it's capability for auto-generation. Any science or technology includes trustworthy "methods for the discovery of new truth" within [the subject] domain. As a science or a dependable technology, modeling and simulation must have some 'truths' within its purview that are independently corroborable and sufficiently stable to assure value-added in the application of the subject technologies. While for simulation, there is no independent referent about which propositions are formed whose truth values are so discovered, there does, nevertheless need to be some mechanism for discovery (or invention) of stable value within the domain.

By way of action-oriented recommendation, therefore: *Establish a shared appreciation of the processes available for elaborating and extending M&S practice, through implementation of standards, best practices, etc. based on a systematic program of basic and applied research.*

Technology-base investment and consensus building within the M&S community go hand in hand.

## CONCLUSION

We believe that there is a need for maturation of the modeling and simulation profession, industry, and marketplace. We feel that the existence of an extremely powerful modeling and simulation technology is the basis of the opportunity to realize this future state. A significant inhibition to achieving this goal is the lack of appreciation of modeling and simulation as a distinctive branch of knowledge, discipline, department of learning, and professional field. Based on an analysis of the attributes of fields that are accorded the standing of science or technology, we have identified the following areas that warrant investment:

- Identification and specification of the M&S Body-of-Knowledge
- Establishment of effective recognition of the domain-known by conducting a campaign to cultivate acknowledgement of modeling and simulation as a particular branch of knowledge or study, and as a recognized department of learning.
- Establishment of standard taxonomic relationships within the Body of Knowledge and between the M&S BOK and those of other significantly related fields.
- Establishment of a shared appreciation of the processes available for elaborating and extending M&S practice, through implementation of standards and best practices based on a systematic program of basic and applied research

These findings and recommendations have been educed from the perspective of consideration of simulation as science and/or technology. This analysis was motivated (in this paper at least) from a wider concern for the evolution of the state of modeling and simulation profession, industry and marketplace. It is interesting, and probably inevitable, that many of these same ideas have arisen in other fora whose topics relate to the subject. In particular, the SimSummit Convention, held in San Diego in July 2002 and sponsored by NTSA, SISO, and SCS included both reference to this workshop and to many of its topical issues and findings.

It is our firm conviction that a widely ecumenical campaign or program initiative to influence the state of modeling simulation technology, professionalism, industrial robustness and market viability is both necessary and possible ...*now*. It is our adamant recommendation and earnest hope that all of the several constituencies with interest in the evolution of modeling and simulation may yet succeed in cooperating effectively to achieve this collective goal.

## REFERENCES

Oxford English Dictionary, Second Edition, Oxford University Press, Oxford, UK, 1989.

[2] Modeling and Simulation Glossary, Defense Modeling and Simulation Office, Alexandria, VA, January 1998.

# Walking Back the Cat

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## PREFACE

Models and simulations are epistemological devices which

- Help us to know, explain and predict real events and processes,
- Underlie most, if not all, sciences,
- Provide a basis for selecting, developing and conducting experiments,
- Require calibration to determine their valid range of applicability.

There has been, and continues to be, a serious need to understand, characterize and illuminate the significant aspects of these devices and their uses. To this end it is very helpful to regard them from a scientific point of view, both in their constructs, processes and applications. This point of view should led also to increased professionalism for the device practitioners and their communities.

## A PAT ON THE BACK AND SOME CHALLENGES

The rapid emergence of computer technology over the past fifty years has greatly accelerated the use and importance of models and simulations. They have been highly successful in helping to reveal causality and providing useful insights into many complex systems, processes and events, particularly in the DOD study and analysis arena.

Many other arenas deserve the level of interest, effort and funding accorded to the DOD arena for the conceptualization, development and use of models and simulations. Candidate arenas include those in which extensive experimentation is prohibitive because of safety, time or cost. Such arenas include the effects of drugs on humans, natural disasters as forest fires and floods, and the long-term depletion and replacement of natural resources.

## ABOUT THIS PAPER

"Walking Back the Cat" is a phase used by the intelligence community to describe the process of looking backwards from an event to track and expose the sequence of actions that preceded and led to the event. Obviously, an application of this process has been underway since 9/11.

The Concepts and Technology Group (CTG) was formed in1998 and has offices in Tehachapi , CA and Tacoma, WA. It explores, studies, develops and promotes

- Concepts for using advanced technologies
- Simulations of applied concepts

- Operational flexibility in planning and action

It has ongoing efforts in nanotechnology, warning and evacuation systems and flexibility in planning and operations. CTG has been "Walking Back the Cat" in the sense of looking at primarily previously used models and simulations that could be adapted to studying terrorism and counter-terrorism.

Selected examples found in our limited search are discussed briefly in this paper.

## A CALL TO ARMS

It has become fashionable to blame the intelligence and law enforcement communities for failing to provide adequate warning of the 9/11 terrorist attacks and taking appropriate preventive measures. While these communities share the primary blame for these failings, other communities, such as the DOD model and simulation share some of this blame. This community had and has a serious responsibility to model and simulate terrorist operations and wars, particularly those in which terrorist actions produce strategic consequences. A further obligation of the participants in this community is to relate whatever insights, ideas, even suspicions, it develops, to appropriate levels of the National Command Authority, law enforcement agencies and other policy or action agencies. The modeling and simulation of tactical agents and forces engaging strategic targets, either military or civilian, and the accompanying political, economic, and societal considerations is the most challenging endeavor this community now faces. Success in this endeavor can help significantly in deterring, avoiding and minimizing terrorist actions and their effects.

History shows us there are alternative approaches (alternative to the current U.S. approach) to dealing with terrorists, terrorist organizations and their supporting states, e.g., see Caleb Carr's latest work, The Lessons of Terror. These alternatives need to be studied, analyzed, and compared to the strategies, policies and operations now being pursued by the U. S. and its allies.

## MODELING THE SURVEILLANCE OF POTENTIAL TERRORISTS

CTG has been investigating models that can be adapted to simulate the surveillance of potential terrorists, We have resurrected a surveillance model created by George Kimball and myself in the mid-60s. The model was used

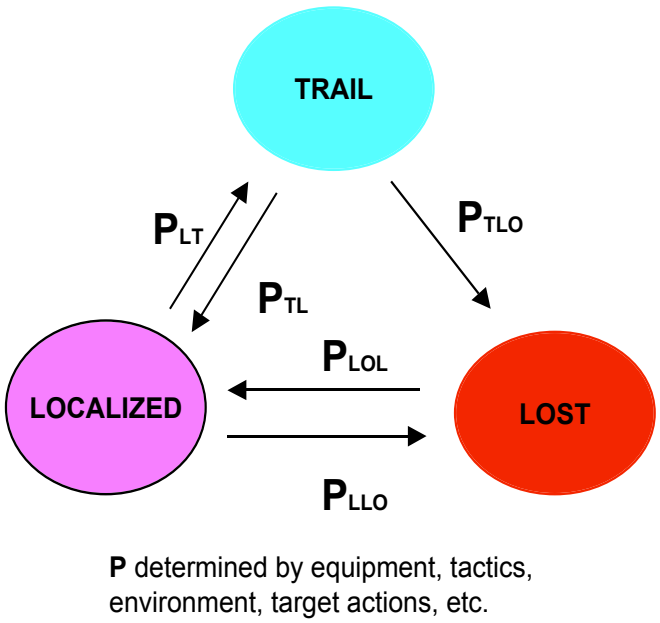


**Figure 1.** Markovian Model for Submarine

to study operations of the U.S. Navy attack submarine forces dealing with the threat of Soviet FBM submarines. This Markovian model is displayed in Figure 1.

The target submarine is initially detected by various barrier or network surveillance systems that help the trailer initially acquire the target with its onboard sensors. The target submarine is assumed at any further point in time to be in one of three states, i.e., trailed, localized within an area searchable by the trailer or lost to the trailer. In the last case a wide area surveillance net, external to the trailer, helps the trailer find the target. Various transition probability equations among the Markov states were established from the characteristics and capabilities of various equipment, tactics, environments, and so forth. Actual operational data was used to construct these probabilities. A separate model considered attack of the target should conditions warrant.

Now, you will see immediately (Figure 2) where I am going in regard to a model for the surveillance of potential terrorists.

In this case we need to identify and characterize the transition probability factors and equations related to the terrorist and trailer as well as those of any external surveillance networks which help the trailer. Obviously, some questions remain regarding the value and validity of this approach.

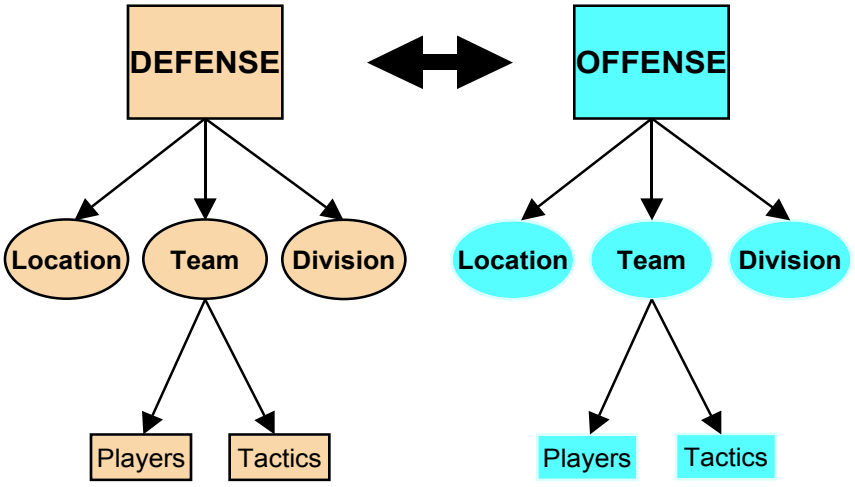


**Figure 2.** Markovian Model for Trailing Terrorists

This approach to representing terrorists has several attributes:

- Understand the means and mechanisms of trailing suspects including the resources and tactics used by trailers
- Characterize sensor and communication networks which help the trailers
- Examine trailing countermeasures

## MODELING TERRORIST FORCES AND BEHAVIOR

Slam Dunk is an interactive basketball simulation created by Pat Halvorsen in late '80s. It allows selection of game strategy, operational approach, choice of players, substitution,

scoring, time steps, etc. In its 6th dimension, WHY, emerges. In playing it, pivotal roles emerge for staff officer in the big picture. Figure 3 illustrates the interactive relationships it supports.

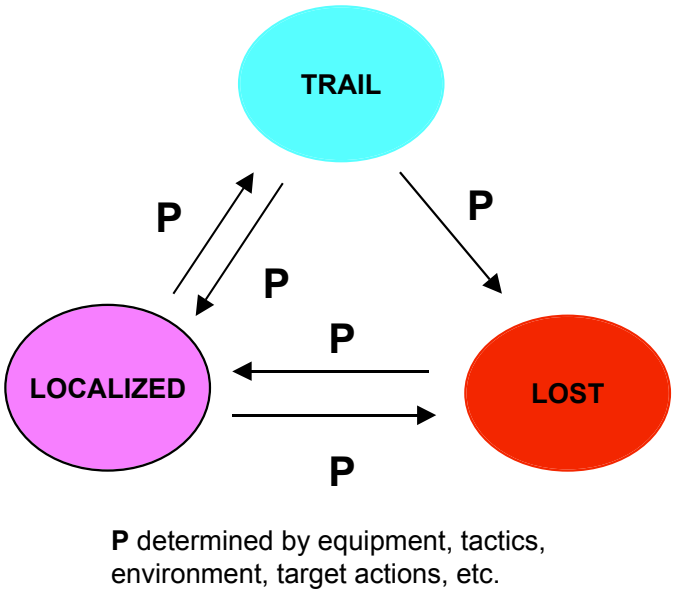


**Figure 3.** Interactive Aspects of Slam Dunk.

Slam Dunk has several other interesting and relevant characteristics:

- Play by play commentary plus play versus the computer or play games automatically
- Different offensive or defensive styles of play
- Automatic accumulation of statistics every time games are played
- Play college teams against pro teams and full control over player substitution
- Realistic play by position and includes player fatigue and double teaming
- Play with either College or Pro rules
- Create new pro or college teams using your own statistics or create divisions/leagues
- Calculate most effective 5 players at any time during game
- Display individual leaders in 12 statistical categories
- Keeps history of all games played in a schedule format
- Display team statistics in over 15 categories in various formats
- Display division/league standings, including home/road records
- Auto-scheduler, and schedule-player. Schedules can be run in background.
- Plays games in seconds
- Keeps track of individual game record. Save, print and display box scores at any time
- Games at a neutral location (home court advantage)
- Includes injuries, technical fouls, and other strange plays
- Can create/edit players and teams, using the powerful team editor
- Various sounds during game play
- And much more

Slam Dunk has aroused our curiosity in terms of a kind of simulation for the study of terrorist force behaviors and additionally as a filtering mechanism for selecting courses of action for larger or more detailed force on force cases. The simulation can relate the behavior of coaches, teams and players in terms of their respective strategies, capabilities and tactics.

The idea of Slam Dunk can be carried over directly to a course of action simulator. Important characteristics of such a simulator include

- Need for simple, force on force, interactive simulation to select COA's for detailed consideration
- Must account for strategies, operational and tactical strengths, flow of battle, etc. for both sides
- Utilize military judgement and historical and analytical data but allow free play ideas

Figures 4 illustrates the interactive features of such a simulator that can be adapted from Slam Dunk.

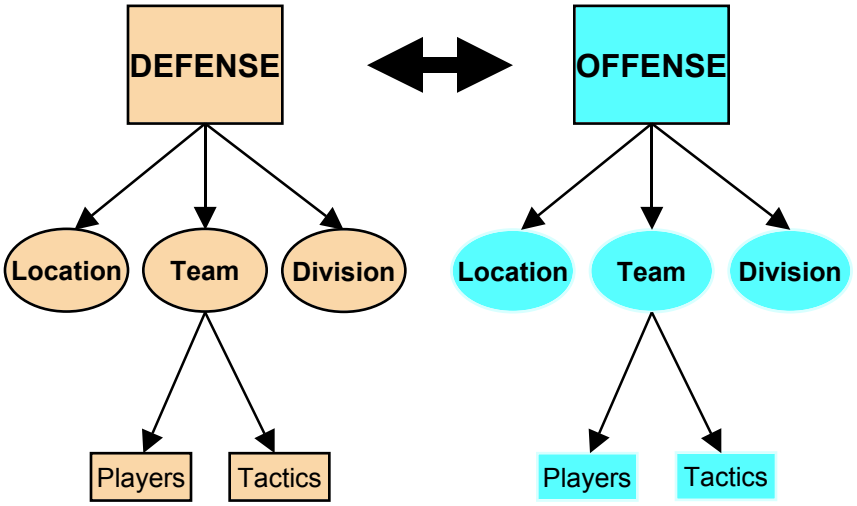


**Figure 4.** Interactive Aspects of "Slam Dunk" COA

Other features that can be adapted from Slam Dunk include

- Defensive and offensive strategies (e.g., defense in depth, use of reserves, etc.)
- Order of battle, i.e., choice of units, assignment of strengths and weaknesses
- Realistic interplay including unit casualties, concentration of forces, and deception
- Choose rules of engagement
- Create task forces
- Runs in seconds on laptop (palmtop?)

- Display results in up to 12 statistical categories
- Keeps history of all battles in a schedule format
- Display unit statistics in over 15 categories in various formats
- Auto-scheduler, and schedule-player. Schedules can be run in background.
- Keeps track of individual unit engagement. Save, print and display at any time
- Considers terrain advantages and penalties
- Includes penalties such commo failures, and other battlefield phenomena
- Can create/edit units and task forces, using the powerful editor
- Battlefield sounds, if desired
- And much more

This kind of simulation represents a departure from many of the force-on-force simulations used in the DOD community over the last decades. It doesn't replace higher resolution simulations but tends to expose on a more macro level and in a more rapid play simulation the relationships among various strategic, operational and tactical factors.

## OPERATIONS AND PLANNING FLEXIBILITY

The current military operations planning process is flawed in several ways

- Fighting the plan, not the enemy
- Single course of action approach
- More art than science (guess vs. calculation)
- Contingency planning used for unexpected obstacles & opportunity

It is built around a single course of action (COA) idea, has some planning steps out of sequence and handles important concepts such as deception poorly.

An alternate approach, which CTG is further developing and advertising considers the use of simultaneous, interrelated, courses of action, a recasting of the operations planning steps, and recognition of the inherently deceptive aspect of operations. We call this the operational flexibility concept and it has the following characteristics:

- The ability to conceive, plan and execute multiple, simultaneous courses of action
- Recognizes the dual nature of military actions; manipulation and exploitation
- Use the control and behavior of own forces to control (manipulate and exploit) enemy behavior

Figure 5 shows the symbolism we use to illustrate interrelated courses of action.

Figure 6 uses this symbolism to show the potential of this approach for direct control of enemy courses of action by using friendly courses of action.

Figure 7 addresses the use of indirect control measures such as specific actions or equipment to raise or lower the observables of selected activities, units or locations.

The course of action analysis steps required for implementing the operations flexibility approach include

1. Commander's Planning Guidance: bounds friendly and enemy behavior
2. Staff Estimates: presents friendly and enemy functional capabilities and COAs
3. Correspondence: comparison of friendly and enemy COAs (identify potential manipulations)
4. Divergence: comparison of friendly and enemy COAs (identify potential exploitations)
5. Combination: matched sets of corresponding and diverging COAs
6. Feasibility: relative cost-risk-reward assessment of matched COA sets: (predict "best" friendly COA set and most probable enemy COA)

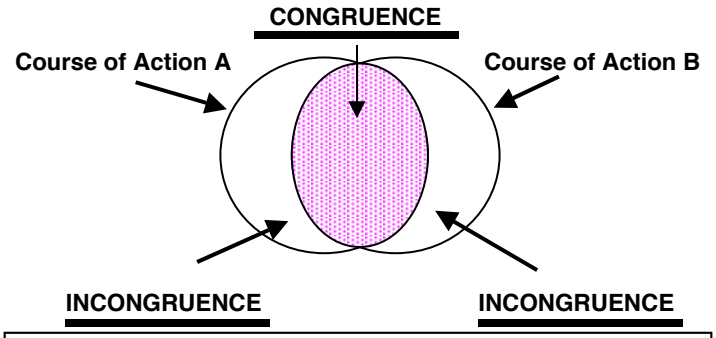


**Figure 5.** Symbolism for Interactive Courses of Action.

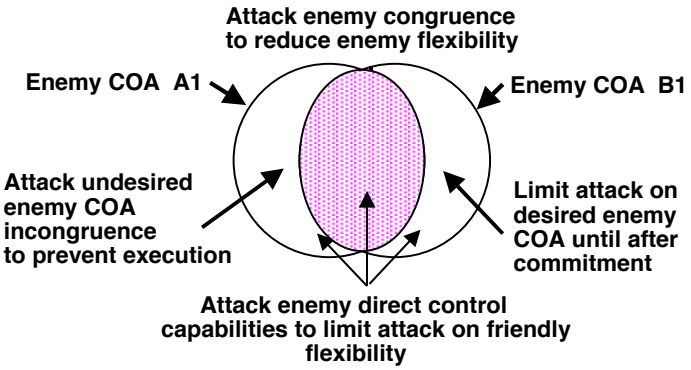


**Figure 6.** Shaping the Battlefield with Interactive Courses of Action.

Major implications of adopting the operations flexibility approach are

- Development of training programs for commanders and staff officers
- Revision of military doctrines
- More comprehensive and flexible models and simulations

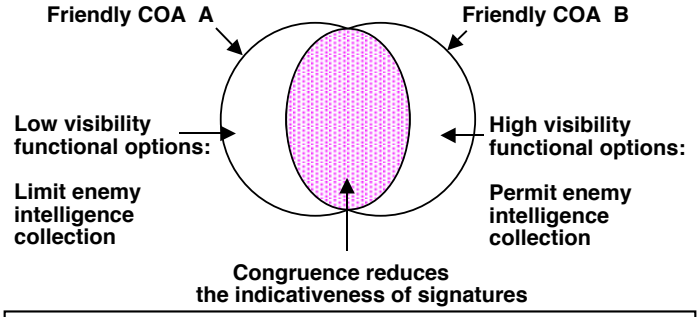


**Figure 7.** Indirect Control Measures for Controlling COA Signatures.

Note that the use of this approach will require more comprehensive and flexible simulations of military operations and activities.

# A Discrete Event Computational Basis for Simulation Science

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## INTRODUCTION

Scott Harmon [1] and Dale Pace [2] take the position that a science of simulation is desirable and possible. Philosophers of science have offered many variations of, and even strong disagreements with, the traditional view of science and how science proceeds. Nevertheless, I will start from a rather simplistic formulation with some additions. This may offer an easier way to understand how the activities that we associate with modeling and simulation differ from, and might evolve, to a more scientific standing.

## A SIMPLISTIC MODEL OF SCIENCE

Figure 1 presents this simplistic view of science in the form of a data flow diagram. In the beginning there are *phenomena* in the domain of interest as well as business *practices* that relate to these phenomena. For example, the motions of the starts in the sky are salient phenomena and related practices include the development of calendars for conducting religious ceremonies and agricultural time management (e.g., scheduling the planting of crops, etc.). Without claiming that the development of physics was motivated solely by its applications potential, it seems quite plausible that, once a certain level of accuracy had been achieved in predicting the motions of starts, this knowledge could be exploited for more applied purposes. For example, precise prediction of the timing of the seasons could eventually move calendars from the mysterious intellectual property of the high priest, to the widely disseminatable, open form of the farmer's almanac.

We move toward science when controlled observation and *experimentation* replace haphazard observation. Recurrent observations, and repeatable experiments, then get recorded as *data* which can be "mined," summarized, and regularities described. *Theory* formation introduces hypothetical entities, not directly apparent in the data, that can explain or predict some parts based on others. Eventually, if theory survives repeated confrontation with data, it becomes the basis for improved practice. It is interesting to ask whether there was a "killer app" that brought Newton's abstract theory firmly out of the ivory tower and into general acceptance as a basis for engineering. For example, it may have been that cathedral construction had reached a height plateau and that Newton's laws were critical in breaking through this barrier [3].

Using this characterization (characture) of the science of physics, we can assess the relative state of M&S as a science of this nature (Figure 2). Harmon [1] has pointed out the benefits of controlled experimentation to learn how M&S really works in large projects. Currently, such projects leave very little formal trace of their activities and results, so that "lessons learned" are very difficult to draw. There are distinct phenomena that characterize M&S, such as its concern with models and their relationships to the real

world and to the simulators that execute them. These phenomena distinguish M&S from related disciplines such as computer science, software engineering, systems engineering, and mathematics.

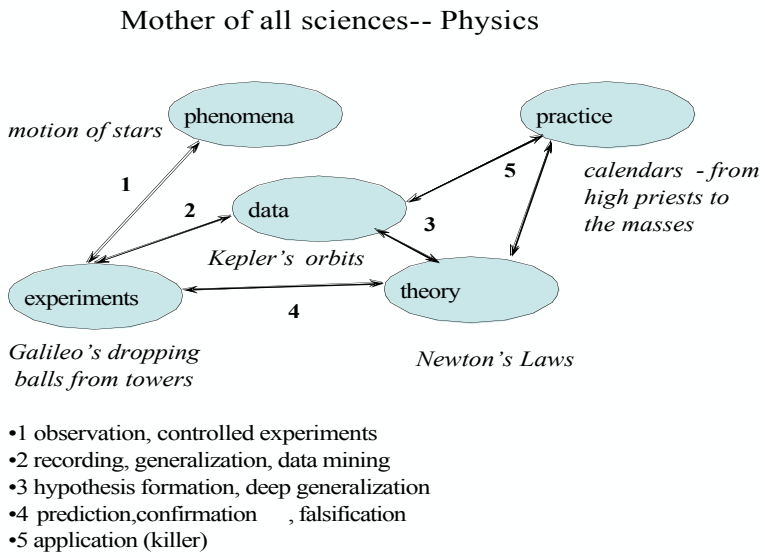


**Figure 1.** Data Flow Diagram for Science (physics).

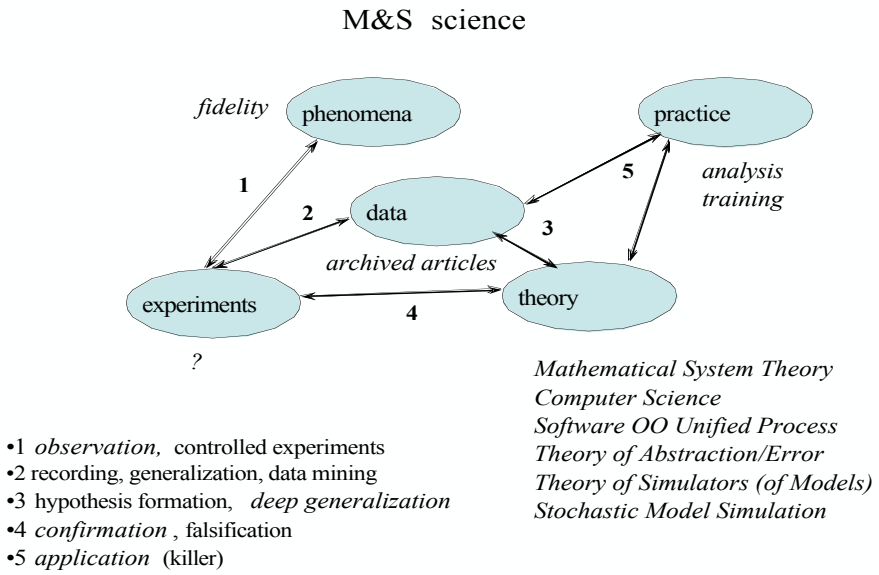


**Figure 2.** Data Flow Diagram for Modeling and Simulation Science.

Relating to Figure 2, I believe that M&S has some of the attributes that might characterize a nascent science. Although data on the conduct of large M&S products are not abundant, there is a not-insignificant data set in the form of journal articles, conference papers, and books dealing with most aspects of M&S. There is even digital library of M&S literature in the making [4]. While there are experimental studies on a

small scale of various techniques and methods, there is a dearth of description of large-scale development projects, at least in the form that controls and comparative analysis are evident. Since there are really very few documented large-scale experiments, there can be little in the way of theory to summarize and go beyond these data. However, the latter statement holds only if you accept the simplistic model of physics. On the other hand, there are taxonomies of M&S [5,6], there is a theory of modeling and simulation [7] and there are theories of related areas such as mathematical systems theory, computer science, and systems engineering. And since these are not pure fantasies, dreamt up by their authors for no rational purpose, they must relate to the phenomena of M&S, although not in the simplistic manner suggested by our physics-emulating model. Indeed, often the source of these theories is the direct, personal, and anecdotal experiences of the authors and the communities they work within. Often, the theories are the basis for methodologies, i.e., they are prescriptive or normative, telling how best to do something, or what the right answer should look like. To translate theory into practice there are handbooks [8,9,10] although there are no recognized best practices.

I conclude that many of the elements of a science of M&S are already present, but of course, they don't form the coherent whole that constitutes a true science. I will now focus on the theory element.

## THEORY OF MODELING AND SIMULATION

System theory, and its mathematical instantiations, provides a rigorous framework for M&S but it lacks a computational and conceptual infrastructures. Object orientation (OO) provides a strong computational basis for M&S. Currently, OO is being given commonly accepted conceptual interfaces through such the Unified Modeling Language (UML) for general software development. However, UML is inadequate when applied to M&S since it fails to come to grips with elements that are intrinsic to M&S: continuous and discrete dynamics, model composability, abstraction-related families of models, efficient simulation infrastructure, etc. I take the position that a more encompassing M&S theory is needed to address these requirements. We need to develop such a theory that draws upon the Theory of Modeling and Simulation, systems theory and UML but goes further to provide a computational basis for the M&S intrinsic elements just mentioned. There is good reason to believe that DEVS (Discrete Event Systems Specification) can provide such a computational basis. DEVS is based on a formal M&S framework for model specification, execution, and simulation [7]. It is derived from mathematical dynamical system theory and inherits the concepts of structure, behavior, equivalence, and morphism that support rigorous mathematical approaches to difficult issues such as abstraction, verification and validation. DEVS supports hierarchical, modular composition which is essential for scalable complex system development. It has a standard object oriented implementation that provides a computational basis to work with its formal underpinnings. Moreover, recent work is suggesting that is able to support both discrete and continuous modeling paradigms and thereby exploit efficient parallel and distributed simulation techniques for a unified multifaceted modeling framework.

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# SESSION SUMMARIES

## Session 1 – Could a Science of Simulation Exist & Why?

The first session focused upon examining the question of whether a science of simulation might exist and, if so, what benefits it might provide. Mr. Lunceford set the tone for the entire session by explaining that he wanted to improve the simulation workforce. He believes that he can do that by giving simulation practitioners the right knowledge and surrounding them with a productive environment. This workshop seeks to identify the knowledge component of that goal. He cautioned us not to over constrain ourselves by focusing upon the "science" part although he thought that a scientific approach to gaining the requisite knowledge seemed like a good path.

With that prelude, Mr. Lunceford led the participants through discussions of

- Simulation workforce quality,
- Simulation education,
- Simulation science, and
- Simulation core knowledge.

He successfully elicited considerable and vigorous exchange on each of these topics. He then concluded the session by identifying the component goals to advancing a simulation discipline and listing three short-term steps toward achieving those goals.

At its conclusion, Mr. Lunceford captured the essence of the session in several points. The participants agreed that there is or should be core knowledge for simulation. He identified three goals that the participants believed would advance the simulation field:

- A degree program for simulation professionals,
- A set of best practices for both engineers and scientists working in simulation, and
- A set of processes in place to support those practices.

He also identified four short-term steps that we could take toward these goals:

- Establish a set of courses that teach the current best practices in simulation,
- Assemble a set of documents that describe these best practices that students and practitioners alike could use,
- Develop a set of courses (perhaps the same courses described above) within Functional Area 57 to train Army officers about simulation, and
- Create a consistent set of definitions for core terms related to simulation.

He hoped that this workshop would define a set of actionable steps through which to gain the core knowledge necessary to achieve the goals we defined.

## Session 2 – Prior Work on Simulation Science

The purpose of this working session was to begin identifying prior work applicable to a science of simulation that might establish a foundation from which to grow. Prof. Zeigler opened this session by stating its purpose was to identify references that represent prior scientific activities associated with simulation. He admitted that he began this workshop unconvinced about the existence of a science of simulation. He became more convinced that such a science could exist and that its discovery had value to the simulation field.

He drew an analogy between physics and simulation then backtracked to understand how that science evolved. He then proposed applying the same model to simulation as a science.
The participants reflected upon the models of physics as applied to a model of simulation science and, through that comparison, considered a wide range of related topics in this session including

- Nature of science and engineering,
- Various simulation phenomena,
- Past work applicable to simulation science, and
- A lessons learned workshop.

Like the discussions of the first session, while these considerations strayed somewhat from the session's topic, they added to the overall tapestry of information that composes the results of the entire workshop.

Mr. Lunceford summarized the session as follows:

- Having a paper written that describes how to manage a "multi-task" management process for software/large M&S development programs would be extremely valuable.
- Simulation technology has been stalled for the past 5 years. The M&S community appears to be repeating its application development focus without actually having to tend to the science of M&S.

## Session 3 – Simulation Observables & Phenomena

The purpose of this session was to identify a number of properties through which one could observe simulation phenomena. After some discussion, the participants decided to enumerate the phenomena associated with simulations as well. Table 1 lists the simulation observables and phenomena that the participants supplied.

**Table 1.** Results of the Simulation Observables and Phenomena Brainstorming.

| Simulation Observables and Phenomena |
|---|
| Elements of fidelity {i.e., resolution, error, precision, sensitivity, capacity) |
| Detail |
| Implementation aspects (e.g., language, computer, etc.) |
| Immersion |
| Time (real vs. simulation time) |

**Table 1.** Results of the Simulation Observables and Phenomena Brainstorming (continued)

| Simulation Observables and Phenomena |
|---|
| Program management elements |
| Interactivity |
| Man-machine interface |
| Relationships (i.e., model-to-real world, model-to-model, model-to-simulator, model-to-person) |
| Representation |
| Comprehensibility |
| Observability and controllability |
| Maintainability |
| Connectability to the real world and other models |
| Story |
| Objectives (i.e., relationship between simulation design and objectives) |
| How a simulation gets used |
| Performance |
| Usability |
| Complexity |
| Setup |

In the course of building this list, the participants covered a number of topics including

- Simulation phenomena,
- Simulations too hard to build,
- Simulations and models, and
- Specific versus general simulations

The participants did not share a common definition or understanding of the nature of phenomena. However, despite this slight misalignment, they were able to identify possible simulation phenomena and discuss how the understanding of them could advance our core knowledge.

The participants were able to identify several classes of simulation phenomena. These phenomena fell into one of two broad categories, those specific to the nature of simulation and those that influenced simulation but were applicable to any large system as well. Those phenomena that distinguish simulation from the products of other disciplines can probably contribute to identifying simulation's core body of knowledge. The participants also discussed some of the issues that made some simulations too hard to successfully implement and the differences between models and simulations. Finally, they considered the advantages and disadvantages of building simulations to solve specific problems versus building general simulation frameworks that can solve many problems. This dichotomy in particular may represent a fundamental issue in simulation.

## Session 4 – Simulation Hypotheses

The purpose of this session was to identify possible hypotheses that could be tested and, if supported by empirical evidence, could coalesce into core theory about simulation.

Mr. Gross introduced this session by illuminating the nature of the scientific method and the necessary properties of scientific hypotheses. He emphasized that our discussions should recognize that a good hypothesis must be testable. He completed his introduction by indicating his desire to extract some hypotheses that could be validated through some kind of observational or experimental program. Dr. Pace asked if we should explore those hypotheses about what simulation might look like and what some of those might be. Mr. Gross affirmed.

The participants launched into vigorous discussion about simulation hypotheses. In the course of this discussion, they identified several. Table 2 lists the hypotheses that the participants suggested and debated.

**Table 2.** Results of the Simulation Hypotheses Brainstorming.

| Possible Testable Simulation Hypotheses |
|---|
| Different levels of fidelity affect interoperability |
| Simulation development is limited by the domain knowledge |
| Simulation fidelity/validity is limited by domain knowledge |
| Simulations may be useful even though they may not be predictive |
| Every system admits to simulation |
| Complex adaptive simulations are essentially unvalidatable |
| Increased emotional involvement reduces performance but increases retention |
| Simulation performance and capability can be measured |
| Immersion can be measured |
| The efficiency for gaining insights from analytical simulations is inversely related to complexity beyond a threshold |
| Multi-modal interfaces significantly increase simulation utility for some applications (e.g., smell affects immersion) |
| Simulation performance and fidelity can be adversely impacted by scalability |
| Accuracy of the environment is critical to sensor performance(?) |
| Believable environments are important to participants |
| A quality explicit conceptual model reduces simulation development and reuse cost |
| The validity of federated simulations is dependant on consistent interpretation of shared data |
| Appropriate validation and verification can reduce simulation lifecycle cost and/or improve quality |
| Simulations designed to build in multi-resolution representations provide substantial subsequent flexibility |
| Simulation reduces system lifecycle costs |
| Simulation enables design of systems which could not built without simulation |
| Small scale simulations can be more cost effective than large scale simulations |
| Standards reduce cost and/or improve quality |

Considerable discussion interspersed the proposal of hypotheses. Part of this discussion addressed the following topics:

- Characterizing error,
- Valid sample sizes, and
- Simulation hypotheses.

Unfortunately, the sound track on the videotape of this session failed after only 40 minutes of the session. As a result, these topics represent only a small sample of the entire discussion that occurred during this session.

While the participants covered some very important topics during this session, the process of formulating meaningful hypotheses about the fundamental nature of simulation proved challenging. Some participants willingly jumped into the fray and proposed hypotheses but others puzzled over the problem of testability. However, this session did result in a list of germs of hypotheses dealing with the nature of simulation. And, the interactions between those proposing hypotheses and those questioning their testability or validity did stimulate interesting and insightful discussions. In addition, the participants considered the issues of errors and simulation validation from limited sample sizes.

## Session 5 – Experimentation & Observations

The initial purpose of this session was to identify possible experimental paths to gain better knowledge of the fundamental nature of simulation. At the session's beginning, the participants briefly debated the workshop's purpose, as some observed that our discussions seemed to wander somewhat purposelessly at this point.

Mr. Lunceford reminded us that the workshop discussions focused upon the science of simulation because a set of simulation practices founded upon fundamental knowledge did not yet exist. The goal of seeking those fundamentals should drive the workshop. Arriving at the conclusion that no science of simulation existed would be an acceptable conclusion from the workshop but he wanted the participants to address the fundamentals that might underlie simulation whether a science or not. He wanted us to make a series of recommendations about what we needed to do to find those fundamentals (e.g., additional workshops). If we ultimately found a science with which he cannot do anything then we have not helped him.

Dr. Numrich provided a slightly different perspective on the workshop's purpose. She noted that we had said that no foundational research is ongoing in simulation and that we would like some. Her problem comes when trying to pursue that desire for funding for foundational research in simulation. In doing so, she must deal with people with educations in traditional science and they do not see anything foundational about simulation. As best, to them, it seems only an applied part of computer science. She articulated the goal for us to develop a list of basic research topics. For her to find funding for basic simulation research, she needs a good list of foundational topics.

After their careful consideration of the purpose of this session and of the workshop in general, the participants began to examine the issues associated with the means to

perform experiments on simulation or obtain systematic observations of simulation behavior. In this context, they discussed the following topics:

- Simulation as science,
- Simulation fundamentals,
- Relevant prior scientific work/data,
- Various miscellaneous topics, and
- Experimentation and simulation.

While some of this discussion strayed some from the session's focus, all of these topics were relevant to the workshop's theme and contributed to the knowledge derived from this workshop.

In the end, the participants did not agree that simulation could be a science but they did identify several areas of fundamental knowledge the uniquely represented simulation. These areas included

- Managing simulated time and events,
- Conceptual modeling,
- Abstraction and representation, and
- Correspondence with the simuland.

A few of the participants also identified several islands of prior work that demonstrated applying the scientific approach to understanding simulation fundamentals. Finally, the participants recognized the need for quality data from which people could formulate theories about simulation and recommended two specific activities that could supply that data:

- Lessons learned conferences, and
- Simulation competitions.

These activities could create considerable data about various aspects of simulation phenomena ranging from the observations of actual practice to conceptual modeling and abstraction.

## Session 6 – Workshop Recommendations

The purpose of this session was to formulate recommendations for actions resulting from the discussions in the previous working sessions. Dr. Numrich introduced the session by strongly emphasizing that we needed to continue the dialog about the body of knowledge for modeling and simulation. She believed that defining how to make this information available to the simulation community was equally as important.

The participants then proceeded to cover several topics including

- Attributes of a science,
- Capturing core knowledge,

- Existing problems with simulation,
- Validated theory, and
- Need for data on simulation behavior.

Dr. Numrich summarized by elucidating the recommendations that we had touched upon in our discussions. She broke our ruminations and recommendations into advancing our basic understanding, bringing a concrete understanding together, and addressing the need to experiment and deal with the matter of simulation. With regard to advancing our basic understanding we needed to

- Build a list of relevant conferences, textbooks and papers that provide a basic understanding of simulation, and
- Develop a set of books that contained both tutorials and surveys of simulation topics.

Regarding bringing a concrete understanding of simulation together, we need a

- Journal similar to the Reviews of Modern Physics that publishes high quality survey articles, and a
- Lexicon of simulation.

With regard to addressing the need to experiment and deal with the matter of simulation, we need to

- Sponsor a specialized conference, beginning with one capturing the lessons learned from Millennium Challenge 2002 exercise,
- Identify what data the existing literature can provide that tells us more about the nature of simulation,
- Spur the university community to perform experiments and observations and publish their data in forms accessible to a broad community of researchers,
- Understand the nature and needs of a modeling and simulation profession, and
- Explore the current effort to define a program for certifying simulation professionals (e.g., at National Training and Simulation Association).

# WORKING SESSION NARRATIVES

**Note:**

These narratives capture and organize the discussions from the working sessions. Notations in square brackets consisting of a capital letter followed by a three digit number (e.g., [A101]) appear throughout these narratives that link the narrative material to the session transcripts in the appendices. The letter denotes the transcriber (there were two) and the number identifies the particular statement number. To locate a specific statement,

1. Find the appendix corresponding to the session of interest,
2. Find the section in the appendix corresponding to that transcriber, then
3. Find the statement number.

For example, to locate statement [A029] in Session 5, go to the first section of Appendix 8 and find statement 029.

# Session 1 – Could a Science of Simulation Exist & Why?

This session focused upon examining the question of whether a science of simulation might exist and, if so, what benefits it might provide. Mr. Lunceford set the tone for the entire session by explaining that he wanted to improve the simulation workforce. He believed that he could do that by giving simulation practitioners the right knowledge and surrounding them with a productive environment. This workshop seeks to identify the knowledge component of that goal. He cautioned us not to over constrain ourselves by focusing upon the "science" part although he thought that a scientific approach to gaining the requisite knowledge seemed like a good path.

With that prelude, Mr. Lunceford led the participants through discussions of

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- Simulation education,
- Simulation science, and
- Simulation core knowledge.

He successfully elicited considerable and vigorous exchange on each of these topics. He then concluded the session by identifying the component goals to advancing a simulation discipline and listing three short-term steps toward achieving those goals.

## SIMULATION WORKFORCE QUALITY

Mr. Lunceford initiated this discussion by asking "How do I get a well trained workforce and quality [work] from them?" He believes that problem to be the single biggest issue in simulation. Most of the other problems from which the field suffers can be tracked back to the workforce issues. He restated this initial question as

- What makes a quality workforce and
- What surroundings does that workforce need to perform quality work?

Addressing the quality workforce problems will help to give him some management vectors for the near and long terms. He also thinks that developing a science of simulation might take a few years [A001, B001].

Dr. Pace asked for a time dimension on these questions, a couple of years or many years [A002]? Mr. Lunceford desires a quality workforce at some level within two years but he doubts the realism of that wish. He hesitates to focus too closely on these questions because that may compromise the long-term vector. But, he needs to do something in the near term as well [A003]. Mr. Waite indicated that a quality workforce also requires quality leadership [A004]. Mr. Lunceford responded that he expects that to happen anyway because of simulation's value. He asked "How many false starts we must suffer?" and "Can we make it move faster and cleaner?" He pointed out that no one currently understands the value of this direction so they will not fund it [A005]. Dr. Raibert asked, "What are the defects in the value proposition [A006]?" Mr. Lunceford replied that that was a good question but thought that it might distract us from addressing the quality workforce question [A007]. Dr. Pace asked if the quality of a simulation workforce could substantially change the value of simulation. He suggested that the

answer to that question would determine how much quality in which to invest. He said, "Even our blundering has produced results [A008]."

The participants examined the workforce quality problem and briefly considered the impact of peer review upon simulation publication quality.

### Models of Workforce Quality

Several examples of professions with quality workforces exist (e.g., medicine, law, physics, engineering, automobile mechanics) that may offer role models for a simulation profession [A009-012, A016, A018]. Some believed that not all of these professions depend upon scientific knowledge for the quality of their work [A015]. Some of the factors that contribute to workforce quality include

- Consistent training,
- Practitioner certification and licensing programs,
- Professional standards,
- Customers concerned with and willing to pay for quality work, and
- Employing organizations that maintain professional standards [A009, A018-022].

In general, the model professions have evolved to where they do not rely upon the performance of a cottage industry of prima donnas [A009]. While some simulation workforce quality problems in DoD may arise from the Government business model, the Government does employ professions that do produce pretty high quality work [A013, A014]. For simulation to achieve a quality workforce, we must ask ourselves "What factors have led us to where there is a quality problem in the simulation industry [A009]?"

### Quality & Peer Review

The peer review process can improve the quality of published work in a field and many professional organizations rely upon peer review for their publications [A023]. The Society for Computer Simulation (SCS) used to have an archival and peer reviewed publication that had 700-1000 subscribers (see bibliography Ref. [351] for more information on SCS). However, they recently combined their popular and archival publications to create a general interest magazine because their contents were converging [A024, A025]. A few other serious publications, employing peer review, exist for simulation (e.g., published by the Association for Computing Machinery and the Institute for Electrical and Electronic Engineers) but they also have relatively small subscriberships [A026] (see bibliography Refs. [382, 383, 385-389] for more information on simulation publications). To remedy this, Mr. Lunceford hopes to push simulation people back into quality publications to help the workforce (especially people new to the workforce) separate good work from bad [A162].

## SIMULATION EDUCATION

Mr. Waite suggested that we ought to think about improving the quality of simulation education as a coordinated campaign. He recommended that this campaign should include

- Getting courses in place in academia, and
- Establishing standards and a body of knowledge for the industry

We must also create a marketplace where the customers emphasize their presence and expect quality workmanship in the simulation products and services they buy. He believes that these tasks are all doable but that we must proceed carefully [A149].

The participants, in their discussions, added to the elements of a coordinated education campaign. They examined the current state of simulation education and the assumptions associated with formal degrees. They discussed journeymanship as one form of education as well as various ways to structure more formal simulation education. Finally, they debated the nature of simulation best practices, the issues of the simulation profession, and evaluating simulation researchers.

**State of Simulation Education**

Currently, no college or university in the USA offers an undergraduate degree in simulation [A078, B003]. Five to six universities have started doctoral programs in simulation and some of these are also working to establish programs at the master's level [A084, B003] (see bibliography Ref. [354] for a listing of universities with simulation curricula). The University of Central Florida (UCF) presently offers degrees at the associate's (a program that trains people to repair simulators), master's and doctoral levels (see bibliography Ref. [357] for more information on the UCF simulation programs). Their faculty feels that the contents of curricula in mathematics, computer science or engineering and simulation differ too little to justify a program at the bachelor's level [A079, A106]. Other institutions tend to augment other curricula with simulation content because they do not perceive simulation as having substantial core knowledge in itself [A083, A092]. This situation reinforces the impression that elements of simulation are taught widely but not specifically, a situation that may hamper establishing simulation as a separate academic discipline [A092]. Significant difficulties may exist in schools trying to create a formal simulation specialty in existing core disciplines because their current core curricula are already packed with existing material. These very practical problems may hamper starting a simulation discipline without some motivation from a powerful advocate (e.g., the US Government) [A084].

Mr. Lunceford asked why more simulation people do not come from the mathematics department. He maintained that most simulation people could not effectively turn algorithms into simulations [A080]. Dr. Shumaker queried about which area was the weakest in simulation, system design or algorithms [A081]. Mr. Lunceford replied that both were equally weak. He posited that simulation technology could not advance until we have people who can collect real world data and turn that data into algorithms then transform those into a simulation [A082]. Further, the people who can create algorithms for simulations have very different skill sets than those who build general-purpose simulation engines [A099].

**Assumptions Associated with Degrees**

An accredited (e.g., ABET for engineering) educational institution that produces individuals with degrees in a particular field (e.g., electrical engineering) teaches a

codified body of knowledge [A029, A073, A074] (see bibliography Ref. [367] for more information on ABET). This permits employers to safely assume that those individuals possess certain knowledge and this assumption thereby reduces the number of questions that an employer needs to ask a prospective employee to gauge their qualifications [A028, A030]. The employer can then explore such issues as relevant experiences and vocational specifics [A030]. The knowledge that an employer can assume that a degreed individual possesses defines, to some extent, the core knowledge of that field [A030]. The employer then hires an individual with the expectations that they will use a minimum set of established practices to do any jobs assigned to them [A030]. An individual's first job continues the educational process by focusing that person's skills and knowledge in specific areas [A101].

The lack of an established body of knowledge means that employers of entry-level simulationists cannot make that same assumption [A076, A077]. Presently, the only assumption employers can make is that individuals, who have studied simulation in school, have studied some specialty related to or that employs simulation [A095, A096]. The absence of degree accreditation for a simulation curriculum means that almost anyone can simply declare himself or herself a simulationist [A034].

The workshop participants defined some of the knowledge and skills that one should expect individuals degreed in simulation to have:

- Extracting simulation requirements from users [A030, A145];
- Transforming user requirements into specific simulation needs [A030, A145];
- Designing simulation components and systems that meet user simulation needs [A030];
- Identifying the algorithms needed to meet user needs and transforming those into software [A035];
- Tracking requirements and the simulation components that meet those requirements [A145];
- Building a quality simulation engine [A030];
- Selecting commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) products such as a good commercial simulation engine [A030, B016];
- Understanding and effectively employing simulation infrastructures and existing simulation standards such as the DMSO High Level Architecture (HLA) [A145, B016];
- Understanding mathematical abstraction [A035];
- Understanding mathematical modeling (e.g., turning real world data into representative models) [A099];
- Understanding and effectively employing modern software and systems engineering practices and tools [A034];
- Understanding some level of mathematics and physics [A034]; and
- Understanding a simulation specialty [A034].

The participants spent only a small amount of time constructing this list so it, by no means, approaches an exhaustive enumeration of the knowledge that a simulationist should have. However, Dr. Pace noted that a third of the people who he has trained do not possess even this level of understanding [A036]. Mr. Waite wondered about the difference between this list and the list that the core knowledge of simulation would eventually contain [A146].

**Journeymanship**

Historically, immature fields developed and propagated their core knowledge through apprentice-journeyman relationships [A040]. These relationships continue to thrive, even in well-established technical areas, in industry and academia. For example, Boeing specifically defines skills at the apprentice, journeyman and master levels and these levels define the sets of tasks that one can assign an individual. Apprentices work under the direct supervision of masters or they are assigned very small tasks [A142, B011]. One can also see graduate school as a form of apprenticeship [A141]. Employers hiring at the journeyman to master level can expect individuals to execute a set of practices in ways indicative of good workmanship [A143].

**Structuring Simulation Education**

The participants discussed several approaches to improving simulation education including

- Simulation shortcourses,
- Non-degreed simulation courses,
- Advanced degrees in simulation, and
- Basic degrees in simulation.

Each of these paths offers different benefits and has different costs. A unified education campaign could broadly improve simulation education opportunities.

<u>Simulation Shortcourses</u>

Dr. Pace asserted that shortcourses and on-the-job-training provided the only means by which to educate simulation practitioners over the short term (i.e., five years). He felt that fully developed academic programs were ten years away [A113, A114, B005, B013]. Prof. Swartout suggested that the apprenticeship model supported by MS and PhD programs, some already established, supply another short-term answer. Shortcourses suffer from two problems. They give the students knowledge but no hands-on experience. They also need people with experience to teach them [A148]. Dr. Pace reminded us that shortcourses should cover dealing with both small- and large-scale simulations [A138]. This breadth will require instructors with experience in both large and small systems and not by those with narrower experiential bases. These instructors may come from academic programs. Mr. Lunceford asserted that both large- and small-scale simulation programs should exercise the same discipline but Dr. Pace countered that they involve different skills and processes [A140, A141].

Non-Degreed Simulation Courses

Mr. Lunceford acknowledged that he wants an MS degree in simulation but he would really like one good three hour simulation course. He asked the participants if the university system could create a package of courses focused upon simulation technology that he could recommend to his people. This course package must be presented online to minimize the travel costs associated with attending the courses. He described a program that he is developing to educate US Army officers in simulation. Officers in this program would spend their first year learning the Army simulation domain and their second year learning the specifics of simulation practice. This second year could come from a university [A150]. Employing university courses in this program has the advantage of permitting its participants to transfer those course credits to an advanced degree program if they desired [A156]. His office has also had some success in developing the training strategy for Functional Area 57 (see bibliography Ref. [359] for more information on the Functional Area 57 program). This involves a 16-week program that he would like to structure in an academically acceptable way so the credits will be transferable [A156].

Prof. Zeigler briefly described courses in basic modeling and simulation that the University of Arizona, Tucson (OofAz, Tucson) runs at both the undergraduate and graduate levels and that are gaining in popularity (see bibliography Ref. [356] for more information on the simulation education program at the UofAz, Tucson). These courses could be offered online but not without overcoming some implementation difficulties [A153, B014]. The National Technological University (NTU) also makes course material available online throughout the country (see bibliography Ref. [368] for more information on NTU). However, they require a broad demand for any course material they offer [A151, B014]. Mr. Lunceford noted that the Army has thousands of people with an interest in simulation. These people fall into two groups: simulationists and people who must understand simulation (e.g., program managers). Current simulation program managers typically understand software development and program management but not specifically simulation [A154]. He felt confident that he could create the demand from this interest. People outside the Army might also be interested in these courses if they were offered from a university [A152]. Prof. Zeigler responded that his organization is planning to offer a course at Ft. Huachuca that will supply a broad familiarity of simulation technology to managers. This course might stimulate its participants to pursue an MS at the UofAz, Tucson [A155]. He felt that such survey courses guide people toward taking the proper coursework and help them choose an appropriate specialization [A157].

Advanced Degrees in Simulation

The participants briefly explored the issues associated with instituting advanced degrees (e.g., MS, PhD) in simulation [B007, B008]. Dr. Pace noted that many disciplines have no undergraduate degree (e.g., law, theology, medicine). People in those disciplines specialize after getting a more general undergraduate degree [A085-087]. Mr. Alexander suggested that perhaps our community should go to the college testing services and have them build a test, a SimCAT, analogous to the MCAT. This test would ensure that people meet the minimum criteria to advance to another degree [A089]. Prof. Swartout observed that simulation education appeared to be advancing differently than other programs such as computer science. In the early days, these fields had no

undergraduates. Those specialties were taught only at the masters and doctoral levels. Today, there are not many PhD programs in simulation. That suggests that the simulation field does not have the same established academic or scholarly tradition. That may explain the current state of simulation [A045]. Prof. Zeigler commented that most of his students leave after getting their bachelor degrees [A042]. This trend may inhibit populating advanced degree programs.

Basic Degree in Simulation

The workshop participants debated the sensibility of establishing a degree program in simulation at the bachelor's level (see bibliography Refs. [188, 189, 192] for more discussion on establishing a basic degree in simulation). Mr. Lunceford began this debate by commenting that a person with a bachelor's degree today cannot claim to be a simulation person [A093]. To this, Mr. Waite posited that that should be a goal that we want to achieve within five to ten years [A094, A102]. Prof. Zeigler knew of only one university, the University of Skovde, Sweden, offering a bachelor's degree in simulation engineering [A078] (see bibliography Ref. [189] for more information on this program). Prof. Swartout suggested that we should start with masters or doctoral programs [A103]. Dr. Shumaker asked if there was enough knowledge to fill two years and suggested that there might not be enough [A110, B004]. Prof. Zeigler and Mr. Waite contended that there was plenty of knowledge upon which to base a bachelor's program [A111, A112]. Mr. Waite reinforced that the community needs such a program [A112]. Prof. Zeigler concurred and continued to say that, while there are a need and sufficient content for such a curriculum, there are cultural and people issues to overcome [A114]. Even getting a single modeling course into an existing curriculum is difficult because of the weight of existing academic material [A091].

When Mr. Lunceford sought consensus on the reasonableness of offering a degree in simulation at the bachelor's level that creates a view equivalent to that that people currently hold about engineering, Drs. Page and Raibert dissented [A116, A119]. They felt that expanding an existing curriculum, such as electrical engineering or computer science, might be the right thing to do now [A119]. Dr. Shumaker maintained that most students do not enter the university environment with such a specific idea of their major [A134]. Prof. Zeigler argued that being a generalist might only be desirable by default. He believes that simulation people can be very flexible and able to rapidly adapt to a wide variety of professional contexts. Further, a simulation curriculum could offer specialization through minors. A simulation curriculum would give students modern skills that they cannot now get in any orderly manner [A128].

Some of the participants expressed some concern about replacing important existing courses with those required for a simulation major. Dr. Raibert recounted an experience at Carnegie Mellon University when some professors proposed not teaching calculus to make room for other things. He contended that any new program, like a simulation program, at the undergraduate level would suffer those same pressures and critical decisions [A129]. What current material should be replaced with the new material necessary to support a simulation major? Prof. Zeigler retorted that starting fresh might leave room for methodological courses [A130].

Mr. Lunceford summarized this debate by saying that a degree in simulation is a good idea and that it should go down to the bachelor's level. This degree program requires a core body of knowledge. Further, the success of such a curriculum depends upon the willingness of the commercial industry to hire the people produced by this program. Such a program also needs the academics to teach the curriculum and the students willing to enroll in a simulation major [A136, B015]. Mr. Waite pointed out that, for the commercial industry to support such a curriculum, a degree in simulation should mean that people with that degree could perform certain tasks to an expected level [A139]. The participants agreed that such a program must be broad enough so as not to unnecessarily limit the students' employment options [B015].

**Simulation Best Practices**

In parallel with establishing some consistent opportunities for formal simulation education, the workshop participants saw capturing current best practices as important. These practices should represent the skills, procedures and practices that experienced simulation practitioners employ when executing their craft [A136, B016]. Mr. Lunceford is working with the Defense Modeling and Simulation Office (DMSO) to create a set of best practices. They will first put something together for the short term then build upon the product of that initial effort through a peer-reviewed process to improve its quality [A030]. Dr. Pace and Mr. Waite are working to create a set of monographs that capture the breadth of simulation practices [A031, A032]. These volumes will represent the body of knowledge that simulationists should know and describe the practices and processes that simulationists should competently execute [A032]. Despite these initiatives, some of the participants questioned how we might best define and establish simulation best practices [A161] (see Dr. Pace's description of this monograph series in the supplementary mateiral).

**Simulation Profession**

The participants agreed that the success of a simulation degree depends upon the demand for the people who earn that degree [A115, A117, A121, A135]. They proceeded to examine the job market for simulation professionals. Dr. Numrich recounted that Disney does not hire people with computer science degrees since they want artists. They feel that anyone can program a computer. She asked, "What do we expect of people with a simulation degree? Are they people who can design simulation systems or can they do everything simply because they can produce code? [A051]." Mr. Lunceford reinforced those questions by asking why we hire "code poppers" to build our simulations [A052]. Dr. Shumaker asserted that the person running a simulation project does not write code but rather develops the architecture [A055]. Dr. Raibert identified the existence of a job market for people with simulation degrees as partly a marketing problem. He asked, "When do we get to the point where [employers] will hire these people [who have graduated from a simulation program] [A115]." Dr. Page felt that a simulation degree would not be viable unless a market for those people exists outside of the Department of Defense [A117]. Mr. Waite reinforced that if a job market existed then a simulation profession would also exist [A100]. Prof. Zeigler answered that there was such a market [A118].

Mr. Lunceford said that if a person trains as a simulationist then they must believe that a job exists for them when they finish that training. A basic degree in engineering gives its graduates considerable mobility in the job market [A121]. Dr. Raibert pointed out that not only must graduates from a simulation major believe that they can get a job but they must also have pride in their profession. He suggested that it might take two generations to realize these goals since we must have people who have graduated from a simulation program hiring the graduates from that program [A122]. Mr. Waite expanded that he wants a simulation professional who can address a wide range of problems and that requires identity, integrity and persistence [A126]. Mr. Lunceford concurred that if simulationists had pride in their profession and there existed people to hire them then the needed market would exist [A127].

Mr. Gross asked "What's the demand now? Graduating someone in simulation is like graduating someone in circuit design." Mr. Lunceford and Prof. Zeigler responded that some schools currently offer degrees in computer game design, a much narrower specialty than simulation [A131, 132]. Further, the goal of such a job is often strong motivation for enrolling in this program. Prof. Zeigler recounted that two years ago, they had a tremendous flood of people with an interest in computer game design [A135]. Mr. Lunceford believes that the same number of opportunities exist for simulationists as for game designers. Simulationists can always get jobs with the airline industry building flight simulators [A133].

### Evaluating Simulation Researchers

The workshop participants maintained that the process and criteria for evaluating simulation researchers should be different than those applied to practitioners [A044, A137]. Therefore, the questions that an employer would ask and the assumptions underlying those questions would be different [A032]. The body of literature that a researcher knows and in which they stay current distinguishes a researcher from a simple practitioner [A039, A043]. Typically, an employer would not hire someone for a research project who did not have a history of research success and a publication list reflecting the extent of that history [A044].

## SIMULATION SCIENCE

Mr. Lunceford predicted that it might take a couple of years to fashion a science of simulation. He wanted to believe that such a body of knowledge exists but worried that that might not be asking the right question. "There may be no science but just a set of first principles." he commented [A001].

With this stimulation, the participants discussed various aspects of a simulation science including

- Creating a simulation science,
- Repeatability in simulation,
- Simulation as a science versus an engineering discipline, and
- Simulation knowledge discriminators.

This discussion laid the groundwork for the reconsideration of these topics in the later sessions.

**Creating Simulation Science**

Mr. Lunceford posed "If we accept that there is a core body of knowledge, is there a science or formal discipline underlying that [body of knowledge]? Is there a need to create formal definitions for parts of our knowledge [A163]?" To that Mr. Harmon replied that we wanted to identify the fundamentals behind simulation. Scientific discipline presents a proven path to do that. Through executing that discipline we create science, or better, we can add to the existing body of scientific knowledge. This path is somewhat consistent with all of the definitions of science that the previous speakers proposed. Part of that process involves executing controlled and repeatable experiments or making repeatable observations of those phenomena that we cannot sufficiently control. Another part involves formulating theory that explains the results of those experiments or observations. Finally, we go back to the empirical data to test that theory [A164, B024].

Mr. Waite countered that using the scientific method to understand the nature of simulation and finding the fundamental knowledge that underlies simulation are two different things. He asserted that we were after the latter [A165]. Mr. Harmon disagreed. Mr. Lunceford observed that while we understand the characteristics of good research practices, the simulation community does not typically practice them [A158]. Mr. Harmon added that although good research practices, including the need for repeatability, are widely understood, even the scientific community at large does not consistently practice them [A159]. Mr. Lunceford said that the answer to his question has two components, those answers that involve purely simulation and those that involve other disciplines [A166]. He also suggested, as a start, that we could take any basics that we discover and turn them into formal definitions [A056].

**Repeatability in Simulation**

Repeatability plays a central role in empirical science, both experimental and observational. Mr. Lunceford observed that the analytical side of the simulation community does not test the repeatability of their experiments to see if they can get the same results [A056]. Dr. Pace countered that indeed they used to do that when they had multiple simulations doing the same thing to confirm that the simulations were doing the right thing [A057, A059]. Prof. Swartout noted that each simulation tool has implicit assumptions associated with it and that we want to know that those assumptions do not significantly influence the simulation results [A060]. In other words, we want to see how close a simulation is to replicating the real world. In order to do that, we must prove that its implicit assumptions do not make a big difference. In that case, each independent party can construct a simulation experiment to see if they get similar results. In this interpretation, the assumptions are like the contaminants in chemistry experiments [A062]. They are the uncontrolled variables in experiments. Mr. Lunceford reasserted that the DoD/Army analytical processes do not attempt to independently quantify the influences of those uncontrolled factors [A063]. Dr. Pace retorted that a large part of the simulation community does repeat its experiments. It is called benchmarking and they check the influences of using different operating environments or determine if a

modification to a simulation has corrupted its results. In simulation, repeatability goes by that name [A064].

**Simulation Science vs. Engineering**

The participants debated about how much of the core body of knowledge was science and how much was engineering. Prof. Swartout remarked that simulation has considerable knowledge associated with it but that that knowledge seemed much more like engineering that science. For example, taking data that describes some aspect of the real world and creating a model from that seems more like engineering since engineering is concerned with creating things [A174]. Prof. Zeigler noted that we talk about both science and engineering. Knowledge that can improve practice becomes engineering but one needs core knowledge to do that reliably. Being able to predict planetary and stellar motions gives us the ability to codify our practice in many other fields [A175]. Mr. Waite asserted that if the referent does not exist then that is engineering [A178]. Mr. Harmon countered that if it does not proceed to some kind of utility then it is not engineering [A179]. To which Mr. Waite replied that both science and engineering do useful things. He reasserted the need for an objective referent and added that theory could be one place to make some investment but that it does not matter if it is science [A180]. Finally, Dr. Raibert asked if physics was the right model for simulation. He noted that many areas exist in simulation where big systems problems dominate the issues and many other factors can have important effects. Science may not be the most important thing in simulation [A181].

**Simulation's Knowledge Discriminators**

Some of the participants felt the need to identify the characteristics that distinguished simulation knowledge from the knowledge claimed by other disciplines [A046, 167]. Mr. Lunceford framed this pursuit by asking whether simulation is really a technology in itself or whether it was just a component of everyone else's technologies. This question affects the path ahead by determining if one should teach simulation as a separate domain or if one need teach communications between other fields. He continued to comment that building a simulation requires three skills sets:

- Those inherent to simulation,
- Those associated with developing software, and
- Those associated with the domain that the simulation represents [A046, B019].

Part of simulation is mathematics and part is something else so we do not need to create everything from scratch. He implored us to find the pieces of knowledge that uniquely defined simulation [A168].

In response, Prof. Zeigler asserted that his book (Theory of Modeling and Simulation), first written 35 years ago, contains the answers to these questions. His book defines a set (though probably not complete) of the fundamental principles that describe the science of simulation [B017]. We do have a core set of principles that have a mathematical formulation. Stating these principles mathematically helps to confirm their consistency and test their completeness [A169]. Mr. Lunceford acknowledged that we need not start from scratch but believed that all of the contents of this book might not necessarily be

science [A170, A172]. Prof. Zeigler commented that his book did present a theory about simulation [A173]. This theory establishes a nucleus around which to coalesce the results from empirical studies [A182].

Mr. Lunceford wants the people building current simulations to know the fundamentals of building simulations. Once a simulation has been built, it is difficult to revisit and revise its design after knowing fundamentals. Current simulation builders are creating their practices as they go. But, these practices are not fundamental. For example, "... can anyone show that the five time management schemes in the HLA are derived from first principles?" he asked. That knowledge has a fundamental nature [A183]. Dr. Pace remarked that our discussions had missed the heuristics that the early bridge builders gained from their many failures [A184]. Mr. Lunceford liked the analogy with relationship between alchemy and modern chemistry. Early simulation programs were attempting to turn lead into gold but they never succeeded. As the foundations of chemistry came from alchemy's search for the Philosopher's Stone, these early simulation programs may teach us a lot about the fundamentals of simulation [A185].

## SIMULATION CORE KNOWLEDGE

All of the participants concurred that defining a core body of knowledge for simulation was critical to improving simulation workforce quality. But, Mr. Lunceford wanted to know what the components of that knowledge were [A065, B010]. He suggested that this core knowledge could help us unearth the principles that underlie simulation [B023]. Further, this knowledge could also define an expected set of practices and skills that a simulation person needs to perform well in their jobs. He asked us to explore these issues as well as how one should gain domain expertise (i.e., specialties within simulation) and to identify the first step to make progress on these issues [A067].

In attempting to address these issues, the participants examined the following topics to varying degrees:

- Lessons of past simulation projects,
- Simulation certification activities,
- Simulation as a specialty discipline, and
- Existence of core knowledge.

While these topics did not directly address all of issues that Mr. Lunceford raised, they did lay the groundwork for continued fruitful discussion that may lead to doing so.

### Lessons of Past Simulation Projects

The workshop participants agreed unanimously that past simulation projects represent an untapped resource of lessons learned that should be incorporated into the core body of knowledge about simulation. Unfortunately, most of these past efforts have not documented their lessons learned and present efforts have not improved that practice. Further, few programs typically perform any analysis or assessment to determine their failure modes and how they might be avoided [A197]. Prof. Swartout noted that that might result because the failure modes are not particularly obvious or even determinable [A198].

In general, the field lacks a significant archival literature base for these lessons [A186, B018]. Mr. Lunceford felt that we must change this trend to improve the documentation associated with large simulation projects [A187]. Any improvements must include documentation of both failed and successful projects [A188].

These motivations underlie Mr. Lunceford's pursuit of a peer-review process. Over the next six months, he plans to solicit papers about the lessons learned from the Millennium Challenge 2002 (MC02) exercise (see bibliography Ref. [253] for more information on the MC02 program). He will then have these peer-reviewed to improve their content. He wants to understand what actually happened and wants to avoid the stories from people trying to justify their programs [A189, B020]. Dr. Numrich suggested that this pursuit might yield some low level lessons but probably not anything from the higher levels in the programs [A190]. Dr. Pace mentioned that Dr. Pat Sanders tried to collect a similar set of lessons learned but that it was never published [A191]. Mr. Waite described a linkage that the Canadian systems engineering office has made by writing in large system contracts requirements for capturing lessons learned. They offer their assistance in exchange for the lessons learned [A192].

Dr. Raibert noted that any announcement for lessons learned papers must send the message that a program will be judged a success even though what it accomplished might be different than its original goals. This approach begins to establish a culture that people are judged as successful because they learned some lessons [A194]. Mr. Lunceford agreed with this suggestion [A195].

Prof. Zeigler asked if the large failing simulation programs were using the available literature (e.g., Theory of Modeling and Simulation (bibliography Ref. [043]). He wondered if they were not then could the background knowledge in this literature base have helped them meet their goals [A196].

Mr. Lunceford observed that some people considered the Synthetic Theater of War (STOW) program a failure because it did not meet its representational goals (see bibliography Ref. [365] for more information on the STOW program). But, that program did not really fail because it created a huge body of information about large-scale distributed simulation [A199]. Prof. Swartout added that STOW succeeded in acquiring a better understanding of the simulation tools and techniques that it applied but that was not its stated goal [A200]. Mr. Lunceford continued with the feeling that Defense Advanced Research Projects Agency (DARPA) programs should always fail to some degree. Unfortunately, STOW (a DARPA program) received enormous visibility because its test case was a large-scale joint training exercise. That linkage violated the basic tenets of a good research project because the program could not fail or it would lose its funding [A201]. Dr. Numrich added that it became a technology demonstration as opposed to a research program [A202].

The group finally recommended:

1) That successes should be highlighted as a component part of the program to balance the negative aspects of the program;

2) That the peer review committee and the composition of that committee would be extremely important to the success of the workshop; and

3) That there was reasonable cause to pursue the workshop because participants would likely be motivated to submit papers [B021].

**Simulation Certification Activities**

Several of the participants were familiar with the ongoing effort to develop a simulation professional certification program while others were not (see bibliography Ref. [347] for more information on this certification effort). This effort has assembled some of the top people in the simulation field and it will result in both a certification process and a certificate [A068]. Both Dr. Pace and Prof. Zeigler believe that this effort will identify the core knowledge of simulation [A066, A070]. Prof. Zeigler suggested that we should become familiar with their efforts and start from that point [A066].

**Simulation as a Specialty**

The participants explored the need for defining simulation as a distinct specialty as opposed to leaving it a general tool for many other disciplines [B008]. Mr. Waite felt that we should not ask domain experts (e.g., doctors) to learn simulation but that we should first teach people to be simulationists then send them to the specialty applications of simulation (e.g., medical simulation) [A047]. Prof. Swartout recounted that the computer scientists building medical expert systems needed to learn medicine and that the doctors with whom they consulted needed to learn expert systems. A similar thing has occurred in such other fields as mechanical engineering. Now, mechanical engineers build expert systems [A048]. Mr. Waite reminded us that the expert system people kept their domain of expertise (i.e., building expert systems). Simulation does not have that same center and it is too hard to run an industry when you must assume the guise of another field all the time [A049, B009]. Prof. Swartout added that it was a really bad idea for the expert system people to pretend to be physicians at medical conferences [A050]. Dr. Numrich remarked that the simulation problem set is inherently multi-disciplinary and that she would like a team of people including domain experts and an interdisciplinary crew [A097, A123]. She emphasized the importance of a multi-disciplinary background to entry into a modeling and simulation career [B006]. Mr. Waite reiterated that simulation projects demand a comprehensive knowledge of simulation and noted that other disciplines are equally demanding [A098].

**Existence of Core Knowledge**

The workshop participants agreed that either core knowledge exists or should exist upon which to base an academic program in simulation [A069, A071, A072, A088, A105, A144, A160]. Mr. Waite believes that that body of knowledge absolutely does not exist now [A088]. He felt that the tools and practices are neither well defined nor well accepted today [A144]. Dr. Pace reinforced that feeling with his observation of the SIMVAL99 workshop, attended by 100 leaders in the simulation industry, that the ignorance of simulation verification and validation (V&V) technology and practices was astounding [A033] (see bibliography Ref. [346] for more information on the SIMVAL99 workshop sponsored by the Military Operations Research Society).

## CONCLUSIONS

Mr. Lunceford captured the essence of the session in several points. The participants agreed that there is or should be core knowledge for simulation. He identified three goals that the participants believed would advance the simulation field:

- A degree program for simulation professionals,
- A set of best practices for both engineers and scientists working in simulation, and
- A set of processes in place to support those practices.

He also identified four short-term steps that we could take toward these goals:

- Establish a set of courses that teach the current best practices in simulation,
- Assemble a set of documents that describe these best practices that students and practitioners alike could use,
- Develop a set of courses (perhaps the same courses described above) within Functional Area 57 to train Army officers about simulation, and
- Create a consistent set of definitions for core terms related to simulation.

He hoped that this workshop would define a set of actionable steps through which to gain the core knowledge necessary to achieve the goals we defined [A162, B012, B015, B016].

# Session 2 – Prior Work on Simulation Science

The purpose of this working session was to begin identifying prior work applicable to a science of simulation that might establish a foundation from which to grow.

Prof. Zeigler opened this session by stating its purpose was to identify references that represent prior scientific activities associated with simulation [B001]. He admitted that he began this workshop unconvinced about the existence of a science of simulation. He became more convinced that such a science could exist and that its discovery had value to the simulation field.

He drew an analogy between physics and simulation then backtracked to understand how that science evolved. Using the model illustrated in Figure 1, he noted that physics consists of both phenomena and practice. For example, astronomy begins with direct observations then uses those to focus controlled experiments to explain the nature of specific phenomena. These activities create the data that scientists can mine to discover the relationships representing the underlying phenomena that create their observed behavior. These relationships fuel the hypothesis generation that tries to guess the underlying causes. He maintained science cannot influence practice until theoretical explanations of the observed behavior have been developed and validated. Theory enables predicting behavior and that ability leads to improvements in practice. He worried that this example did not adequately identify the killer application of physics, the thing that motivated people to use it [A001]. Mr. Harmon suggested that mechanics represented a pretty good example [A002]. Dr. Whelan suggested that artillery was a more direct application [A003].

He then proposed applying the same model to simulation as a science. Figure 2 illustrates this model.

The participants reflected upon these two models and their comparison then considered a wide range of topics in this session including

- Nature of science and engineering,
- Various simulation phenomena,
- Past work applicable to simulation science, and
- A lessons learned workshop.

Like the discussions of the first session, while these considerations strayed somewhat from the session's topic, they added to the overall tapestry of information that composes the results of the entire workshop.

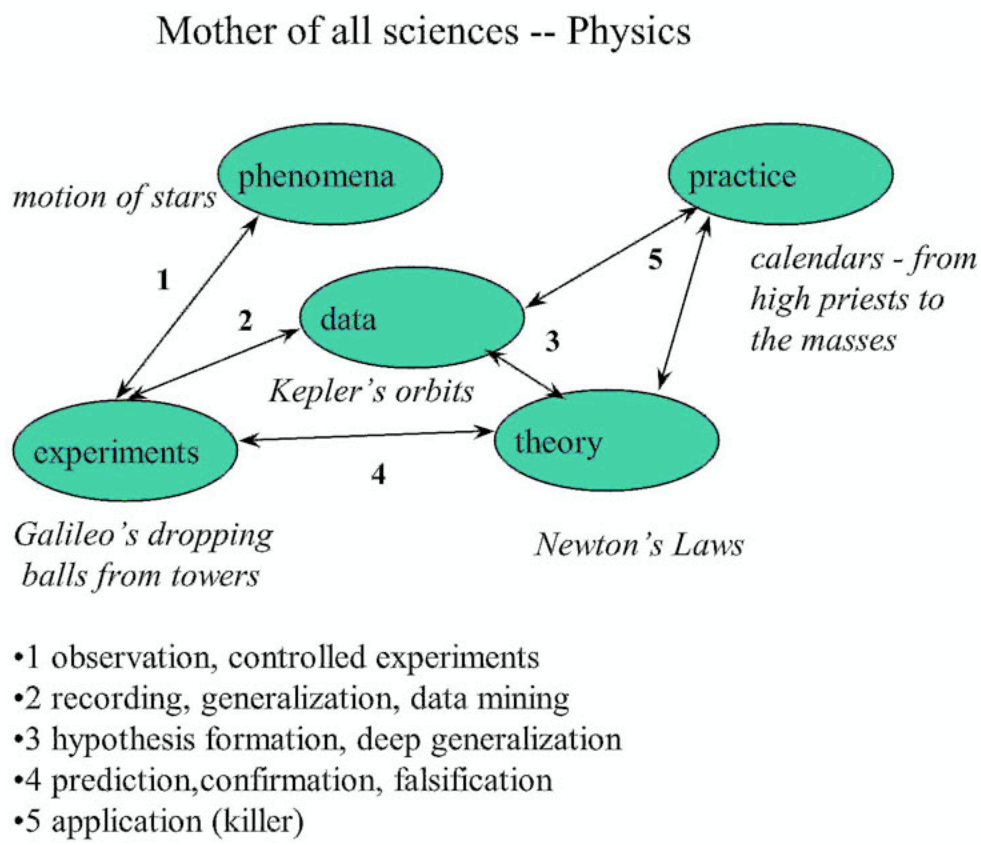


**Figure 1.** Model of the Evolution of Physics as a Science.

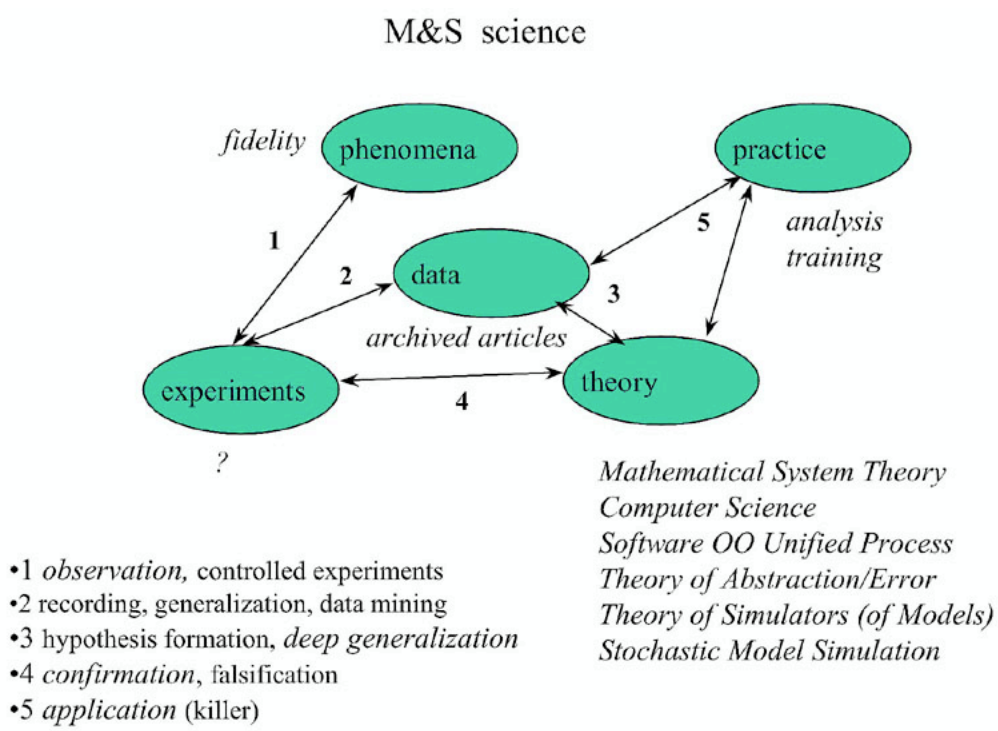


**Figure 2.** Model of the Possible Evolution of Simulation as a Science.

## SCIENCE AND ENGINEERING

In the debate over the differences between science and engineering and what those differences mean to simulation, the participants considered the notion that engineering practice usually preceded the development of scientific knowledge and the idea that limitations in scientific knowledge can limit the levels to which a technology can advance.

### Engineering Precedes Science?

Mr. Lunceford suggested that engineering practices lag physics by one hundred years and physics lags mathematics by another one hundred years [A004]. Prof. Swartout countered that engineering usually preceded physics [A005]. Mr. Harmon reminded them that that ordering was historically true but no longer held. He cited nuclear engineering and solid-state electronics as examples where physics drove engineering practices [A006].

### Technology Limits without Science

Mr. Lunceford noted that we would never have been able to build skyscrapers without Newton's laws [A007]. Prof. Zeigler suggested that the guilds were very successful in building structures of various types from bridges to cathedrals without physics. Some of these were very ambitious [A008]. Mr. Harmon commented that the guilds were only successful to a certain extent. They reached a point where the empirical knowledge of the guilds failed. After that point, the bridges and cathedrals they built collapsed, in some cases catastrophically [A009]. Dr. Shumaker remarked that civil engineers do not use quantum mechanics to design bridges [A043]. Mr. Harmon replied jocularly "Not yet."

Prof. Zeigler stated that at Newton's time, even the existence of masses and forces was not clear [A044]. Dr. Shumaker responded that failure should send you back to the theory to modify it. He reminded us that theories about mechanics did exist before Newton [A045]. Mr. Gross added that new materials and experiences provide the grist for science. When people ask why things happen, they create science [A064]. Mr. Harmon observed that simulation is in its current state because it does not depend upon formality or science. He argued that it would be hard to advance much farther without that [A065]. Prof. Zeigler offered the example of the microelectronics industry. He believes that the advanced state of that industry has resulted from using modeling and simulation. That industry has automated to a great degree and incorporated simulation in those automated processes [A066]. Mr. Lunceford asked if they apply general practice to succeed in a limited domain. He wanted to know if the simulation community could adapt what the microelectronics industry has learned [A067]. Mr. Waite commented that he sees that experience all the time when they sell a simulation product to different domains (e.g., automotive, pharmaceutical). The fluid incorporation of modeling and simulation into other industries seems to be characteristic of the business. He contended that this occurrence lends one motivation for developing a generalized body of simulation knowledge. He said, "There's a huge margin to applying it in the DoD [A068]." Mr. Gross added, "It's like English because lots of people use it for a lot of different things." Prof. Zeigler observed that distinct levels of abstractions exist that relate to general principles that are not associated with the applications [A070].

## SIMULATION PHENOMENA

The participants began identifying the phenomena associated uniquely with simulation. These included

- Simulation requirements, and
- Abstraction.

Later sessions addressed these and other simulation phenomena in more detail.

### Simulation Requirements

Dr. Pace asserted that we do not now have any theory or even an unambiguous process for identifying what a simulation must represent or at what fidelity to serve a particular application. He believed this to be a fundamental modeling problem [A058]. Prof. Zeigler used a system developed for an imagery interpretation domain to illustrate one area where someone had developed a scale through which to identify the level of capability (in terms of imagery detail) an application needs [A058] (see bibliography Ref. [380] for more information on this imagery rating scale). Dr. Raibert asked if any simulations have been abstracted from those applications [A059] and Dr. Numrich wanted to know how we could do such a thing across a broad range of systems and applications [A060].

### Abstraction

Mr. Waite reminded us that a core part of modeling and simulation lay in the process of abstracting the simuland into the model. He suggested that we should look for information on that process [A052]. Profs. Zeigler and Swartout and Mr. Waite recommended looking for references on abstraction in the cognitive science literature, a community that has studied abstraction extensively [A052-054].

Mr. Lunceford observed that our difficulty in simulating some phenomenon, such as human behavior or performance, might not result from a simulation problem but rather from a poor understanding of the phenomenon in question [A055]. Dr. Numrich emphasized that one should articulate the problem and try to stay removed from the solution space. In other words, one should go to the right phenomenologist with the right problems [A056].

In searching for a better theory of abstraction, Mr. Waite cited the example of Parnas' simple criteria for modularizing software, a test of semantic self-consistency. That insight is almost theoretical guidance with huge implications. This example might define a fruitful path for examining abstraction [A071]. Dr. Page noted that the military has defined a pretty good hierarchy that could serve as a model for abstraction [A072]. Mr. Waite cautioned that one can always find an example that challenges any application. He wondered if any theoretical basis existed for thinking about the abstraction problem then mapping that into practice [A073]. Dr. Page replied that nothing in science codifies the creativity that drove Newton to devising the laws of classical motion [A074]. Mr. Waite countered that we could find ways to codify abstraction usefully [A075]. Prof. Zeigler added that his book (i.e., Theory of Modeling and Simulation) describes homeomorphisms as a part of abstraction [A076] (bibliography Ref. [043]). Dr. Page recounted that Michael Overstreet proved that proving the equivalence of two

descriptions is undecidable [A077] (bibliography Ref. [061]). Mr. Lunceford concluded this discussion by asking how he could build a representation to move forward and noting that one may or may not be able to automate the abstraction process [A078]. Mr. Waite added that much of physics could not be automated so the automation of a process is not a good criterion for useful theory [A079].

## PAST APPLICABLE WORK

In their considerations of past work applicable to simulation science, the workshop participants identified either the existence of prior work or the lack of it in some cases. The topics they examined included

- Observations versus controlled experiments,
- Examples of prior experiments and data,
- Validated theory, and
- Current state of simulation.

Other later sessions identified additional applicable prior work.

### Observations vs. Controlled Experiments

Prof. Zeigler remarked that the simulation community has collected many observations but has not really performed any controlled experiments per se [A010]. Dr. Pace argued that the community performs experiments every time they compile and execute a simulation then compare its results with the behavior of the simuland [A011]. He continued by observing that the problem with these experiments is that usually experimenters in other fields follow established experimental protocols and methodologies and simulationists neither follow established methodologies nor report their experiments in sufficient detail so that others can replicate them [A015].

Prof Zeigler mentioned that his group has developed a theory for hypothesis generation but that that theory is not rigorously connected to the empirical data that supports that theory. He reported that they do have some confirmation that their theory works through practice and application but that they have never obtained sufficient data for falsification [A012] (see bibliography Section I.E.12 for references on these applications). Both their work and the work of others applying their theory has generated considerable data but not in the form of use cases and much of that data relates to small applications that do not scale to larger cases well. They have also discussed such phenomena as fidelity in their work [A014]. He felt that in simulation, in general, researchers could neither say what has not worked nor identify what should be done to improve the situation from the data they have collected [A016].

Mr. Waite asserted that many things that Prof. Zeigler discussed were on the periphery of simulation and on the margins of other disciplines as well. He believed that we were trying to solve specific problems rather than understand the nature of simulation. Therefore, all of the examples proposed as data corroborating any theory were domain-specific and did not represent the results of scientific experiments [A017]. Dr. Numrich reminded us that observations and experiments always worked the instance [A018]. It takes the theory to generalize these data away from the specific. Mr. Gross observed that

the Synthetic Theater of War (STOW) effort created data and that something should be able to be learned from that data (see bibliography Ref. [365] for more information on the STOW program). Perhaps the data from the STOW effort could be mined [A019]. Prof. Zeigler wondered if that data existed in a form that it could be used [A020]. Mr. Gross noted that these programs existed and that they all produced artifacts of some sort so they all represent potential resources for data reflecting simulation phenomena [A021].

Mr. Waite asserted that building bridges that collapse and learning from those experiences is an engineering process and not science. He felt that most of what simulationists do is more like building bridges and is therefore engineering, not science [A023]. Dr. Numrich responded that we could look at the collapse of bridges and the behavior of the Joint Semi-Automated Forces (JSAF) as phenomena and probe or observe them to understand them [A024] (see bibliography Ref. [362] for more information on the JSAF program). Prof. Zeigler suggested that we might even be able to perform controlled experiments on some existing simulations to get at the science of simulation [A025]. However, Mr. Gross asked "What do you want me to do [to get truly controlled experiments], fund [the development of] two WARSIMs [A026]?" Mr. Waite cited their trying to get funding to assess the last six to eight simulation efforts to understand the lessons learned from them as an example of such a direction. They found that the potential sponsors were not interested. He suggested that data collection efforts and controlled experiments in support of gaining scientific insight into simulation was not in the culture of simulation. He thought that we must find ways to be acceptably received in order to advance science along the experimental axis [A027].

**Examples of Experiments & Data**

Several of the participants discussed various sources of experimentally derived data. Dr. Pace noted that the software engineering community performs studies to quantify the effort associated with each of their development processes. He observed that the simulation community does not typically perform such studies. He has learned that small simulation efforts usually spend 10-20% of their budgets on actual simulation issues and more than 50% on human interface issues. He believes that how one allocated what a simulation represented is an interesting topic [A029]. Dr. Pace cited the National Institute for Standards and Technology (NIST) study on software engineering as an example of this sort of study in software [A031] (bibliography Ref. [291]).

Prof. Zeigler cited the simulation text authored by Cloud and Rainey (bibliography Ref. [010]) as another example of a possible source of data about simulation. He felt that they considered many aspects of simulation and covered a lot of relevant ground [A032]. Mr. Gross added that we must consider the Defense Modeling and Simulation Office (DMSO) Verification, Validation and Accreditation (VV&A) Recommended Practices Guide (RPG) as another source (bibliography Ref. [344]). He believes that Cloud and Rainey provides more data than the RPG [B004] (bibliography Ref. [010]).

Dr. Numrich continued the discussion by asking, "What are experiments [A034]?" Prof. Zeigler replied that experiments tested theories. He cited a theory about the use of discrete event representations versus continuous representations and how it could be proved which was better for various situations. He believes that we should check to see if that theory applies. He asked "Is it right enough for some applications?" and suggested

that that could lead to controlled experiments [A035]. Dr. Page reminded us that we have groups that already do that sort of thing well (e.g., the distributed simulation people). He noted that they have done many controlled experiments (e.g., optimistic vs. conservative synchronization) (see bibliography Section I.B.3). He also noted that this group has produced considerable theory (e.g., time warp vs. Misra) (bibliography Ref. [082]). He believes that this work provides many examples of science applied to simulation phenomena [A036]. Prof. Zeigler recommended Richard Fujimoto's book as a good general reference to some of this work [A037] (bibliography Ref. [077]).

Dr. Numrich asked if we wanted to use existing simulation instances to generate observations of simulation phenomena in the absence of any theory. She continued by asking, in general, where we could get this data [A038]. Dr. Shumaker responded "every implementation tests existing theory [A039]." Mr. Harmon qualified that with the observation that it depends upon what has been implemented. An implementation depending upon heuristics just tests those heuristics [A040]. Dr. Shumaker believes that a heuristic represents theory too [A041]. Prof. Zeigler distinguishes heuristics and theories because a theory collects and explains rules of thumb. They provide deeper characterizations than heuristics alone [A042].

### Validated Theory

Prof. Zeigler noted that we do not have any examples that test any simulation theory [A046]. Dr. Shumaker suggested that STOW tested the theory that we have enough information to build such a distributed simulation [A047] (see bibliography Ref. [365] for more information on the STOW effort). Dr. Page replied that a posteri, one could propose that STOW performed such a test [A048]. Prof. Zeigler suggested that microelectronics industry might be a good model for an industry that tests its theory and the existence of a validated theory helps to advance its technology [B006].

### Current Simulation State

Mr. Lunceford believes that simulation technology has been stalled for the last three to five years. The phenomena that we can simulate today are no different than those that we could represent five years ago. We do not move forward because we allow people to cycle through the same ideas over and over again. The current system has no rigor and that hinders our progress in advancing the technology and, thus, practices [A061]. Dr. Page reinforced that we have been working on the same simulation systems for the last five years [A062].

## LESSONS LEARNED WORKSHOP

Mr. Lunceford described a peer-reviewed lessons-learned workshop that his group was thinking of running. In it, he would ask the people involved in simulation efforts to generate post mortems. For example, he could ask, "How hard was it to implement multi-cast groups in STOW?" since the bulk of the effort in that exercise was spent doing that [A028]. He suggested that we ought to do this regularly because he cannot get the Government to pay for capturing lessons learned in a separate effort. However, he wondered if he did run such a workshop "... would I get more than two papers [A081]?" Dr. Shumaker responded that one or two might be enough [A082]. Mr. Waite cautioned

that Mr. Lunceford needed to frame the question that the workshop would explore carefully so that it rewarded the exposure of real problems and negative experiences as well as successes and positive experiences. He believed that that could be done but that it would take an articulate and well-managed announcement [A083]. Dr. Raibert then showed the group the outtakes from his dynamic legged locomotion experiments. He cautioned that he was very uncomfortable with showing them before showing the successes. He felt that people tended to remember the failures [A084]. Prof. Swartout confirmed that people do remember failures and Mr. Harmon added that that was because failures aroused people's emotions [A085, A086]. Dr. Raibert countered that failures also emphasized the successes achieved, at least in his work [A087]. Mr. Lunceford replied that everyone attending this workshop considered failures success because of the knowledge gained from them [A088].

Mr. Gross felt that the announcement of such a workshop would produce a mix of papers. But, he confirmed the need to get these observations in an accessible form. He added that generating useful observations was different than abstracting theory from them [A089]. To the end of getting accessible observations, Mr. Lunceford wondered if he could make publication of such lessons-learned papers rewarding in any way. He suggested that maybe he should give a monetary award for the best lessons-learned paper [A090]. Mr. Harmon confirmed what Mr. Waite had said previously about the sensitivity of the announcement and added that the review committee for such a workshop would also be very important to avoid the failures being rejected [A092].

Mr. Waite declared that the people in this workshop controlled many opportunities in SCS and SISO (bibliography Refs. [350, 351]) and that we could communicate with the people in those organizations to make such a workshop happen [A093]. Mr. Lunceford suggested looking at the Grand Challenges Conference (see bibliography Ref. [345] for more information on the Simulation Grand Challenges Conference) and asked about its rejection ratio [A094]. Dr. Page replied that it was forty percent. Prof. Swartout observed that the current simulation literature does not contain many reports of negative results [A095]. Mr. Lunceford responded that the results should not be characterized as either positive or negative. He suggested looking at multi-cast groups and said, "It's hard. How do we do it [A096]?"

Prof. Swartout mentioned that some video game magazines include articles that discuss lessons learned and suggested that we should look at those [A097] (bibliography Ref. [384]). Dr. Page remarked that he had written a paper discussing the lessons learned using the Aggregate Level Simulation Protocol (ALSP) (see bibliography Section I.E.13.b for these references). He suggested that we should consider that [A098]. Mr. Lunceford suggested that, in the papers for this workshop, we need to let people say "Let me tell you about my little piece [and what I needed to do] to achieve success and how hard that was [A099]." Prof. Zeigler added that we should be asking, "What can we do now that we could not do before your contribution?" He suggested that that view put a more neutral connotation on any contributions [A100]. Prof. Swartout recounted his experience with the Conferences on the Innovative Applications of Artificial Intelligence (see bibliography Ref. [377] for more information on this conference series). In those, they had strict review criteria and reasonably high rejection proportions. They tried to get people from industry to participate. Every paper, not just one, accepted to this

conference got an award and they published the proceedings as a book. This way the papers enhanced the contributors' resumes [A101]. Mr. Lunceford suggested that they could determine which organizations published the most papers to the lessons-learned workshop and give them an award. That would make it an organizational competition and might reduce the barriers to presenting other-than-positive lessons learned [A102].

## CONCLUSIONS

Mr. Lunceford summarized the session as follows [B008]:

- Having a paper written that describes how to manage a "multi-task" management process for software/large M&S development programs would be extremely valuable.
- Simulation technology has been stalled for the past 5 years. The M&S community appears to be repeating its application development focus without actually having to tend to the science of M&S.

# Session 3 – Simulation Observables & Phenomena

The purpose of this session was to identify a number of properties through which one could observe simulation phenomena. After some discussion, the participants decided to enumerate the phenomena associated with simulations as well. Table 1 lists the simulation observables and phenomena that the participants supplied.

**Table 1.** Results of the Simulation Observables and Phenomena Brainstorming.

| Simulation Observables and Phenomena |
|---|
| Elements of fidelity {i.e., resolution, error, precision, sensitivity, capacity) |
| Detail |
| Implementation aspects (e.g., language, computer, etc.) |
| Immersion |
| Time (real vs. simulation time) |
| Program management elements |
| Interactivity |
| Man-machine interface |
| Relationships (i.e., model-to-real world, model-to-model, model-to-simulator, model-to-person) |
| Representation |
| Comprehensibility |
| Observability and controllability |
| Maintainability |
| Connectability to the real world and other models |
| Story |
| Objectives (i.e., relationship between simulation design and objectives) |
| How a simulation gets used |
| Performance |
| Usability |
| Complexity |
| Setup |

In the course of building this list, the participants covered a number of topics including

- Simulation phenomena,
- Simulations too hard to build,
- Simulations and models, and
- Specific versus general simulations

The participants did not share a common definition or understanding of the nature of phenomena. However, despite this slight misalignment, they were able to identify possible simulation phenomena and discuss how the understanding of them could advance our core knowledge.

## SIMULATION PHENOMENA

Since this session dealt with identifying the phenomena associated with simulation, the participants questioned the definition of phenomena. Dr. Numrich, Dr. Davis and Prof. Swartout asked if the phenomena were the simulation representations, either entities or their behavior [A028, A029, A032]. Mr. Harmon responded that phenomena are the things that make the observables change over time [A031]. They are the causes underlying those observable changes (e.g., the relationship between simulation cost and usability, the relationship between simulation cost and its fidelity [A033, A138]). Mr. Gross restated that these were the correlations between observables [A139]. Dr. Numrich noted that many such important relationships existed (e.g., between the simulation and the human, between the models and the simulation) [A064]). Mr. Waite recommended that we use the universal modeling language (UML) to build a model of all of these relationships [A065]. He emphasized "a theory that does not admit to this representation is not sufficient because you don't understand it [A067]."

Dr. Pace suggested that some simulation phenomena might be the relationships between the simulation's purpose and its implementation (e.g., software, hardware, visualization) [A022]. Dr. Whelan asked if that separated the model from the simulation [A023]. Dr. Pace responded that the model is part of the algorithms encoded by the software but hardware-in-the-loop (HWITL) and human-in-the-loop simulations (HITL) involve much more than just that software [A024]. Mr. Waite emphasized the significance of the distinction between implementation and the representation domains [A025] and Dr. Numrich agreed [A026]. Mr. Waite proposed that fidelity, part of the abstraction process, and the conceptual model definition represented phenomena uniquely associated with simulation. He said that anything that follows those concepts and processes remains important but, without the modeling part, can be done by software, hardware and systems engineers [A048]. Dr. Pace maintained that interoperability is not just a software problem [A054]. Mr. Waite responded that that depended upon the kind of mistake that you thought you would make. He explained that the people with whom he associates think that getting the software right solves the entire simulation problem and he felt that that was the likely error. In thinking about how to build a simulation, the time model, time advance model, implementation mechanics and production of the artifact all fit within the simulation's scope. For him, implementation includes time representation, mechanization of the simulation (e.g., digital, analog), language choices, biomechanics, operator interfaces and other things [A055].

In an endeavor to delineate simulation phenomena through another course, Mr. Lunceford asked Prof. Zeigler what he taught as the fundamentals of modeling and simulation [A140, A143]. Prof. Zeigler replied that they started with three concepts: a model, a simulation and the real world. They then proceed from that point [A141]. Mr. Waite agreed that we should concentrate upon simulation fundamentals [A174]. Mr. Lunceford suggested that we needed to sample a few simulation courses [A143] (see supplementary material and bibliography Sections I.D.13 and II.F for more information on simulation curricula).

The phenomena that the participants identified could be broadly partitioned into two categories:

- Core simulation phenomena, and
- Peripheral phenomena.

The core simulation phenomena describe the behavior associated uniquely with modeling and simulation. The peripheral phenomena describe those phenomena that could be associated with many other fields.

**Core Simulation Phenomena**

The core simulation phenomena that the participants discussed include

- Fidelity,
- Time representation,
- Immersion,
- Interactivity,
- Comprehensibility,
- Abstraction,
- Models and objectives, and
- Problem formulation.

These phenomena belong exclusively to the discipline of simulation.

Fidelity

The participants briefly debated about the interpretation of simulation fidelity. Prof. Swartout began this discussion by suggesting that the fidelity of simulations for analytical purposes would have a different set of attributes than the fidelity of a simulation for training purposes where immersiveness might play an important role [A003]. Mr. Gross countered that Prof. Swartout really means believability rather than fidelity [A004]. At that, Dr. Numrich asked if the community has a common definition of fidelity [A005]. Mr. Harmon responded that the Simulation Interoperability Standards Organization (SISO) (bibliography Ref. [350]) now has a consistent definition but that definition was not universally accepted [A006] (see bibliography Section I.D.1 for references to simulation fidelity). Mr. Waite added that the SISO definition is not bad and he noted that when people debate fidelity they invariably confounded its definition [A007]. Dr. Davis asked if fidelity was a super set of resolution and other things [A008]. Mr. Gross affirmed [A009] and Mr. Harmon described fidelity as a means to consistently characterize the representational capabilities of a simulation [A010]. Mr. Waite argued that that description did not discriminate fidelity from scope, another way of describing simulation capabilities [A011].

Mr. Gross enumerated the components of fidelity as resolution, accuracy, precision, sensitivity, capacity and probably more [A012]. When Mr. Waite asked if these components are subsets of fidelity, Mr. Gross responded that describing fidelity as a roll-up term was not very useful [A013, A014]. Dr. Davis asked if fidelity provided a way to describe the goodness of a simulation [A015]. Mr. Harmon reiterated "No. It's a way of describing what a simulation can represent. Goodness has to do with purpose." Mr.

Waite continued to explore the fidelity issue through a Gedanken experiment. He described two possible models of a fair die, one a highly detailed representation of its structure and dynamics and another a random number generator that chose integers between one and six. He described the first as a highly detailed representation that could have either high or low fidelity. He described the second as a high fidelity representation but with a very low level of detail [A017]. Dr. Numrich characterized the first as high fidelity in geometry and the second as high fidelity when it is rolled [A018]. Mr. Gross noted that detail is part of resolution [A019] and that fidelity describes the phenomena uniquely associated with simulation. He observed that some people tend to drive their models down to where they think that they have approximated reality [A036]. Mr. Waite asked if the relationship between the referent and the simulation is different than fidelity [A061]. Mr. Harmon replied that that relationship was error, a component of fidelity [A062].

In discussing the relationship between fidelity and immersiveness, Prof. Swartout commented that he did not see the elements of story in fidelity [A108] (see bibliography Section I.D.11 for references on immersion in simulation). Mr. Lunceford maintained that story is a component of fidelity [A110], a perspective that Mr. Harmon thought interesting [A111]. Mr. Lunceford continued with the comment that a story line provides a new view of the representation and, in some simulations, that story is part of fidelity [A112, A116]. Prof. Swartout countered with the observation that a good story line may create an experience less faithful to the real world in order to increase immersiveness [A113]. Mr. Lunceford responded that a simulation is not an absolutely faithful representation of the real world. Its fidelity should be only as good as one needs to achieve a purpose. For example, training simulations may need not to be faithful to the real world to increase the training experience [A114]. Dr. Raibert added that these are reasons why fidelity is not synonymous with utility. That fact provides the room to let the simulated events (i.e., the story) proceed in a different direction than they would in the real world [A115]. Dr. Numrich suggested that story and immersion are usability factors [A117]. Mr. Gross proposed that a hypothesis might be embedded within these arguments about story [A118].

Time Representation

Dr. Page, Mr. Waite and Mr. Gross all supported that representing time is characteristic of simulation [A051-053]. That consideration includes the speed of the simulation clock relative to real time. Dr. Page asserted that the advance of time in simulation is an observable phenomenon but he was not sure if it was part of fidelity. He noted that researchers have performed many experiments on temporal representations [A051] (see bibliography Section I.D.3 for references on temporal representation).

Immersion

Prof. Swartout maintained that immersion represents a simulation-related phenomenon, a relationship [A027, A049, A063] (see bibliography Section I.D.11 for references on immersion). Mr. Gross concurred [A050]. At the most basic level, this relates to how the simulation presents its output, as an immersive environment or just a bunch of numbers [A027]. One can measure whether a person interacting with a simulation feels immersed in a number of ways [A043]. How much immersion and what kind are both observable [A104]. For example, subjects can simply be asked, “How much were you engaged by

the simulation?" Or, one can observe the physiological responses of subjects to the simulation [A085]. Immersion depends upon the characteristics of the models involved as well as the displays and other things [A043]. The training community is very concerned about immersion. Mr. Gross cautioned that the concept of immersion is very soft in the literature [A084]. Mr. Lunceford felt that all simulations are immersive but they all give different feelings of immersion. Immersion resembles going to the movies. It does not seem so much a phenomenon of simulation as something that one can do with a simulation [A103]. Dr. Shumaker asked why immersion was not just a man-machine interface issue because without the human there is no immersion [A124]. Mr. Lunceford countered that someone is always there because they look at the simulation results. It may not be real time immersion [A125].

The participants also discussed the possibility relating fidelity to immersion. Mr. Lunceford asked why immersion was not a fidelity question [A105]. Mr. Gross responded that that was an interesting question and that the fidelity should lead to a certain level of immersion [A106]. Dr. Page pointed out that immersion is also a function of the interface to the simulation [A107]. Prof. Swartout insisted that something in addition to fidelity existed with regards to immersion. He did not see the elements of story included in fidelity. This determines how much one is engaged by the simulation experience [A108]. Dr. Numrich observed that she may want a very high fidelity representation of chemical warfare but might not want to feel immersed in it [A109].

Interactivity

The participants also believed that the nature of the interactivity of a simulation represented an important phenomenon and that that aspect differed from immersion [A056-059]. Dr. Davis suggested that interactivity is a subset of the man-machine interface issue [A058]. Mr. Waite added that interactivity included controller modes as well as others [A059].

Comprehensibility

Dr. Davis argued that the comprehensibility of a simulation was another important phenomenon. He noted that representation was related to both comprehensibility and the simulation's purpose [A030]. Dr. Raibert asked about including observability and Dr. Davis responded that that was included in comprehensibility [A072, A073].

Abstraction

The participants concurred that the process of abstraction represented a fundamental phenomenon associated uniquely with simulation [A034-038]. This concept includes the process of building models from core data [A037] and includes the representation of time [A040-042]. Abstraction creates the difference between the simulation representation and the real world (i.e., the simuland) and is the underlying concept for validation [A060]. Mr. Waite maintained that only abstraction and conceptual modeling distinguish simulation from other fields [A038]. Mr. Lunceford asked who owned the process of abstraction [A034] and Mr. Harmon asserted that the scientists describing the observed phenomena owned it [A035]. Prof. Nicol recommended listing capability and explained that that describes the size of a model [A127].

Models & Objectives

Dr. Davis proposed that we need to characterize simulations in terms of the purposes for which people use them. That means asking "What it's good for and what questions you're going to ask of it [A001]." Mr. Waite reminded us that that means establishing both an appropriate metric and the value of that metric [A002]. Prof. Zeigler suggested that the relationship between a model and the purposes that it can support might be a better phenomenon than simply the model's uses [A119]. On consulting the brainstorming list, Dr. Raibert reminded us that the original notation of objectives described the relationships between the objectives and the simulation's design [A128]. Dr. Davis reiterated that you must always characterize models with regard to what you want to do and what data is available to do it [A142].

Problem Formulation

Mr. Lunceford suggested this category and noted that it includes how to formulate, abstract and validate a simulation problem [A136].

**Peripheral Phenomena**

The participants' discussions touched upon a number of areas that contribute to simulation as well as other areas. These more general phenomena could be grouped into four broad categories:

- Software engineering factors,
- Program management factors,
- System engineering factors, and
- Interface/Connectability.

The participants agreed that the phenomena from these peripheral categories could contribute to the success or failure of a simulation effort but they have similar implications on the development and use of other systems as well.

Software Engineering Factors

Prof. Swartout noted that he would consider some aspects of simulation as part of computer science [A021] (see bibliography Section I.F.4 for some references on software engineering factors). Mr. Gross remarked that a simulation's algorithms represent one of its aspects [A135]. Dr. Pace suggested that some of those simulation phenomena relate the programming language to the simulation's code properties and runtime characteristics [A020]. He asked if we wanted to consider the effects that software engineering has upon simulation [A054] and the group agreed that we should list those phenomena.

Program Management Factors

The participants listed other factors under simulation observables and phenomena as related to program management. Mr. Gross commented that the taxonomy he presented in his position paper addressed these issues among others [A102]. Prof. Swartout asked if the current simulation problems were describable in program management terms [A149]. Mr. Lunceford thought not [A150] and Dr. Page noted that even good science could not assist in making good funding decisions [A151].

System Engineering Factors

The participants listed a number of observables and phenomena related to simulation that they classified as classical system engineering considerations including (see bibliography Section I.F.5 for references on system engineering factors)

- Changeability [A081],
- Maintainability [A081],
- Cost [A099, A101],
- Life cycles [A099],
- Applications [A099],
- Development time [A101],
- Usability [A130, A131],
- Maintainability [A132],
- Availability [A133],
- System set-up [A163], and
- Accessibility [A164].

Mr. Waite argued that we were just listing the attributes of a system and that it could be any system, not just a simulation. Many of the attributes we listed were implementation domain oriented [A100]. He believed that only some of the attributes listed were simulation-specific and the rest are system engineering problems [A133]. He argued that all of the system engineering issues were tied only into the development activities and their effects manifested solely in their artifacts. They only manifested in performance and utility [A137].

Dr. Davis observed that systems engineering covered a lot of ground. He chided us to think of what people want their simulations to do and noted that that was more than just implementation. He reiterated a number of simulation-specific issues including the relationships between the simuland and the model, the creation of the conceptual model, and the implementation of that conceptual model. He encouraged us to separate the simulation-specific issues from the system engineering and program management issues [A144].

Mr. Waite reinforced that we needed to keep our notions modular by separating the representational issues from those related to the concept of operations and the system utility [A145]. Mr. Harmon countered that some simulation phenomena cross the boundaries of system engineering and representation. He cited interoperability as an example [A146]. Mr. Waite agreed that interoperability was a good phenomenon, important to simulation. Mr. Harmon continued by encouraging that we realize that some simulation relationships will cross the boundaries of the broad categories we listed [A148].

Interfaces/Connectability

Dr. Davis maintained that another set of simulation phenomena related to the connections between the simulation and other things including the real world, other simulators, other types of equipment, video clips, and audio tapes to name a few. The interconnectivity of the simulation is part of its characteristics [A089]. Dr. Pace wondered if that notion just formed a superset that included the man-machine interfaces [A090]. Dr. Davis responded that this category of phenomena described a simulation's ability to participate in a larger picture [A091]. Prof. Swartout commented that this category included several architectural issues [A092]. Dr. Davis pointed us to Prof. Zeigler's book (bibliography Ref. [043]), indicating that it addressed many of these issues although it did not include immersion. He asked us not to rewrite this book but rather to make sure that other material was added to that knowledge [A095].

## SIMULATIONS TOO HARD

Mr. Harmon asked what factors make simulation too hard to build and use [A156]. Dr. Davis cited high complexity as one problem. He said, "This stuff is generally harder than mere mortals can learn [A157]." Dr. Pace elucidated two contributing problems: (1) the lack of adequate knowledge about the phenomena being modeled and (2) the complexity of the relationship and the number of parameters and interactions involved. He said that it takes a long time to learn about those things. In short, complexity and ignorance make building and using simulations hard [A158].

## SIMULATIONS & MODELS

Mr. Lunceford asked if any mathematical representation that can advance in time is a simulation [A068]. Dr. Page replied that the database people maintained that position [A069] and Mr. Harmon affirmed the correctness of that position [A070]. Mr. Lunceford disagreed by arguing that a database full of data collected from a number of sources does not represent anything [A071]. He continued this line of thinking by asking why we tended to separate models and simulations [A074]. Dr. Davis remarked that simulations belonged to the set of models [A075]. Dr. Page indicated that the military part of the world seemed the only part that distinguished between models and simulations [A076]. Dr. Pace observed that the Sargent circle distinguishes models from simulations and the SCS adopted that view (see bibliography Ref. [148] for more information on the Sargent circle). They represent a community much broader than just the military [A080]. Prof. Zeigler asked if a model written in Fortran is just the code itself [A077]. Dr. Page responded that different versions of models exist [A078]. Prof. Zeigler noted that we had models expressed in Fortran in the 1960s, in C in the 1970s and in Java in the 1990s. He argued that making a distinction between these models is necessary to discuss what aspects of the whole are related to the real world, the model and how the model is executed. That combination makes the simulation [A079].

## SPECIFIC VS. GENERAL SIMULATIONS

The workshop participants explored the differences between building general-purpose simulation infrastructures and building simulations for narrow purposes. Mr. Lunceford began this discussion with a story about the WARSIM simulation (see bibliography Ref.

[366] for more information on the WARSIM program). He asserted that it was the wrong simulation from the beginning. People tried to build too big a thing. The purpose does not require the level of detail that it makes available. He thought that the desire to build a large general-purpose simulation might drive people to make this mistake. Training simulations do not require the capabilities that WARSIM provides. Running simulations with a 5000 person training audience only trains them in communications and that can be done with a much smaller simulation. Further, WARSIM has apparently reached the technology breakpoint where they cannot make it functional [A161] (see bibliography Ref. [360] for more information on the WARSIM program).

He described another development, JSIMS (see bibliography Ref. [363] for more information on the JSIMS program). In that case, the people developing the requirements for JSIMS surveyed the users to identify what they wanted. Despite the results of that survey, they are building exactly the opposite of what the users said they needed. Nobody seems to care or understand that the JSIMS users and the people developing the JSIMS requirements did not agree on what was needed [A161]. The intended training audience for JSIMS is the joint task force commanders but with JSIMS there will be five levels between the simulation interfaces and the commanders. It will end up being a $400 M board game [A165] (see bibliography Ref. [357] for more information on the JSIMS program).

Mr. Lunceford noted that the JCATS simulation was interesting (see bibliography Ref. [361] for more information on the JCATS program). It supports mounted and dismounted infantry exercises. It is simple and has a poor interface. But, a number of users like it because of its ease of use, flexibility and simple set-up. Comparing a large simulation like ModSAF with JCATS produces very unsatisfying results. Users prefer to use JCATS [A152, A159]. Dr. Raibert observed that ModSAF wants to use automation where as JCATS allows the user to do it themselves [A160].

Dr. Davis recounted that in the eighties The Rand Corporation built a large composable wargaming system, investing considerable effort in the project. But, no one outside of Rand used it for its composability. The users just wanted to "put data into it and push a button" for their answers. He felt that this was characteristic of how the DoD does business. The issues of deciding which type of simulation to use (i.e., general purpose or specific) are not just technical but management as well [A153]. Mr. Lunceford commented that need drives the situation not the desire to drive to the lowest possible cost. He indicated that a phenomenon could exist there [A154]. Dr. Davis replied that there are probably two reasons. First, some problems are just hard and tackling them provides learning experiences. The second problem is more characteristic of the analysis community. In some cases, the complexity of the models and the data upon which they depend makes the analysis results meaningless because one can get any answer desired. There seems no interest in using the simplest and fastest models first then looking at the results of detailed representations only when they are needed [A155]. He commented that bright people could quickly construct a model that is useful for a specific job but that cannot be generalized for other problems. On the other hand, people seem driven to build enormously flexible simulation infrastructures that are supposed to allow the rapid composition of specific simulation exercises. But, he warned, he has never seen that approach work. Even within Rand using their tools, people do not want to turn off the

parts of the simulation that they do not need. He asked, “How can we train people better? It [seems to be] a generational issue ... [A162].”

Dr. Raibert responded by asking how painful people found stovepipe solutions. He noted, “Adding such things as reusability and interoperability adds a lot of cost and [technical] challenge [A166].” Mr. Lunceford replied that most people do not understand simulation so they do not understand the fundamental flaw in building general-purpose solutions for people wanting to do very specific things. He felt that people should look at what currently exists and be willing to use that whenever possible. Building a new simulation for each need is also not very efficient. That perspective leads us to search for general-purpose solutions. He wants to put tools into people’s hands quickly and efficiently. In the limit, he would like a user to be able to describe his problem then push a button for the answer. We also seem prone to think that simulations need to have the same fidelity as the real world to prevent people from gaming the system [A167].

Dr. Raibert reflected, "Building institutions that create effective simulationists is the opposite of trying to build simulations that solve every problem [A168].” Mr. Lunceford added that he does not want engineers to build simulations. They should just use simulations in their job and customize them for their problem if necessary [A169]. Dr. Davis observed that JWARS seemed to have a really good technology and asked what could be done with the tools and infrastructure they developed. He also felt that Janus represented another simulation success story. He recommended that we consider what JWARS has done [A170] (see bibliography Ref. [360] for more information on the Janus program). Prof. Swartout proposed that a fundamental dilemma exists between allowing people to build ad hoc simulations versus giving them large infrastructures that require effort to answer their questions [A171]. Dr. Pace countered that the majority of the money spent to develop simulations is not being spent upon infrastructures but instead on developing the models themselves. He worried that our discussion seemed to focus upon only one aspect of simulation (i.e., infrastructure) as if it represented the entire problem [A172]. Mr. Lunceford asserted that building a general-purpose model and building a model for a specific application both depend upon the same underlying phenomenology [A173].

## CONCLUSIONS

The participants were able to identify several classes of simulation phenomena. These phenomena fell into one of two broad categories, those specific to the nature of simulation and those that influenced simulation but were applicable to any large system as well. Those phenomena that distinguish simulation from the products of other disciplines can probably contribute to identifying simulation’s core body of knowledge. The participants also discussed some of the issues that made some simulations too hard to successfully implement and the differences between models and simulations. Finally, they considered the advantages and disadvantages of building simulations to solve specific problems versus building general simulation frameworks that can solve many problems. This dichotomy in particular may represent a fundamental issue in simulation.

# Session 4 – Simulation Hypotheses

The purpose of this session was to identify possible hypotheses that could be tested and, if supported by empirical evidence, could coalesce into core theoretical knowledge about simulation. Mr. Gross introduced this session by showing two slides the supplied some basic information. His first slide, shown in Figure 1, described the components of the scientific method (bibliography Ref. [326]). He slightly modified the traditional view of the scientific method by adding directed observations to account for where controlled experiments may be difficult to perform [A001]. When he thinks of classical experiments, he thinks of repetition and, particularly repetition by independent observers. He does not believe that we can conduct classical experiments on some types of simulation problems. For example, if someone proposed a hypothesis about the construction of a large simulation (e.g.,WARSIM) then he did not believe that anyone would build a second large simulation with exactly the same functionality (e.g., a second WARSIM) to validate that hypothesis [A015].

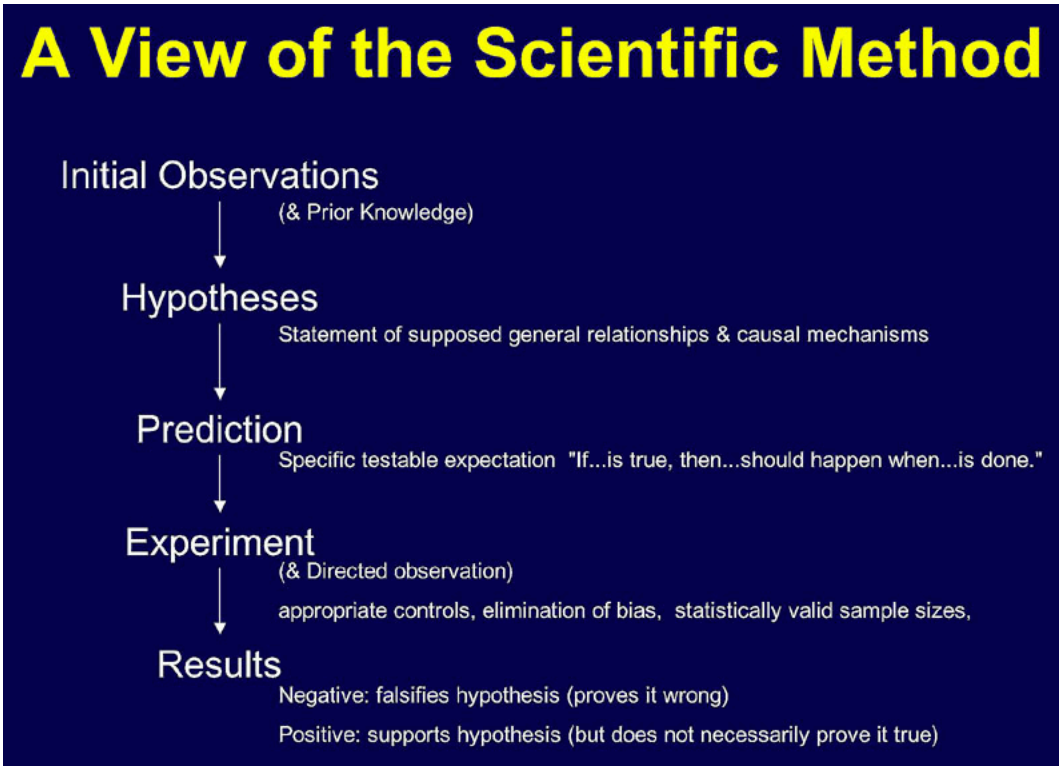


**Figure 1.** A View of the Scientific Method.

His second slide, shown in Figure 2, identified the properties of hypotheses (bibliography Ref. [327]). He emphasized that our discussions should recognize that a good hypothesis must be testable. He also commented that he did not necessarily agree with the constraint that a hypothesis must be answered with a small set of variables. He noted, "Some good hypotheses [may] come from what we think is true but have never been actually verified either by some derivation or experimentation [A001]."

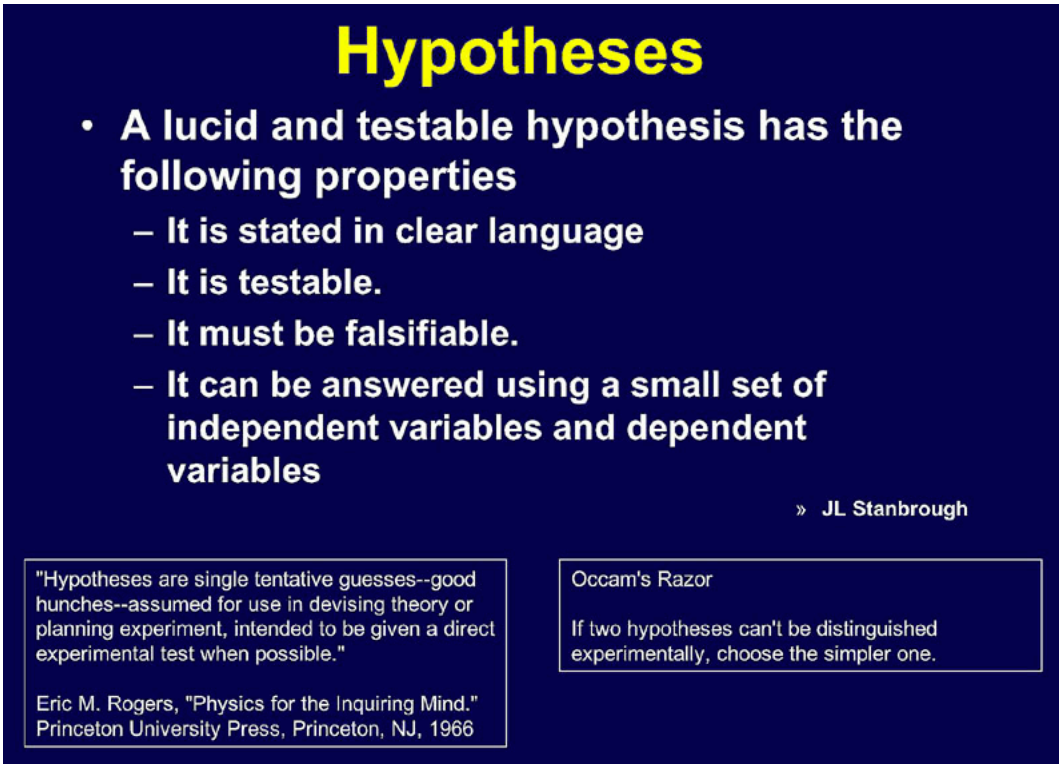


**Figure 2.** Properties of Good Hypotheses.

He completed his introduction by indicating his desire to extract some hypotheses that could be validated through some kind of observational or experimental program [A019]. Dr. Pace asked if we should explore those hypotheses about what simulation might look like and what some of those might be [A036]. Mr. Gross affirmed [A037]. Prof. Nicol reiterated the need for those proposing hypotheses to also propose tests for those hypotheses [A071].

The participants launched into vigorous discussion about simulation hypotheses. In the course of this discussion, they identified several. Table 1 lists the hypotheses that the participants suggested and debated.

**Table 1.** Results of the Simulation Hypotheses Brainstorming.

| Possible Testable Simulation Hypotheses |
|---|
| Different levels of fidelity affect interoperability |
| Simulation development is limited by the domain knowledge |
| Simulation fidelity/validity is limited by domain knowledge |
| Simulations may be useful even though they may not be predictive |
| Every system admits to simulation |
| Complex adaptive simulations are essentially unvalidatable |
| Increased emotional involvement decreases task performance but increases retention |
| Simulation performance and capability can be measured |
| Immersion can be measured |
| The efficiency for gaining insights from analytical simulations is inversely related to complexity beyond a threshold |

**Table 1.** Results of the Simulation Hypotheses Brainstorming (continued).

| Possible Testable Simulation Hypotheses |
|---|
| Multi-modal interfaces significantly increase simulation utility for some applications (e.g., smell affects immersion) |
| Simulation performance and fidelity can be adversely impacted by scalability |
| Accuracy of the environment is critical to sensor performance(?) |
| Believable environments are important to participants |
| A quality explicit conceptual model reduces simulation development and reuse cost |
| The validity of federated simulations is dependant on consistent interpretation of shared data |
| Appropriate validation and verification can reduce simulation lifecycle cost and/or improve quality |
| Simulations designed to build in multi-resolution representations provide substantial subsequent flexibility |
| Simulation reduces system lifecycle costs |
| Simulation enables design of systems which could not built without simulation |
| Small scale simulations can be more cost effective than large scale simulations |
| Standards reduce cost and/or improve quality |

Considerable discussion interspersed the proposal of hypotheses. Part of this discussion addressed the following topics:

- Characterizing error,
- Valid sample sizes, and
- Simulation hypotheses.

Unfortunately, the sound track on the videotape of this session failed after only 40 minutes of the session. As a result, these topics represent only a small sample of the entire discussion that occurred during this session.

## CHARACTERIZING ERROR

Mr. Harmon noted that Mr. Gross had listed the elimination of bias as a critical component of experimentation. He suggested broadening that notion to include the characterization of error [A020]. Mr. Waite commented that Dr. Numrich had discussed the need to carry error bars with their results [A022]. Mr. Harmon said that that was one aspect of error characterization, its quantification, but other components existed as well, for example, understanding the error sources [A023]. Dr. Pace added that researchers in the Department of Energy (DoE) ASCI Program were working to quantify the uncertainty associated with both the simulation codes they used and the experimental data they used to validate their simulation results (see bibliography Ref. [358] for more information on the ASCI program). He recommended that we become familiar with that work because it represents a serious step to use a fairly comprehensive and rigorous scientific approach in the simulation community [A025].

## VALID SAMPLE SIZES

Dr. Pace asked about the criteria for a statistically valid sample size [A010]. He wanted to know if a sample size of one could meet those criteria [A012]. He observed that a number of simulation validation experiments have a sample size of one or close to it [A014]. Mr. Gross responded that one should be able to estimate the variance of a population from an adequate sample size [A011]. He did not feel that a sample size of one met that criterion because it gave no sense of the variance within the population.

Dr. Pace used the example of a missile flight experiment to validate a ground-based midcourse missile defense simulation. In this example, the researchers can only perform one or, at most, a handful of missile flight experiments. They must then correlate their simulation results to that data in the hope of gaining some level of confidence in their simulation under a broad range of conditions [A016]. Mr. Gross suggested using the term observations of the real world in place of repeatable experiment because one could not replicate such an experiment [A017]. Mr. Harmon added that people do collect considerable data in the missile flight experiments so they really provide much more than a single sample. He described those experiments more as a single occasion from which the investigators collect many observations of the same phenomena [A018].

Mr. Gross proposed that validating simulations from small sample sizes represented the root of a hypothesis. He personally did not believe that as a valid approach for doing business but people are still doing it [A026]. Dr. Page affirmed that no statistician in the world would subscribe to the idea that one could reliably predict the results of missile flights from the observations of a single shot [A027]. Dr. Pace agreed saying that part of the work in validating computational solid mechanics simulations had stated that the correspondence between the simulation results and test data for singular or even a small number of events has little or no meaning. In other words, that correlation cannot confirm a simulation's validity [A029]. Mr. Harmon cautioned that this interpretation depended upon the meaning of "small number [A030]." Dr. Whelan reminded us that a sub-discipline of statistics that deals with the effects of small numbers exists and that he was sure that the missile people were aware of the mechanisms that field provides [A031]. Dr. Numrich asked whether we were referring to the sizes of real world measurements or to the number of the simulation runs when we talk about statistically valid sample sizes [A032].

Dr. Pace elaborated on what the missile people actually do. Before they fire a test missile, they execute a batch of simulation runs that approximate what they think will be the conditions during the actual test flight. After the test flight, they rerun the simulations, correcting for the original assumptions they had made for the environmental factors for which they have better data. They then use some subset of the simulation results to compare with the actual test flight data to evaluate the simulation validity. So, the real question is how to compare the results from multiple simulation runs with the data from a single missile flight and evaluate whether the simulation agrees with the observed data. He asked if one should compare the parameter values from the actual flight against the means of those parameters produced from all of the simulation runs or if one should compare the actual flight with the run that seems to produce the behavior closest to that flight? He asserted that that was a very difficult question to answer [A033].

## SIMULATION HYPOTHESES

Dr. Davis pointed out that we might talk about two different types of hypotheses related to simulation. One type includes those hypotheses that say something about how good simulations are. The other type includes those hypotheses about the real world that people use simulations to investigate [A038]. Mr. Waite added that one could formulate hypotheses about the nature of the science of simulation [A039]. Mr. Harmon emphasized that the workshop sought hypotheses that described the fundamental nature of simulation.

The discussion that the videotape captured addressed only a few of the hypotheses that Table 1 lists.

### Simulations & Perfection

Dr. Pace jocularly proposed a hypothesis about his first law of simulation. That law states that no simulation works perfectly all of the time [A002]. Mr. Gross accepted that that might be a good hypothesis. He felt that it had a gut-level truth but also that he has never verified its veracity [A003]. Dr. Pace maintained that he has never found any counter examples [A004]. Mr. Gross compared that feeling to "getting to truth by exhaustion [A005]." Mr. Waite asserted that that hypothesis was unfalsifiable [A006] and Dr. Page agreed [A007]. Mr. Harmon added that astrologers had not found any counter examples to their hypotheses either [A008].

### Fidelity & Interoperability

Mr. Gross hypothesized a relationship existing between a simulation's fidelity and its interoperability with other things (see bibliography Section I.D.7 for one view of this relationship). In this relationship, differing levels of fidelity affect interoperability [A041]. Dr. Davis responded that interoperability is a matter of degree depending upon the application [A042]. Mr. Gross believed that sooner or later the differences in the fidelity of two simulations would prevent their interoperating sufficiently to support an application [A043]. Mr. Harmon added that that outcome would only occur in the limits [A044]. Mr. Gross regarded the limits as the testable regions [A045]. Mr. Waite clarified the hypothesis to two simulations having different levels of fidelity will be difficult to make interoperable [A046, A047].

Prof. Nicol stated that testable hypotheses would require quantitative characterization, perhaps statistical, and asked how one could test interoperability quantitatively [A048]. Mr. Harmon asserted that one can test interoperability by evaluating validity and that well-defined criteria determine validity (bibliography Refs [151-154]). These criteria come in the form of minimum fidelity requirements or the fidelity tolerances needed to serve a particular purpose. One then measures the fidelity of the results produced by a simulation composition and compares those measurements with the fidelity requirements to determine sufficient validity [A049]. Dr. Nicol asked if that approach assumed that no care was taken in assembling the simulation composition [A050]. He asserted that another component of modeling deals with the glue between models operating at different levels of fidelity. He offered the example of models of data traffic flows represented as fluids interacting with packet models of traffic. He maintained that the designer had considerable discretion in configuring these interactions [A052].

Dr. Davis provided another example where a simulation represents ground forces at the individual entity level during some times and at the unit level at other times. He asserted that the validity of the simulation did not depend upon the resolution of the movement representation because the effects of that depend upon doctrine and terrain and not on how they march. "That's a case where the same simulation has different levels of resolution." he said [A053].

Mr. Harmon responded that these two examples represented the same phenomenon. He noted that Dr. Davis' example certainly incorporated manifold representations of the same objects and maybe functional dependencies existed between those models as well. The manifold representations problem requires the existence of transforms between the two different resolutions and, depending upon the order of events, those transforms may need to be invertible to preserve interoperability [A054-056] (bibliography Refs. [153, 154]). Dr. Davis added that the transforms between different resolutions may or may not depend upon history [A057]. Mr. Harmon agreed and added that the interoperability criteria may include entry and exit criteria for these transforms. But, these criteria have not yet been proven as a necessary and sufficient set. More work is needed in this area [A058]. Mr. Gross added that creating testable experiments might be difficult [A060].

Dr. Page challenged the fidelity hypothesis with the example of coupling an exponential distribution of bank traffic to a detailed model of a bank teller. He asserted that these two models would interoperate perfectly enough to predict teller utilization even though their representations had completely different levels of abstraction. He maintained, "That falsifies the fidelity and interoperability hypothesis [A073]." Mr. Waite advocated that these two models did have different levels of detail but comparable levels of fidelity because their representations were correct at the semantic level of interest. He observed that detail and resolution are the same while fidelity is different from both of them [A074]. Dr. Page countered that his traffic distribution was a bad exponential distribution so the fidelity is obviously poorer [A075]. Mr. Gross responded that fidelity did not have anything to do with poorer or better and maintained that a hypothesis should not be a tautology [A076].

**Limitations of Simulation Development & Fidelity**

Dr. Pace proposed two hypotheses [A061, A062, A063]:

- Simulation development is limited by phenomenology knowledge/domain knowledge (of the simuland).
- Simulation fidelity/validity is limited by domain knowledge.

He felt that these were both testable [A063].

Dr. Page complained that he did not understand the first but interpreted the second as "you can't represent what you don't know about [A064]." Dr. Pace responded that the first hypothesis says, "You can't represent what you don't know about." and the second one says, "you can't tell how good it is until you have knowledge of the domain [A065]." Dr. Page asserted that he did not know anything about how the brain works but that he could build a simulation of the brain albeit one that is completely wrong [A066]. He proposed that as a counter example to the first hypothesis [A068]. Dr. Pace ceded that one could construct representations of the brain without knowledge of its workings but

reiterated that knowing absolutely nothing about the brain limits what one can actually represent. The second hypothesis deals with the goodness of a representation [A069].

### Simulating Complex Adaptive Systems

Dr. Davis cited that some critics of simulation say that attempts to simulate complex adaptive systems are doomed to failure because their results are so sensitive to their initial conditions (bibliography Refs [156, 157]). He asked to what extent we should even try to simulate them especially if they would be used only for one simulation run [A077]. Dr. Page asked that we try not to propose a hypothesis without also proposing its test. He felt that no one could test the complex adaptive system hypothesis [A078].

### All Models Are Wrong

Dr. Davis proposed and Dr. Pace refined the hypothesis that all models are wrong but some models are useful [A079, A080]. Dr. Davis proposed the test of taking a simulation that operated in one execution environment (e.g., computers, operating system, programming language support) and executing it within another environment to see if the same conclusions could be drawn from its results. He added, "Some people argue that you get such different answers that it clearly has shown that this is not the right way to do your work [A079]."

Dr. Davis extended his hypothesis by reiterating that building predictive simulations of complex adaptive systems may not work. He advised that we might be fooling ourselves and our clients [A081]. Mr. Gross added that these simulations might be useful although not predictive [A082]. Dr. Pace emphasized that simulations of adaptive systems should not be extrapolated very far in time [A084] and Dr. Davis noted that one incurs serious problems when doing so [A085]. Dr. Whelan asked if they were saying that some limit of error existed that defined whether these simulations are useful or not [A087]. Mr. Gross commented that that presented an interesting assertion because many people in the analytical community have identified that problem [A088]. Dr. Page asserted that the "all models are wrong" hypothesis could not be empirically tested [A090].

## CONCLUSIONS

While the participants covered some very important topics during this session, the process of formulating meaningful hypotheses about the fundamental nature of simulation proved challenging. Some participants willingly jumped into the fray and proposed hypotheses but others puzzled over the problem of testability. However, this session did result in a list of germs of hypotheses dealing with the nature of simulation. And, the interactions between those proposing hypotheses and those questioning their testability or validity did stimulate interesting and insightful discussions. In addition, the participants considered the issues of errors and simulation validation from limited sample sizes.

# Session 5 – Experimentation & Observations

The participants briefly debated the workshop's purpose, as our discussions seemed to wander somewhat purposelessly at this point.

Mr. Waite elucidated that we could be talking about the simulation itself, or the validity of the simulation (i.e., the merit of its representation relative to the simuland and a purpose), or the practices and processes used to build and use the simulation, or the science underlying any of these areas. He asserted that if we were talking about the underlying science then that was a null set [A012]. He believed that simulation exists as a technology and not a science the way we normally think about science. He recommended that we concentrate the discussion on the technology rather than the science because the challenges reside there [A014]. He reassured us that he believed simulation a worthy subject for universities to teach at the undergraduate level. However, his personal experience verified that existing faculties raised barriers to that [B001]. In an attempt to resolve to a set of specific actions, he suggested that we enumerate a set of topics and relationships for simulation that could then be explored and recommend a set of research topics [A030]. There exists a need for that information and an institutional way to use it [A033]. Prof. Swartout concurred and noted that these topics could be the chapter titles for a simulation textbook [A031].

Dr. Whelan asked whether we thought that the simulation technology was the easiest of the issues Mr. Waite raised [A017]. Dr. Pace responded that it was certainly the untouched part [A018]. Dr. Whelan expressed that he thought that we already know how to solve the issues associated with simulation construction [A019]. To which Dr. Davis reminded him that several big ongoing simulation efforts are currently failing to meet their objectives [A020]. Dr. Whelan continued to say that our discussions seemed to be scraping the side of improving the simulation community's professionalism to address the problems plaguing those programs. He thought that we needed to understand all of the aspects of the professionalism problem including the education and basic tenets [A034].

Mr. Harmon agreed that this workshop was trying to focus on the basic tenets of simulation and the ways to find them [A035]. Knowing these tenets would surely improve the educational and professionalism aspects of simulation. He said, "The question I was trying to answer is 'What things are in this science [of simulation]?'" He expected that we would probably find a small set of literature describing our scientific understanding of simulation. He hoped that the participants would agree on the merits of pursuing the scientific exploration of simulation phenomena [A028]. Dr. Davis added "... whether or not that is a small area."

Dr. Davis cautioned that, for the most part, our discussions seemed to have blended the notions of model validation with the professional construction of those products. He believed that these were distinctly separate issues that warranted separate discussions [B003].

Mr. Lunceford reminded us that the workshop discussions focused upon the science of simulation because a set of simulation practices founded upon fundamental knowledge did not yet exist. The goal of seeking those fundamentals should drive the workshop.

Arriving at the conclusion that no science of simulation existed would be an acceptable conclusion from the workshop but he wanted the participants to address the fundamentals that might underlie simulation whether a science or not [B004]. He wanted us to make a series of recommendations about what we needed to do to find those fundamentals (e.g., additional workshops). If we ultimately found a science with which he cannot do anything then we have not helped him [A027].

Dr. Numrich provided a slightly different perspective on the workshop's purpose. She noted that we had said that no foundational research is ongoing in simulation and that we would like some. Her problem comes when trying to pursue that desire for funding for foundational research in simulation. In doing so, she must deal with people with educations in traditional science and they do not see anything foundational about simulation. As best, to them, it seems only an applied part of computer science. She articulated the goal for us to develop a list of basic research topics. For her to find funding for basic simulation research, she needs a good list of foundational topics [A032, B006].

After their careful consideration of the purpose of this session and of the workshop in general, the participants began to examine the issues associated with the means to perform experiments on simulation or obtain systematic observations of simulation behavior. In this context, they discussed the following topics:

- Simulation as science,
- Simulation fundamentals,
- Relevant prior scientific work/data,
- Various miscellaneous topics, and
- Experimentation and simulation.

While some of this discussion strayed some from the session's focus, all of these topics were relevant to the workshop's theme and contributed to the knowledge derived from this workshop.

## SIMULATION AS SCIENCE

The participants vigorously debated the suitability of regarding simulation as a science. They examined the difference between science and engineering and between the benefits of disciplined versus undisciplined science.

### Simulation – Science or Engineering

The participants deliberated on the nature of simulation, a science or engineering discipline. This debate began with Dr. Whelan's introduction to the session. He stated that he was convinced that simulation is not a science because models are epistemological things and they underlie all of science. Models and simulations provide a path to understand the real world and are therefore tools of science [A001]. In this suggestion, he used the notion of simulation as a model passing through time [A003]. Dr. Pace noted that Dr. Whelan was not talking about the implementation of a simulation in

this context and that that implementation process is certainly an engineering sub-discipline [A004].

Dr. Davis agreed with Dr. Pace and said, "There are so many special features of simulation [as systems] that it, at least, qualifies as an engineering discipline. Whether it is a science is arguable [A002]." He added that we often talk about systems science but, in practice, most systems work is really engineering and that does not apply merely to implementation. While systems engineering is a broad and real field in itself, digital simulation includes many other topics as well (e.g., implementation issues like software engineering) [A005].

Mr. Waite interjected that we could talk about the technology of the science of simulation but that he felt that would consist of a null set [A012]. Dr. Davis asked whether by null set he meant the properties of uniqueness and so forth and stated that the issue is not that there is no science in simulation technology but rather whether it rates being a separate field [A013]. Mr. Waite reiterated that in his opinion there was no science there, at least not the science that he thinks about as relating to an objective reality [A014]. Dr. Numrich asked "A science is something where there's an objective reality that we're trying to learn more about, hence, computer science is not a science [A015]?" Mr. Waite responded that in his opinion, the answer was yes [A016].

Mr. Lunceford added further fuel to the question by asking Dr. Davis if there was a bona fide field of military science [A081]. Dr. Davis responded that if he used that term to mean a systematic body of knowledge then yes. He continued to say that the former Soviets had developed such a body of knowledge about military operations. They trained their officers in this science but we did not. He believed that there was something to that notion [A082].

**Disciplined vs. Undisciplined Science**

Mr. Lunceford initiated this discussion of the merits of applying loosened scientific discipline to the simulation problem. He asked if one could build the argument that no science of simulation exists as a separate field then could we productively apply good scientific practice to look at the piece parts of simulation. In other words, if we could parse the simulation problem then administer formally structured inquiry to the resulting parts then we have gotten somewhere [A079, B012]. Mr. Lunceford proposed that one could interpret science strictly or simply as a codified body of scientific knowledge. He suggested that the latter interpretation perhaps better suits simulation [A083].

Dr. Davis recommended asking instead if a clear and coherent realm of activity exists. He offered that simulation fits that criterion and that it has foundational areas that its practitioners should know. He further proposed that simulation has considerable fundamental knowledge associated with it and the work of Zeigler and Fishwick contributed to that knowledge (see bibliography Refs. [043] and [011] for discussions of Zeigler's and Fishwick's work, respectively). Assuming an interdisciplinary perspective to simulation increases this established knowledge base [A080].

Dr. Davis continued by opining that science is not what the philosophy of science people discuss, It consists much more of a discovery process. Another part includes those people who propound theories that may not have much to do with the real world. He

asserted that the scientific method could get us into a lot of trouble. He maintained that physics and chemistry did not grow from that nice neat stuff [A084]. He said, "Where we are in simulation is not where we should be concerned about the rigorousness of experiments. We are still in the discovery stage in simulation [A086]." He referred to many social-science studies in which the "scientific method" has had terrible effects by causing an overemphasis on pure statistics. He said, "They end up looking where the lamppost is [A088]." Dr. Davis offered the evolution of modern chemistry from alchemy as an example. In the beginning, the alchemists did not perform rigorous experiments as we define them today yet they still produced useful knowledge from their efforts despite the sloppiness of their methods [A093].

Mr. Harmon strongly objected to these arguments. He described the soul-searching in which the scientific community was currently immersed. Recent prominent incidents in which researchers short-circuited the scientific method have precipitated this mass introspection. Everyone in science has come to agree that those researchers were not practicing science and that the knowledge they produced suffered from their shortcuts. He insisted that the strength (i.e., truthfulness) of the knowledge composing science arises from the discipline the researchers exercised when discovering that knowledge [A085] (see bibliography Ref. [325] for another view of this conviction). He further observed that anyone could take a good methodology and produce crap from it by doing the wrong things. The people doing this may have perfectly good intentions when they do it but that does not make their efforts or the products of those efforts right. He noted, "Science isn't just numbers [A089, A091]." And, the discipline is not that constraining. Adhering to the scientific discipline does not preclude or even limit being creative [A094].

Prof. Swartout said that that is not were the argument is. He confirmed that taking the scientific method and applying it inappropriately might miss the boat. He cited the case of survey people who get their numbers to look respectable but who miss capturing and portraying the real story underlying those numbers. He believed that oft times that story is closer to truth than the results of the survey [A090].

Dr. Numrich concluded this discussion by remarking that any scientific endeavor begins with many observations before a single controlled experiment is performed. This "nosing around" assesses the underlying phenomena. "We didn't have a notion of atomic theory first," she commented, "just lots of systematic observations." She maintained that this "nosing around" is not necessarily science. She believes that simulation is still in the "nosing around" stage [A092]. Mr. Gross agreed that part of science is "nosing around" [A095].

## SIMULATION FUNDAMENTALS

The participants spent some time asking themselves again about the fundamentals of simulation knowledge. They discussed the distinct paths to obtaining those fundamentals and identified several topics that contributed to simulation fundamentals.

**Path to Simulation Fundamentals**

Nearly all of the participants agreed that a fundamental knowledge of simulation exists and can play an important role in advancing simulation practice but they debated the best path to find this fundamental knowledge.

Mr. Lunceford emphasized that the real purpose for the workshop was not necessarily to find a science of simulation but rather to find the set of underlying principles upon which to build better practice. While having a science would enable building tiered knowledge products, our discovering that no science of simulation existed would be an acceptable outcome. He proposed that maybe we should try to identify how to apply scientific discipline to uncover the fundamental principles of simulation [A023].

Mr. Harmon described two proven means to improve a practitioner's knowledge. The oldest involves assigning an apprentice learning a journeyman's craft by observing the journeyman work and working under the journeyman's critical eye. The other involves finding, through scientific inquiry, the principles that underlie a practice and teaching those principles and their implications to the craft through formal educational infrastructures (e.g., classroom instruction, textbooks, videotaped instruction). Both means have proven to be effective at improving the workforce quality. However, the apprenticeship model is far less efficient. A single teacher can effectively and consistently instruct 20-50 students simultaneously, or even more in some situations, in such complex topics as physics. On the other hand, a journeyman can work side by side with only a few apprentices at a time, one-on-one being the most effective ratio. In this case, the efficiency of the knowledge transfer gets very thin. He stressed that this workshop should concentrate on identifying the underlying principles of simulation. Exploring the guild model may deserve another workshop [A024, B005].

Prof. Swartout pointed out that we might actually need both approaches. The rightness of the approach depends upon the maturity of the codified knowledge. A guild model works best if the skills are not well understood. Then working with a master may offer the only path to learning a skill. If a codified body of knowledge or practices exist then those can be more easily taught in a classroom situation. Medicine provides a good illustration of this. Doctors learn their basic knowledge in the classroom situation then progress to internship that combines classroom instruction with work under master doctors. As they progress into their specialties through residency, they spend more and more time working under the direct supervision of experienced doctors and less time in the classroom. A transition occurs as the practitioner moves from apprenticeship to expert knowledge. A single strategy will not suffice. The strategy must change with the degree of expertise desired and the level of foundation knowledge change [A025].

Dr. Davis warned that apprentices from guilds that teach simulation of physical systems could not apply those same concepts to building simulations of complex adaptive systems because they have been given the wrong knowledge. The core curriculum must teach where different approaches are needed and identify the overlap between these approaches. Students must also learn that these inherently interdisciplinary areas may make them uncomfortable [A038] (see bibliography Section I.D.9 for references on complex adaptive systems).

**Fundamentals of Simulation**

Prof. Swartout asserted that core knowledge exists that one should know when entering a simulation effort. A variety of things contribute to a simulation working satisfactorily [A041]. In the course of this discussion, the workshop participants identified several concepts that were fundamental to simulation, the constituents of this core knowledge.

Prof. Swartout continued by saying that in addition to this core knowledge, simulation is a highly interdisciplinary study and the mix of contributing disciplines differ as the simulands change. If a simulation involves human representations then the discipline mélange must include people who understand human behavior. If the simulation represents weather phenomena then the discipline mix must include expertise on those phenomena [A041].

Managing Time & Events

Prof. Swartout suggested that how to deal with time, how to manage time, and how to manage simulated events were part of the core knowledge that someone needs to understand when they become involved in simulation [A041].

Conceptual Modeling

Both Mr. Waite and Dr. Pace agreed that conceptual modeling was fundamentally important to simulation [A047, A050]. Mr. Waite recounted that the experiences of many have confirmed this assessment. He said, "The qualities of the referent are really influential [A047]." Dr. Pace did not feel as if we were advancing our understanding of basic principles in the same way or at the same rate as other engineering disciplines [A050].

Abstraction & Representation

Dr. Pace asserted that we do not have any substantive experimental evidence describing how to choose problem decomposition practices or interrelationships or how to select the features of a simuland without corrupting the resulting simulation, especially for those simulations of different complex systems. He said that we have not been doing structured experiments to advance our knowledge so that we understand what has worked and can build systematically upon what we have learned [A050].

Dr. Pace, Dr. Davis and Mr. Waite all emphasized the fundamental importance of the process of abstraction to simulation [A046, A047, A050]. Dr. Davis recounted a case in which the Los Alamos National Laboratory (LANL) experimented with different representations of motor vehicle traffic flow. At first, they tried building detailed models of traffic but could not get them to behave correctly. Then, they represented traffic behavior as a complex adaptive system. Even though only a few rules governed the behavior of these models, their behavior appeared more consistent with the flow characteristics of real traffic [A046]. Mr. Waite concurred that LANL's experience and those of many others confirmed the importance of representation choices to simulation [A047]. Dr. Page suggested that this experience provides an example of an experiment from which we can learn about the representational effectiveness to solve a class of problems [A048].

Mr. Lunceford recounted another representation-related incident, his experience with the Synthetic Theater of War (STOW) program (see bibliography Ref. [365] for more

information on the STOW program). They were trying to build a distributed simulation that could represent 100K entities simultaneously. They began with the vision of what they wanted to achieve but did not have anyone who understood that 100K entities needed to operate as an integrated force unit (e.g., a corps). Their people did not understand how to architect the integrated simulation and who understood the constraints, limitations and values of, not only the mechanics of simulation but also, how to apply simulation to the real problem they were trying to solve. He believed that the initial STOW vision was not practical and that they did not understand how to achieve the program goals. He lamented, "We're not any better today [A049]."

Correspondence to the Simuland

Mr. Gross asserted that the only phenomenon uniquely associated with simulation is its correspondence with the real world (i.e., the simuland) [A095]. As such, this should stand as one of the fundamentals associated with simulation.

## RELEVANT PRIOR SCIENTIFIC WORK/DATA

Dr. Page reminded us that in our discussions of the performance aspects of simulation, we were ignoring much theoretical and experimental work in many different areas [A063]. He added that it was important to highlight the existence of some success stories in modeling and simulation initiatives in such areas as event list management schemes, random number generators and complexity theory [B010]. However. Dr. Pace countered that we must put this prior work into perspective. Much of the work to which Dr. Page alludes resembles the work in formal methods as applied to simulation; it tends to be splintered or fragmented as far as the simulation community is concerned [A075, B011]. Prof. Swartout disagreed and asserted that all of the work that Dr. Page mentioned was important to training systems [A076]. Dr. Pace responded by noting that we have incorporated random number generators into simulations since the invention of computers. None of their problems have prevented the advance of simulation technology. He said, "An awful lot of effective training systems have been built without advanced [random number generators]." He chided us to keep this existing work in the perspective of obtaining a quality simulation workforce [A077].

The discussion this exchange elicited produced a number of areas where simulation researchers have invested significant effort, both theoretical and experimental.

### Time Flow Management

Dr. Page mentioned that much work had been done on evaluating the effects of both conservative and optimistic time flow management schemes [A063] (see bibliography Section I.D.3 for some references to this work).

### Event List Management

Dr. Page listed event list management as an area where significant theoretical and experimental work had been done, particularly to develop efficient event list management schemes [A063] (see bibliography Section I.D.5 for some references to this work).

**Monte Carlo Convergence**

The researchers exploring Monte Carlo simulations have expended much effort trying to understand their convergence properties. Dr. Page asserts that this work has followed rigorous scientific discipline [A063] (see bibliography Section I.D.2.b for references to work on Monte Carlo representations).

**Random Number Generators**

People have been performing both theoretical and experimental work to try to understand the attributes of good random number generators [A063] (see bibliography Section I.D.4 for some references to the work on random number generators).

**Representation & Performance**

Dr. Page said that lots of good science had been done on the dependencies between representation and performance [A063] (see bibliography Refs. [061, 084] for references that provide insight into the literature on this topic).

**Analyzability & Expressiveness**

Dr. Page cited a number of efforts that applied computability and complexity theories to simulation. He said that these are good bodies of theory that simulation researchers have employed over the last ten to fifteen years to explore the tradeoffs between simulation analyzability and expressiveness (see bibliography Section I.F.3 for references on these topics). He asserted that the simulation validation problem has been proven undecidable. He supported that assertion by saying that the problem of deciding the equivalence of two models is fundamentally undecidable. This theoretical work is founded upon the Turing halting problem [A063] (see bibliography Section I.F.3 for references on this topic).

**Performance & Expressiveness**

Dr. Page alluded to the work of many people who have considered efficient simulation algorithms from a complexity theory perspective (see bibliography Refs. [027] and [084] for pointers into the literature on this work). He asserted that from an expressiveness standpoint, he could compare different formalisms (by combining complexity theory and formal language theory) to determine which is more expressive and which is more analyzable. He indicated that much prior work exists, of both theoretical and experimental nature, in the area of model representation and the limits of different representations. Some of this work also examines the limits of automated support for examining and evaluating model representations. He claims that this prior work forms part of the scientific knowledge about the nature of simulation [A063].

At this point, Mr. Harmon cautioned about confusing mathematics with science. He admitted a passing familiarity with complexity theory and was not aware of much formal experimental work supporting it [A064]. Mr. Waite countered that the existence of formal notations and their power of expressiveness remained hugely useful to simulation. He suggested that we needed to incorporate as much of it that applies and help it find its way into our practices and processes [A066]. Dr. Page confirmed that people have done quite a bit of work on that [A067].

### Heuristics as Experiments

Dr. Page asserted that considerable experimental work has been done on heuristics and that the process of inventing a heuristic is purely experimental in nature [A065].

### Simulating Perceived Phenomena

Prof. Swartout suggested than another area where people have pursued considerable experimental work was looking at how various perceivable phenomena in the world work and how they could be effectively simulated. He cited work on understanding how light and sound were perceived. He noted that people have done much work on how to depict the effects of various phenomena so they appeared realistic to humans interacting with a simulation [A068]. Mr. Harmon asked, "This involves the perception of light and sound [A069]?" Prof. Swartout agreed.

Dr. Numrich observed that this problem had two parts. In one, the human participant must sufficiently believe that they are experiencing the real situation. In the other, under different circumstances, that same depiction must be perceived by other, nonhuman, parts of the system (e.g., automated sensor systems). At times, these other perceptions must be consistent with the phenomenon that the humans perceive. She described the notion of different portals. Through some of these, the human and machine perceptions must remain consistent. Through others, that consistency constraint can be relaxed. However, understanding the necessary relationships between these different portals is crucial [A072]. When Prof. Swartout asked if she meant the consistency between human and automated sensors, she affirmed but added that this consistency is not always necessary [A073, A074].

### Human Behavior Phenomena

Prof. Swartout cited solid experimental work on developing human performance/behavior representations. He said that this work was akin to understanding physics [A070]. Mr. Harmon countered that he knew of very little work that tried to understand the physics underlying human behavior other than his [A071] (see bibliography Ref. [168] for physically-based models of human behavior and Section I.D.10 for more references on cognitive modeling).

### Simulation Programming/Implementation

Dr. Davis suggested that the activity of programming a simulation consists of an experimental process. He said that, from that perspective, significant amounts of data exists on that topic [A096].

## MISCELLANEOUS TOPICS

The workshop participants discussed several topics peripherally related to simulation experimentation including

- Physical systems versus complex adaptive systems,
- Simulation architectures, and
- Representation and comprehensibility.

These topics resulted from the diverse nature of simulation.

**Physical Systems vs. Complex Adaptive Systems**

Dr. Davis maintained that a fundamental distinction exists between simulations of physical systems and simulations of complex adaptive systems (e.g., human representations or other adaptive systems such as robots) (see bibliography Section I.D.9 for references on simulating complex adaptive systems). Constructing simulations of physical systems looks more like engineering. Constructing simulations of adaptive systems looks more like research. He recommended reading The Hidden Order (bibliography Ref. [160]) to better understand the issues associated with representing complex adaptive systems [A036]. He continued to say that complex adaptive systems have multiple levels with parallel but overlapping paths and are governed by their own laws. Building simulations of these systems from the bottom upwards cannot capture the subtlety of their behavior. Further, these systems change their behavior through interaction with their environments (i.e., they adapt). This property complicates performing experiments because their behavior cannot be strictly controlled [A038, B007]. When Dr. Whelan asked if there was something inherently fuzzy about these systems, Dr. Davis replied "No. I said that a big portion of the world consists of complex adaptive systems and they are different [from physical systems] [A042, A043]."

Prof. Swartout confirmed that the methodologies for experimenting with these systems were different that what one would use for systems whose behavior can be limited to a few free variables [A044]. To this, Dr. Whelan disagreed that the number or complexity of variables really changed the fundamental issues. He cited the contrast between classical and quantum theories and asserted that the experimental tenets remain the same for both [A045].

**Simulation Architectures**

A number of participants concurred that architectural design was important to simulation. Mr. Waite noted that our capacities to specify and implement simulation architectures were pretty pathetic and slipshod [A053]. As an example of the importance of understanding architectural design to simulation, Mr. Lunceford cited the case of WARSIM (see bibliography Ref. [366] for more information on the WARSIM program). He recounted that the people building WARSIM also built the Close Combat Tactical Trainer (CCTT) (see bibliography Ref. [364] for more information on the CCTT program) and that the WARSIM architecture closely resembles that of CCTT (see bibliography Ref. [358] for more information on the CCTT program). The problem with this resemblance is that CCTT is a visually oriented implementation and WARSIM is a command and staff trainer; they serve two fundamentally different purposes [A056, A058].

In the architectural context, Dr. Pace asked if the specification of simulation architectures should go higher than the Joint Technical Architecture (JTA) (see bibliography Ref. [379] for more information on the JTA). Mr. Waite responded, "Yes. JTA is a certain class of answers for a certain set of problems. Simulation is an application domain where there are architectural considerations." He felt that JTA was a system engineering approach to a class of architectural problems. He reiterated that we do not understand

very well the processes for specifying simulation architectures and choosing among architectural features. He suggested that the people pursing JTA are not likely to devise solutions to these problems [A060]. Dr. Pace posited that if simulation people only got as far as the JTA then they would be at least ten steps of where they are today [A061]. Mr. Harmon observed that that sounded like a hypothesis warranting an experiment to him [A062].

**Representation & Comprehensibility**

The workshop participants discussed the relationships between a simulation's representation and its comprehensibility and the importance of those relationships. Dr. Whelan began this discussion by maintaining that one of our objectives should be to simplify our understanding of the real world, models and simulations. That means that an underlying simplification exists. Simulation people often answer a query into what they have done with the reply that it is too complex to explain. He asserted that we needed to simplify our understanding of simulation to the point where it can be explained [A111, B015].

Mr. Waite illustrated this point with the example of a brigadier general asking for an explanation in two slides. He concurred that the art lies in creating an explanation that is as simple as possible but not simpler. That guidance forms one of the tenets of representation. He felt that simulation professionals must understand that notion and that may take work. Requisite complexity applies to representation and, at a meta-level, to communications with a perceived audience [A112].

Prof. Swartout noted that these observations tied to Dr. Davis' previous comments on making simulations understandable to people, their comprehensibility. This consideration relates partially to how people build simulations. He asserted that if we really want comprehensible simulations then we might need to build them differently than we do now. This may require representing some of the design decisions as part of the simulation itself. Doing this will make them more understandable to the next people who try to apply the simulation. This creates a form of self documentation and it helps adapt the simulation to new purposes as well [A113].

Dr. Davis added that some commercial tools like Analytica and Mathematica provide good models for that notion (see bibliography Refs. [365] and [366] for more information on Analytica and Mathematica, respectively). He described the abilities of these products to automatically create documentation as part of a good structured design process. These environments enable building the conceptual model into the simulation at the very earliest stages of design. However, he warned that these products do not ask designers to generate what they are describing. In visual design environments, much of the conceptual model becomes part of the visualization but that visualization provides no hints to what additional explanation someone will need to use the resulting simulation product. He suggested that we needed to define what generic questions to ask. Having complete information associated with a model would have a significant effect upon the scientific utility of the end product [A114, B014].

## EXPERIMENTATION & SIMULATION

The participants considered several issues related directly to experimentation and the nature of simulation. The topics they discussed included

- Simulation as experiments,
- Possible simulation experiment areas,
- Need for quality data, and
- Candidate ways to collect that data.

Although the participants all had some degree of misgivings about applying the scientific method to understanding the nature of simulation, they enthusiastically sketched a rough path to performing simulation experiments and recommending two avenues through which to obtain data about the nature of simulation.

### Simulation as Experiments

Dr. Whelan reminded us that digital simulation represents only one category of simulation. Another category includes dropping an apple off a tower [A006]. Dr. Davis agreed that experiments are simulations in a sense [A007]. Dr. Whelan continued by saying that two elements of experimentation have bothered him for a long time. First, people have waxed about proper experimental design but he sees very little of that practiced. Second, people seldom think of a simulation as an experiment itself. It can help to define what one must do during an experiment and help to identify what problems one could encounter. He proposed that a good scientist should to design experiments using simulation. He noted that all simulations give only indirect information [A008, B002]. Dr. Pace remarked that Dr. Whelan's perspective seemed more oriented toward simulation validity than simulation technology [A010].

Dr. Davis observed that one could perform controlled experiments about how to build simulations with such hypotheses as modularity is good or multi-resolution is feasible and practical. One could also test whether simulations are any good from a validity perspective. He felt that these two different perspectives had confused our previous discussions. But, asking about the validity of simulation looks like other stuff out there. Learning how to build simulations well is a worthy subject in itself, the roots of which lie perhaps in systems science. One could perform experiments testing the techniques that people use to construct simulations [A009]. He added that another fundamental might come from the view that computational approaches give us a different way of codifying knowledge and learning, as well as a way of performing experiments. He proposed that much of the future would involve computational experiments to discover more about the real world. In the past, we built simulations and compared them with our observations of the real world. Increasingly, people will use simulation to perform computational experiments to understand the nature of the real world. This perspective applies particularly to trying to understand the nature of complex adaptive systems. He suggested that these different perspectives of simulation experiments comprise the first couple of courses that one should teach, in addition to systems engineering and object-oriented modeling, to simulation professionals [A038].

**Possible Simulation Experiment Areas**

Mr. Harmon asked what experiments might be performed to better understand the nature of simulation [A051]. Dr. Pace suggested, and discussed, several areas exploring simulation technology (as opposed to simulation validity) [A010, A052]. He believed that if we wanted to move toward a science of simulation then the experiments that ought to concern us should be related to simulation technology in particular. He said, "We have a unique opportunity here because no one else is looking at the experiments that would advance the simulation technology [A010]." During his discussion and afterwards, others added to the list of experimental opportunities. Mr. Waite mentioned that he liked the idea of broad-based experimentation through structured observations. This approach could provide a succession of improvements to current practices [A115].

Visualization

Dr. Pace felt we used visualization for a variety of simulation purposes (e.g., output analysis, process control) without understanding its fundamentals. He knew of no literature describing the applications and limitations of visualization. That represents a critical area requiring better understanding that we could obtain through experimentation. He remarked that lots of literature on using visualization for training purposes existed and that that work largely considered the validity of the visual environment. However, he knew of nothing that discussed the technology aspects of visualization [A010, B008, A052].

Abstraction for Purpose

Dr. Pace and Mr. Waite agreed that abstraction for a purpose (i.e., the process of analyzing a problem to determine the entities, attributes and interactions that a simulation needs to portray to solve a particular problem) represents a potentially fruitful area for experimentation. These experiments need to explore the effectiveness of different techniques and processes for abstraction for a variety of purposes [A021, A052, A053, B009]. Dr. Whelan believed that we did know how to address the issues associated with abstraction but just have not addressed them yet [A022].

Building from Conception vs. Flexibility

Dr. Davis suggested experiments looking at the necessity of building simulations from conception to be useful. He believed that many reasons existed for this attribute of success but thought them poorly understood. On the other hand, building general simulation infrastructures increases their flexibility and broadens the number of problems they can explore. He wondered if we could build automated software to add flexibility to simulations as opposed to building every simulation from scratch. He noted that today we do this by hand and that leads to many representation and implementation errors [A104].

Selecting Implementation Factors

The participants identified several implementation-related factors that might yield to experimentation. These factors all involve selecting the best operational or implementation characteristics including

- Architectural design [B009, A052],

- Implementation approaches for different models (e.g., object-oriented design) [A021],
- Implementation approaches to achieve particular purposes [A021],
- Implementation languages [A052], and
- Computational styles [A052].

Dr. Pace indicated that no information exists beyond people's direct experiences and prejudices in making these (and other) implementation-related decisions [A021]. These are areas where we need to make progress. He described a study of a large number of basic science codes that discovered approximately 10 significant errors per thousand lines of code. This same study found that a FORTRAN implementation required two times the number of lines of code than the same implementation in C. He said that the simulation community has not performed similar studies [A052].

Conceptual Model Specification

Mr. Waite reminded us that the problem of specifying simulation conceptual models has not been solved yet [A053, B009]. He believed that the solution to this problem could help to regularize the practice and processes associated with simulation [A115].

Building Comprehensible Simulations

Dr. Davis suggested that we needed to build comprehensible models and simulations and that we do not currently know how to do that very well. Further, we do not verify any observations related to comprehensible simulations through controlled experiments [A096].

Dependencies between Representation & Implementation

Dr. Numrich asserted that we do not sufficiently understand the dependencies between a simulation's content, its models and the infrastructure through which it is implemented [A011]. These aspects are not independent although they are sometimes treated that way.

**Need for Quality Data**

Mr. Gross observed that the lack of available data describing the behavior of simulation phenomena plagues the growth of a simulation science. He said, "In astronomy, anyone can look up at the stars. We don't have the data through which to nose around [A095]." This critical situation prevents the simulation community from devising meaningful hypotheses to test experimentally [B013]. He noted that the random number generator people tended to publish their generators or, at least, the numbers that their generators produced. These publications enable other people to test their results independently. He knows that many reasons exist for the absence of observations of simulation phenomena in the public domain but, despite these, the situation must be remedied somehow [A097].

He recommended that people could publish in many different ways but that he did not want to see what they thought they should have done but rather what they really did. Software processes often document what people are supposed to do and that is not what they really do. He recognizes that the literature contains many publications describing the right way to build a simulation. Unfortunately, very few of those publications reinforce their pronouncements with actual data. He reiterated that he wants what people

actually do and not their conjectures about the best way to do it [A106]. Dr. Davis concurred by saying that people have published lots of wonderful stuff in artificial intelligence but they are usually dealing with toy problems. They may have even applied their techniques to real problems only to find that these techniques do not work but they do not publish those failures. The same situation applies to simulation [A107].

Mr. Gross also cited the example of the distributed simulation community's current movement toward standardizing a conceptual model. He feared that this effort would draft a standard, pass it through the SISO standards process then proclaim that standard as the right way to formulate a conceptual model when people had only applied that standard to only one or two cases. Mr. Gross believes that we could make significant progress in simulation if we can get a large number of quality observations. The conceptual model situation offers an opportunity. He proposed that we should ask a thousand people to build simulation conceptual models then we could standardize on what they actually did [A108]. Mr. Waite cautioned that we must be careful about what people say they do and what they actually do. He asserted that we do not want to legislate what people have actually been doing wrong [A109]. Mr. Gross agreed that that situation represented the other side of the problem [A110].

**Ways to Collect Data**

The workshop participants recommended two mechanisms through which to collect data on simulation phenomena:

- Lessons learned workshops/conferences
- Simulation design competitions

These suggestions provided concrete recommendations for how the experimental exploration of simulation phenomena might proceed.

Lessons Learned Conferences

Mr. Gross and Dr. Davis suggested that Mr. Lunceford should sponsor a workshop at which people could present their lessons learned, perhaps from the Millennium Challenge 2002 experience [A097, A098] (see bibliography Ref. [253] for more information on the MC02 exercise). Dr. Davis suggested that Mr. Lunceford might want to obscure the exact source of information to protect the commercial interests in a way similar to that used by the social science people when they perform their surveys [A098]. Mr. Gross expressed nervousness about the social science analogy but supported the general idea [A099].

Mr. Lunceford explained that the MC02 exercise would be held in a couple of weeks (from the workshop date). This large-scale simulation exercise involves 59 different federates in the core and has experimentation as its purpose [A116]. Mr. Harmon remarked that these experiments explored military force structures rather than the nature of simulation explicitly [A117]. Mr. Lunceford continued to describe that this exercise was part of J9's examination of the DoD transformation. It is a very large simulation and looks as if it will work. He asked, "If I were going to have ten people come in and tell us about their little piece then what would be the ten papers that would tell us what they

actually did [A118]?" He believed that the successes of MC02 would produce a significant body of knowledge but was uncertain that the technical lessons learned would be documented for the simulation community at large [B016]. He recognized that a workshop on MC02 provided a unique opportunity to formally document the considerable knowledge gained and that this sort of exercise would be done again [A120].

The participants made several suggestions regarding this idea. Mr. Waite wanted information on how they built their conceptual models and what the implications of those choices were [A119]. He also wanted to know about how their system integration effort did and did not work and what they would do differently the next time [A125]. Dr. Numrich suggested that we wanted to ask the people who built the tools for their lessons learned because the tools were constructed to help people understand the inner workings of the simulation [A121, B017]. Mr. Lunceford added that he wanted information on what people had to do to make the multi-cast groups work [A122]. Prof. Swartout desired to see a paper from the people concerned with the reorganizing question. This paper should address how that question influenced the conceptual modeling and design of the system as well as how it changed their approach [A126].

Mr. Lunceford believed that people would present many briefings on MC02 but that most of those would not contribute to understanding the science of simulation. The part that those briefings will miss is what was actually done to achieve their successes and what failures they encountered [A128]. He wants to get the people who actually built the simulation to participate in this workshop [A124]. Dr. Davis added that the true story would be a lot more ugly but interesting [A127]. Dr. Pace concurred that MC02 did provide a unique opportunity to collect the data we desire [A129]. Mr. Lunceford felt that Mr. Steve Moore might be the right person to contact about this. He feared that this exercise might be too close and that planning for the next one might provide the opportunity to instrument the actual exercise better [A130]. Dr. Numrich suggested that Mr. Tony Cerri could "point to all the nits in the geek world [A131]." Mr. Waite emphasized the importance of structuring the question, a set of ideas and the feedback that we wanted [A132]. Mr. Lunceford concluded by recommending that we do a peer-reviewed conference on MC02. The peer-review process brings a higher quality to the writing and having the conference gives people the impetus to write their paper. SCS may or may not provide the right forum. He felt that we could get J7 to run the conference because they would gain the most from it [A133].

Simulation Competitions

In another attempt to get data about simulation phenomena, Mr. Gross suggested that we get a bunch of graduate students to generate lots of data for us [A095] (see bibliography Ref. [355] for a link to another simulation competition). He proposed a model competition where we asked the competitors to develop models of the same phenomena. We could then pick one as a winner and award a cash prize. This competition would provide about one thousand models that we could then analyze [A099, B013]. Mr. Lunceford said that the competitors do not actually need to implement the model [A100]. Mr. Waite agreed that the conceptual models were all we needed [A101]. Mr. Gross tentatively concurred with having only conceptual models submitted. He thought that the

subject simuland could be the Chunnel or some accessible mechanism such as that [A102]. Mr. Lunceford felt that we needed to pick some phenomenon that one could actually measure in the real world [A103].

Mr. Gross recommended that we might want to ask for measures of merit that represented the simulation and see what the competitors provided. That could give us a body of observations that might lead to stronger hypotheses that could then be tested more rigorously. He observed that there are 89 industrial engineering departments that teach simulation. All of these represent potential sources of competitors and that does not include the computer science departments that teach simulation courses. These seem like good resources from which to get a common body of observations [A104].

Dr. Whelan inquired about the expected cost of such a competition and Mr. Gross replied that we could offer a $10K scholarship [A134, A135, B013]. Mr. Waite estimate that organizing and managing such a competition would require two to three man-years of effort so the amount of the prize constituted a small part of the total cost [A136, B013]. Dr. Numrich asked if a university could provide the required labor [A137]. Mr. Gross suggested that we could either seek help from SCS or from an interested graduate school [A138]. Mr. Waite noted that the solicitation is only one facet of such a competition. Another is constructing the event. He believed that such an event was both of value and within scope [A140].

Mr. Lunceford recounted his experience with trying to organize a computer generated forces (CGF) competition, like the robo-soccer competition. He approached the Institute for Creative Technologies and discovered some practical problems with the idea but those could be overcome [A139] (see bibliography Ref. [352] for more information on ICT). With this competition, he hoped to stimulate the university community to build CGF simulations. He admitted to one fear about the idea. Any such competition might generate 100-200 representations and that quantity may take five years to analyze. But, he believed that that quantity might be necessary to ensure a sufficient number of entries with a high enough quality to be interesting. Further, people needed to believe they had a chance to win [A141].

Prof. Swartout mentioned that a couple of different versions of robo-soccer currently existed. One of these actually involved real robots. The other stages the matches completely in simulation. Part of the cost of the simulation version lies in constructing the soccer simulation that everyone uses in their development and competition activities. He advised that that cost must be factored into our estimates. Finding this common base for the idea makes the competition more manageable and insures more consistent data [A142]. Mr. Harmon asked if we could use the existing robo-soccer simulation environment. He suggested that that could provide the needed infrastructure and was probably pretty stable [A143]. Mr. Lunceford suggested that we could use the Chunnel idea or build upon something that uses a commercial simulation product like SimCity [A144] (see bibliography Ref. [371] for more information on SimCity).

Mr. Gross suggested that we did not really need to pick a winner of this competition. We could give several $100 merit awards issued by DMSO. That would be a big thing to a graduate student because it represents something to add to their resume [A145]. Dr. Davis asked when science was ever advanced by a competition. He felt that it sounded

wrong [A146]. Mr. Waite responded that the British held a competition for an accurate clock for ship navigation. That competition had a terrific impact upon the advance of science and technology [A147].

## CONCLUSIONS

The participants did not agree that simulation could be a science but they did identify several areas of fundamental knowledge the uniquely represented simulation. These areas included

- Managing simulated time and events,
- Conceptual modeling,
- Abstraction and representation, and
- Correspondence with the simuland.

A few of the participants also identified several islands of prior work that demonstrated applying the scientific approach to understanding simulation fundamentals. Finally, the participants recognized the need for quality data from which people could formulate theories about simulation and recommended two specific activities that could supply that data:

- Lessons learned conferences, and
- Simulation competitions.

These activities could create considerable data about various aspects of simulation phenomena ranging from the observations of actual practice to conceptual modeling and abstraction.

# Session 6 – Workshop Recommendations

The purpose of this session was to formulate recommendations for actions resulting from the discussions in the previous working sessions. Dr. Numrich introduced the session by strongly emphasizing that we needed to continue the dialog about the body of knowledge for modeling and simulation. She believed that defining how to make this information available to the simulation community was equally as important [B001].

The participants then proceeded to cover several topics including

- Attributes of a science,
- Capturing core knowledge,
- Existing problems with simulation,
- Validated theory, and
- Need for data on simulation behavior.

Dr. Numrich summarized by elucidating the recommendations that we had touched upon in our discussions.

## ATTRIBUTES OF SCIENCE

Dr. Whelan and Mr. Waite interacted briefly about the nature of science. Dr. Whelan said that science focuses upon simplifying knowledge about the real world. He suggested that we needed to strive to simplify the knowledge about modeling and simulation [B012]. Mr. Waite replied that we must work to make our knowledge as simple as necessary but no more. He said, "Boiling anything down too far results in nothing [B013]."

## CAPTURING CORE KNOWLEDGE

The participants identified several ways to capture and distribute the core knowledge of simulation:

- Taxonomy of existing simulation literature,
- Professional certification,
- Monograph series,
- Reviews of simulation journal,
- Recommended reading list, and
- Lexicon.

These topics all represent the means to contain simulation's core knowledge or the means to build and stabilize that core knowledge.

### Taxonomy of Existing Simulation Literature

Mr. Lunceford noted that, as Dr. Page indicated, considerable literature, and accompanying knowledge, exists about random number generators, among other things,

that support simulation. However, most of this knowledge has uses in addition to simulation by itself. Most of Dr. Page's list of well-covered topics comes primarily from computer science and as we move away from that core of more broadly useful knowledge, the available literature gets thinner [A073]. Mr. Gross asked, "But, within those boundaries, what is the literature?" He said that the literature bases on software engineering and program management are also broad and well populated [A074]. Mr. Waite responded that we must accept the fact that most of the knowledge related to simulation also relates to other areas as well [A075]. Mr. Harmon suggested, "We must go out and determine what is there otherwise we cannot make that statement [A076]." Mr. Waite replied that we tended to weight technical papers as significant. He recommended that we should assemble a topical list for simulation and a relationship diagram of those topics [A077]. Mr. Harmon agreed but cautioned that we cannot now make such a list [A078]. Mr. Waite continued to say that we should build a topical taxonomy of simulation and that would be hugely useful [A079]. Mr. Gross interjected that he had presented such a taxonomy in his position paper as a starting point. He said that the science of simulation is a narrow branch of that taxonomy and that not much has been written on it. He opined that we could not have much success influencing the peripheral areas that we discussed (e.g., software and systems engineering, program management) [A080].

**Professional Certification**

Mr. Gross indicated that we ought to take advantage of the ongoing efforts to establish professional certification for simulation (see bibliography Ref. [347] for more information on the effort to develop certification of simulation professionals). He believed that people might not have good knowledge of those efforts [A066]. Mr. Lunceford responded that he did not believe that the current efforts would contribute much to what the field needs. He did think that someone needs to do something in that area but he did not like what the current effort has produced so far [A067]. Mr. Gross replied that we should then identify specifically what we do not like of what they have done [A068]. Mr. Lunceford replied that he wants to be able to attach some level of proficiency to an individual with a certification. This would reduce the number of things about which he must worry. In this way, the certification levels would actually mean something. He understands that the current certification efforts will not produce the equivalent to professional engineer certifications. In that case, the certification associates a certain level of working knowledge, gauged by certification tests, with a level of experience and understanding of the field. He wondered how the current people working on certification for simulation could be forced to do something that has explicit meaning [A069]. Mr. Waite responded, "That's the objective [of the current effort]. The problem is [their] getting started." [A070]. Mr. Harmon agreed that we should learn more about what has already been done in this area [A072]. Mr. Waite agreed to send the workshop participants information about the simulation professional certification program [A071].

**Monograph Series**

Dr. Pace and Mr. Waite proposed developing a series of monographs that captured the fundamental knowledge and best practices of modeling and simulation (see Dr. Pace's description of this series in the supplementary material). They recommended that this

series should document the core body of knowledge that a journeyman would need to be proficient in modeling and simulation. Each book would also contain a threaded tutorial of its topic [A001, B005]. Dr. Numrich noted that those with experience in the field could use a survey of a topic while those inexperienced people needed a tutorial [A011]. Dr. Pace indicated that this series would consist of six to ten volumes and that each volume would address topics large enough to serve as the text for an undergraduate course on the topic [A001, B003, A002]. Mr. Waite offered that this series would be analogous to the Military Handbook on Infrared Technology [bibliography Ref. [323]). Dr. Davis concurred that enough material exists in the field to warrant such a series [B002]. Dr. Pace suggested that this series could be packaged as a CD, as well as a printed form, to increase its accessibility [B003].

Mr. Waite expressed the frustration that they are having trouble getting this idea started [A002, A006]. Mr. Lunceford suggested that someone could pay people, such as those participating in the Millennium Challenge 2002 exercise (see bibliography Ref. [253] for more information on the MC02 program), to document the best practices they executed. These could then be peer-reviewed to insure their quality. This would establish an informal beginning that could then be advanced toward more formality. This approach might lead to identifying the right people to author these books. After that, we could interest a publication house [A003]. Mr. Waite expressed the concern that then the publication houses would own the product. He strongly believed that the modeling and simulation community must own this series because the content is so important to the evolution of the industry [A004, B004].

Dr. Page cautioned that any definitive work like that suggested must consider the breadth of the existing literature in the field (bibliography Sections I.A-E provide some insight into this existing literature base). He suggested that we could identify where that literature was deficient then enlist authors to address those areas and have them publish their work in an appropriate journal. This approach would grow the needed information within the existing literature base, a body of literature that will necessarily be diverse. Dr. Page further suggested that we worry about packaging the material as a CD later [A007, A009]. Mr. Waite countered that that approach would not deliver the needed story line and consistency. He felt that only a single coherent body could produce this series in order to center upon the enterprise [A008]. He warned, "A coherent body of description will not come together by itself. This product must be designed and built intentionally [A010]." Dr. Page mentioned that a book called the Handbook of Simulation already exists [A013] (bibliography Ref. [005]). Mr. Waite replied that that was not what the field needs. He said, "It's just a bunch of stuff slapped together [A014]."

Dr. Pace summarized that this suggestion would squarely address the problem of making the modeling and simulation workforce more competent and that it would take three to six months per volume. With the proper funding, an initial set could be completed within one year. This would capture the current knowledge and give those concerned with improving the workforce something upon which to build. It would also give the academic community the material upon which to build M&S courses. "But, " he warned, "I cannot see this getting done without help [A012, B005]." Mr. Waite asserted that we

must establish a program to find funding for this effort. He indicated that the program plan for the effort could be formulated within a month [A006].

**Reviews Journal**

Dr. Davis suggested establishing a parallel with the Reviews of Modern Physics for simulation since nothing currently exists as a vehicle for pulling work from various sources together [A020] (see bibliography Ref. [381] for more information on the Reviews of Modern Physics). Prof. Swartout added that such a journal would provide high quality opinionated survey articles [A021]. Dr. Davis remarked that much of the literature in simulation barely reaches journal quality [A022]. Mr. Waite concurred that this idea could meet a present need but that the real problem was how to make it happen. He said that SCS would be delighted to have such a journal but no one knew how to do it [A023] (see bibliography Ref. [351] for more information on SCS).

**Recommended Reading List**

Mr. Gross, Dr. Numrich and Mr. Lunceford all believed that the field needs a list of books with which simulation people should be familiar, a recommended reading list [A040, A042, A043, B015]. Mr. Lunceford suggested that one of the actions coming from this workshop might be the recommendation to assemble and publish such a list, one representing all manner of technical publications, on a website for the modeling and simulation community. This could be the first step toward accumulating a common body of modeling and simulation knowledge [B011]. He felt that such a list could help to focus someone interested in learning about different aspects of simulation and steer them away from poor quality literature [A045].

Mr. Waite opposed the idea of recommending any reading because such a list would appear to endorse specific resources [A041, A044, A046]. Mr. Lunceford did not see the problem with suggesting a reading list [A047]. Mr. Waite suggested that telling people the contents of the desired knowledge (as a monograph series would) would be best. He said, "We should tell people what they need to know [A048]." To this, Mr. Lunceford expressed the concern about separating the wheat from the chaff in doing that, partitioning the good and helpful literature from the bad and misleading literature [A049]. Dr. Swartout added that in the process of writing a survey article or monograph, one must decide what to include and exclude in the citations. He did not see the difference between the results of that decision process and one that provides a recommended reading list [A050]. Mr. Waite emphasized that any solution that only gives references, such as a reading list, overlooks the essential story [A051]. Prof. Swartout responded with a suggestion to annotate the reading list so that it describes this story along with providing other important information [A052]. Mr. Waite agreed that that was essential and recommended that we must advertise the domains of competency [A053].

Mr. Lunceford wanted to know what needed to be done to get started within six to nine months. He suggested that we might need to bundle some material from a set of journals [A054]. Prof. Swartout recommended that an incremental approach might exist (e.g., a website summarizing the key topical areas that could grows with the addition of knowledge) [A055]. Mr. Gross remarked that that is a recommended reading list [A056].

Dr. Numrich added that partial solutions are always better than no solution. She suggested that we must give examples of where to get needed knowledge [A057].

### Lexicon

Mr. Lunceford contributed another topic for discussion, a simulation lexicon. He commented that other sciences and professions appear to have a consistent vocabulary. It seems that simulation people use words differently. He asked if it was time to start stabilizing the vocabulary used to describe simulation [A087, B017, A096]. Prof. Swartout asserted that the vocabulary is an artifact of the maturity of the field. He said, "It's analogous to our confusion in other fields." Simulation encompasses some concepts upon which we can agree and those establish the basis for a stable vocabulary. Simulation also encompasses emerging concepts, the meanings upon which we do not agree. However, he agreed that we needed to start building a consistent vocabulary [A088]. Mr. Lunceford suggested that everyone would have a definition for a simulation engine. The problem is that those definitions will not agree [A089]. Mr. Gross suggested that we should use a peer-review process to build a consistent vocabulary and agreed that we need a glossary of simulation terms [A090, A092]. The following discussion pointed out that a number of glossaries of simulation terms already exist (e.g., DoD Glossary of Modeling and Simulation, BMDO Glossary of Modeling and Simulation). These existing works have varying degrees of utility [A093, A095] (see bibliography Ref. [331] for access to the DoD M&S Glossary). Mr. Waite agreed that we must institute a broad process for improving the syntactics and semantics of simulation but that was a hard job [A095, A101]. He continued that we should post a position and look for a way to get started [A097]. Dr. Pace cautioned that much more diversity exists in simulation outside that considered by the defense community. He suggested that we might only be able to address the lexicon used within the defense community [A098]. Mr. Lunceford disagreed with keeping the focus upon the defense community. He wants simulation terms to have the same meanings throughout the entire universe although multiple definitions may be necessary in some cases [A099]. Prof. Swartout encouraged that if we built something useful then people would use it [A100].

## EXISTING PROBLEMS WITH SIMULATION

In an endeavor to understand more about the fundamental knowledge required to build successful simulations, Mr. Gross inquired about the difficulties encountered in building WARSIM [A082] (see bibliography Ref. [366] for more information on the WARSIM program). Mr. Lunceford responded that the major problems arose because our schools do not train computer scientists to be system thinkers. He said, "We need a system guy to build such big complex systems [as WARSIM] and they typically do not understand how to build simulations [A083]." Dr. Numrich added, "On any given day, you want to represent the universe." To which Mr. Lunceford responded, "No. On any given day, the developer wants me to represent the universe." He added that he did not believe that these developers understood how to build simulation engines [A085]. Mr. Waite continued that multiple problems caused our current dilemma [A086]. Mr. Lunceford concurred and added that we also did not understand how to translate user requirements [A087].

## VALIDATED THEORY

Mr. Harmon noted that a body of theory related to simulation does exist but that that theory might not have been validated by experiment. He asked if any of the participants knew what theory had been confirmed through actual practice and how well it had been confirmed [A060, A062]. Dr. Pace remarked that people have built some simulations from theory but that no one had identified the benefits of using one theory over another or over using none at all [A061]. He continued to say that the issue is not does using theory work but rather how well does it work [A063]. Mr. Harmon asked, "What is the scope of existing theories about simulation; where do those theories agree and where do they conflict [A064]?" Mr. Gross responded that he does not know if the existing theories could be validated [A065].

## NEED FOR DATA ON SIMULATIONS

Mr. Harmon, Mr. Gross and Dr. Davis all agreed that, from a scientific perspective, the community needs more visible data through which to discern the fundamental nature of simulation and that this data is not now available thereby creating a data-poor situation [A015, B006, A016, A024]. For example, we do not understand the issue of fidelity very well [A018]. Dr. Davis noted that some of this data could be obtained experimentally and some would be experiential in nature [A024]. He suggested that we could plan a couple of conferences to provide forums for making such data available through the conference proceedings. He concurred with Mr. Lunceford that we could start with after-action reports from MC02 (see bibliography Ref. [253] for more information on the MC02 exercise). These conferences could also help to define what deficiencies existed [A024, B008]. Mr. Harmon suggested that one or more workshops would be a better idea than conferences since they would be less formal but that we also need another mechanism, like a group of people going out and collecting available data. He lamented that the modeling and simulation community did not have any instrumentation for collecting data, the equivalent to the telescope for the astronomy community [A025]. Dr. Davis suggested that the Internet is a sort of a telescope in that it facilitates running other people's computer programs [A026]. Mr. Harmon replied that the Internet corresponds to the glass for lenses but is not, in itself, a telescope and added that with the proper instrumentation we would get better data and understand the nature of the errors in that data better [A027]. Mr. Gross agreed and offered that the recent notions of fidelity provide that [A028] (see bibliography Section I.D.1 for references to this simulation fidelity work). Mr. Harmon asserted that that fidelity work identified what to measure but does not make the actual measurements. He asked if anything already exists [A029].

Dr. Page believed that a myriad of textbooks and journals report much data in some areas (see bibliography Sections I.A-E for some of this literature base). He cautioned that we needed to be careful about complaining about what we do not have [A017, A030]. He continued that hundreds of publications exist that address the nature of modeling and simulation [B007]. Mr. Gross agreed that many publications on modeling and simulation exist but that they are all in the assertion realm. He was not convinced that much real data does exist [A019]. However, he agreed with Dr. Page that data is available for some narrow areas (e.g., random number generators, event list management) [A031]. Dr. Numrich asked if data is available describing how something works when implemented

in simulation [A032]. Mr. Gross replied, "No [A033]." Dr. Page countered that we must embed random number generators into simulation and that some researchers have done specific exercises to measure the effects they have. He continued that a large body of literature exists describing that area and such areas as event lists and multicast groups [A034]. Mr. Lunceford suggested picking a couple of these areas and exploring the literature base to see what prior data really does exist [A035]. Dr. Page volunteered to recommend a list of relevant textbooks (bibliography Sections IA-B) and conference proceedings (bibliography Section III.B). He wants to be sure that we understand the limits of the existing literature base before organizing another conference [A037]. Mr. Harmon agreed with that sentiment [A038].

## CONCLUSIONS

Dr. Numrich summarized the proceedings of the session. She broke our ruminations and recommendations into advancing our basic understanding, bringing a concrete understanding together, and addressing the need to experiment and deal with the matter of simulation. With regard to advancing our basic understanding we needed to

- Build a list of relevant conferences, textbooks and papers that provide a basic understanding of simulation, and
- Develop a set of books that contained both tutorials and surveys of simulation topics.

Regarding bringing a concrete understanding of simulation together, we need a

- Journal similar to the Reviews of Modern Physics that publishes high quality survey articles, and a
- Lexicon of simulation.

With regard to addressing the need to experiment and deal with the matter of simulation, we need to

- Sponsor a specialized conference, beginning with one capturing the lessons learned from MC02,
- Identify what data the existing literature can provide that tells us more about the nature of simulation,
- Spur the university community to perform experiments and observations and publish their data in forms accessible to a broad community of researchers,
- Understand the nature and needs of a modeling and simulation profession, and
- Explore the current effort to define a program for certifying simulation professionals (e.g., at NTSA) (see bibliography Ref. [348] for more information on NTSA).

# SUPPLEMENTARY MATERIAL

This section serves several purposes. It effectively collects information related to the workshop topics that could not be easily integrated into main sections of the final report. The participants supplied much of this information after the appropriate sections of the final report were completed. This section also contains discussion from participants who wanted to emphasize their differences of the positions described in the report narratives and conclusions.

Including information in this section should not diminish its importance to the results of the workshop but rather should enhance its importance because people took the considerable trouble to add it. Its inclusion in the other sections was just impractical.

## Additional Information on the Simulation Body of Knowledge

Mr. Larry Alexander recommended the following pointer to the website of professional certification and included an excerpt of some material describing the components of a core body of knowledge.

**Simulation Professional Certification Website:** http://www.simprofessional.org (Body of Knowledge - A 1997 study on What Makes a Modeling and Simulation Professional, organized and edited by Dr. Ralph Rogers, identifies core body of knowledge that anyone claiming to be a simulationist or holding a degree with simulation as part of its title should know to an appropriate level. This simulation core consists of an inner or foundation core grounded in a model-based discipline such as physics, engineering, human behavior, or biology. The other aspects of the inner-core include competency in the use of empirical based methodologies (i.e., statistics and experiment design) and competency in computer technology and computer science. The simulation and modeling outer-core consists of the three areas of discrete systems simulation, continuous systems simulation and real-time systems simulation. These three areas should be familiar and conceptually understood by a simulationist. The degree or depth of knowledge in each area will vary depending on the specialization and domain of the problems pursued, it is necessary that all simulationists receive sufficient education in these three areas to provide a common basis to facilitate communications, cooperation, and methodical exchanges within the diverse community.)

## Information on the Quality of Scientific Software

Dr. Dale Pace provided the following excerpt from the Proceedings of the 2002 Workshop on the Foundations of Validation and Verification:

**From W.L. Oberkampf**, **T.G. Trucano** & **C. Hirsch**, "Verification, Validation, and Predictive Capability in Computational Engineering and Physics," Proc. 2002 SCS Workshop on the Foundations of Validation and Verification, Laurel MD, 22-24 October 2002, np.

To the disbelief of many, a recent comprehensive analysis of the quality of scientific software by Hatton documented a dismal picture.[1] Hatton studied more than 100 scientific codes over a period of seven years using both static analysis and dynamic testing. The codes were submitted primarily by companies, but also by government agencies and universities from around the world. These codes covered 40 application areas, including graphics, nuclear engineering, mechanical engineering, chemical engineering, civil engineering, communications, databases, medical systems, and aerospace. Both safety-critical and non-safety-critical codes were comprehensively represented. All codes were. mature. in the sense that the codes were regularly used by their intended users, *i.e.*, the codes had been approved for production use. The total number of lines of code analyzed in Fortran 66 and 77 was 1.7 million, and the total number of lines analyzed in C was 1.4 million. As the major conclusion in his study, Hatton stated, .The T experiments suggest that the results of scientific calculations carried out by many software packages should be treated with the same measure of disbelief researchers have traditionally attached to the results of unconfirmed physical experiments. Hatton's conclusion is disappointing, but not at all surprising in our view. We also observe that both Stevenson [2] and Gustafson [3] strongly agree with Hatton's view that the problems uncovered by Hatton's static analysis experiments are basically independent of the programming language used.


[1] L. Hatton, The T Experiments: Errors in Scientific Software, IEEE Computational Science & Engineering, 4(2), 1997, pp27-38.

[2] D.E. Stevenson, A Critical Look at Quality in Large-Scale Simulations, Computing in Science and Engineering, 1(3), 1999, pp53-63.

[3] J. Gustafson, Computational Verifiability and Feasibility of the ASCI Program, IEEE Computational Science & Engineering, 5(1), 1998, pp36-45.


## Reference to the NIST Report on Software Testing

Dr. Dale Pace submitted the following summary of the NIST report on software testing to which he referred in the sessions:

From National Institute of Standards and Testing, The Economic Impacts of Inadequate Infrastructure for Software Testing, NIST Planning Report 02-3, National Institute of Standards and Testing, Gaithersburg MD, June 2002.

**Summary**

Electronic hardware and software are the two product categories driving knowledge-based economic growth. For decades, computer and communications equipment have been pacing information technologies (IT) with increases in speed and decreases in cost. Looking forward, software is assuming an increasingly dominant role as the driver of IT-based growth. Industry forecasts indicate that companies will allocate roughly half their IT budgets to software in order to leverage both the huge installed hardware base and new investment in computers and networks.

Virtually every business in the United States now depends on software for development, production, distribution, and after-sales support of products and services. Innovations in fields such as robotic manufacturing, nanotechnologies, and human genetics research all have been enabled by low cost computational and control capabilities supplied by computers and software. In 2000, total sales of software reached approximately $180 billion. Rapid growth has created a significant and high-paid workforce, with 697,000 employed as software engineers and an additional 585,000 as computer programmers.

Software, however, is as complex as it is unique. Few products of any type are shipped with such high levels of defects. In fact, the process of identifying and correcting defects during the software development process represents approximately 80 percent of development costs. Moreover, complexity is increasing. The size of software products is no longer measured in thousands of lines of code, but in millions. This greater complexity along with a decreasing average product life expectancy has increased the economic costs of errors. Software non-performance is expensive. The media is full of reports of the catastrophic impacts of software failure, but these high-profile incidents are only the tip of a pervasive pattern of failure that software developers and users both agree is causing substantial economic loss.

NIST engaged the Research Triangle Institute (RTI) to assess the cost to the U.S. economy of inadequate software testing infrastructure. Inadequate testing is defined as failure to identify and remove software bugs in real time. Over half of software bugs are currently not found until "downstream" in the development process leading to significant economic costs. RTI identified a set of quality attributes and used them to construct metrics for estimating the cost of an inadequate testing infrastructure. Two in depth case studies were conducted. In the manufacturing sector, transportation equipment industries were analyzed. Data were collected from software developers (CAD/CAM/CAE and product data management vendors) and from users (primarily automotive and aerospace companies). In the service sector, financial services were analyzed with data collected again from software developers (routers and switches, financial electronic data interchange, and clearinghouse) and from users (banks and credit unions).

**Table 1.** Costs of Inadequate Software Testing Infrastructure by Industry Group and the National Economy

| Industry Coverage | Cost of Inadequate Software Testing Infrastructure | Potential Portion of Cost Reduced (i.e., Economic Benefits) from Feasible Infrastructure Improvements |
|---|---|---|
| Transportation Equipment and Financial Services | $5.85 B | $2.10 B |
| U.S. Economy | $59.5 B | $22.2 B |

As indicated in Table 1, the annual cost to these two major industry groups from inadequate software infrastructure is estimated to be $5.85 billion. Similarities across industries with respect to software development and use and, in particular, software testing labor costs allowed a projection of the cost to the entire U.S. economy. Using the

per-employee impacts for the two case studies, an extrapolation to other manufacturing and service industries yields an approximate estimate of $59.5 billion as the annual cost to the nation of inadequate software testing infrastructure.

Thus, if all software bugs could be identified and remove instantly (in real time), the combined economic benefits to the two industry groups and to the economy would be $5.85 billion and $59.5 billion, respectively. Realizing that such a "perfect infrastructure" is not attainable, industry experts were asked for estimates of a plausible reduction in delayed identification and removal of software errors. From this information, a "feasible improved infrastructure" scenario was constructed. This improved infrastructure scenario is estimated to result in a combined annual benefit of $2.10 billion to the two industry groups studied and $22.2 billion to the U.S. economy.

The path to higher software quality is significantly improved software testing. Industry now spends more than $1 billion dollars per year on software testing tools and this expenditure is projected to reach $2.6 billion by 2004. Approximately 302,000 workers are engaged in testing and debugging activities, which represents approximately one-fourth of all computer programmers and software engineers.

However, testing methods have a strong infrastructure character because generally accepted (standardized) approaches must be used to assure buyers that higher quality levels have in fact been achieved. This requirement for common use (standards) coupled with shortening technology life cycles and subsequent pressures to get new generations of software into the market place ahead of competition lead to substantial underinvestment in the infratechnologies underlying software testing.

For example, the lack of quality metrics leads companies to simply count the number of defects that emerge when testing occurs. Few organizations engage in advanced testing techniques, such as forecasting field reliability based on test data and calculating defect density to benchmark the quality of their product against others. Such advanced methods are not readily available, fully proven, accompanied by test suites, and then accepted as industry standards. Standardized testing tools, suites, scripts, reference data, reference implementations, and metrics that have undergone a rigorous certification process would have a large impact on the inadequacies currently plaguing software markets.

The complete report can be accessed at

http://www.nist.gov/director/prog-ofc/report02-3.pdf

Alternatively, bound paper copies can be requested by email from dherbert@nist.gov (refer to the title or Planning Report 02-3)

## Additional Information on Simulation Education Opportunities

Dr. Randall Shumaker and Prof. Bernard Zeigler submitted additional information on their simulation education programs.

### UCF IST

From Dr. Randall Shumaker via Prof. Peter Kincaid:

UCF offers interdisciplinary graduate studies in modeling and simulation leading to master's and PhD degrees. The program provides students with a core body of knowledge in the fundamentals of modeling and simulation including discrete and continuous simulation, quantitative aspects of M&S, and human factors. M&S students should have a baccalaureate degree or previous graduate degree in fields such as engineering, psychology, computer science, or mathematics.

Once enrolled, students pick from any one of seven focus areas:

- Quantitative Aspects of Simulation
- Simulation Infrastructure
- Simulation Management
- Computer Visualization in M&S
- Simulation Modeling and Analysis
- Interactive Simulation/Intelligent Systems
- Human Systems in M&S

Core courses are supplemented by electives chosen by the student in consultation with his/her advisor and approved by the M&S faculty.

The master's program has both thesis and non-thesis options. The non-thesis option requires 36 hours of coursework, and the thesis option requires 30 hours (including six hours for thesis research).

Students will have opportunities to work with faculty and M&S professionals with access to a large array of research labs and other facilities. Such opportunities are invaluable enhancements to the courses taken by M&S students.

The program is administered by two coordinators, one from the College of Arts and Sciences and one from the College of Engineering and Computer Science. For enrollment, curricula and other information, contact:

Peter Kincaid
407-882-1330
pkincaid@ist.ucf.edu

Charles Reilly
407-823-5306
creilly@mail.ucf.edu

**UofA ACIMS**

From Prof. Bernard Zeigler:

The role of modeling and simulation in today's science, technology and education is of increasing importance. To foster basic research collaboration between academia, government agencies and industry, the discrete event modeling and simulation paradigm offers a comprehensive and sound foundation for research and development of combined natural and artificial systems.

Discrete Event System Specification (DEVS) is a systems theory-based formalism for modeling and simulation that offers a framework for analysis and design of today's complex systems. The tutorial starts with a presentation of basic DEVS concepts and the supporting mathematical system theory. This is followed by a review of the latest developments in concepts, methodology and applications.

A segment on DEVS-based modeling and simulation environments showcases efforts to provide comprehensive and effective tools to the working practitioner. A HLA-Compliant DEVS under development in the context of the DARPA ASTT project is highlighted.

Topics:

- Introduction to DEVS-based Modeling and Simulation
- Representation Uniqueness Properties of the DEVS formalism
- DEVS Framework for Modeling Analysis and Design
- Simulation Environments for DEVS-based Multi-formalism Modeling
- DEVS and GIS-based Synthetic Environments
- Automatic Conversion from ODE/PDEs to DEVS; Accuracy, Speedup
- High Level Modelling/High Performance Simulation in DEVS-C++/Java
- HLA-Compliant DEVS Simulation Environment
- DEVS-based Theory of Abstraction and Aggregation
- DEVS Applications in Multifaceted Systems
- DEVS and High Level Architecture

ECE 575: Object-Oriented Simulation/Discrete Event Models

CSE-591: Object-Oriented Modeling & Simulation (ASU)

ECE 473/573: Software Engineering Concepts

CSE 460/598: Software Analysis Design (ASU)

ECE 696B  Distributed Object Computing Environments (CORBA, DCOM, Java)

ECE 471 Object-Oriented Software Design

**UCF PhD PROGRAM**

From Prof. Peter Kincaid, UCF:

Program Requirements

In addition to UCF university-wide requirements for the doctorate, the Modeling and Simulation Ph.D. has the following requirements.  The interdisciplinary nature of the Modeling and Simulation necessitates additional course requirements and a larger and more varied doctoral committee.

Transfer Hours: The doctoral program will allow up to 30 credit hours to be transferred into the program, whether from UCF or another institution.

The program requires a minimum of 72 hours (beyond bachelor's degree) specified as follows:

- Required core courses (6 courses for 18 hrs)
- Restricted core courses (3 courses for 9 hrs)
- Research Seminar (no credit)
- Elective courses (10 courses for 30 hrs)
- Dissertation hours (minimum of 15 hrs)

Campus enrollment requirements:

1. Required enrollment for 9 SCH fall and spring, and 6 SCH in summer, before candidacy exam.
2. Enrollment in dissertation research only after passing candidacy exam.
3. Minimum enrollment for 3 SCH dissertation research each semester after being admitted to candidacy.
4. At least 6 hours must be taken in the College of Arts and Sciences and at least 6 hours must be taken in the College of Engineering and Computer Science.

Students who enter this program are in general expected to have an academic and/or work background which has prepared them in mathematics (introductory calculus and probability and statistics) and computer "literacy" including proficiency with word processing, spreadsheet, and database programs and preferably, familiarity with at least one higher order programming language (e.g., C++). Students with undergraduate degrees in engineering, computer science or mathematics will generally have this background. For students with less technical academic preparation, a core course, "Introduction to Quantitative Aspects of Modeling and Simulation" will prepare them to pursue several, but not all of the focus areas. For example, these students could pursue the Simulation Management or Human Systems focus areas, but would need a number of prerequisite courses in mathematics, statistics and computer science to pursue more technical focus areas such as Simulation Infrastructure. "Quantitative Aspects of M&S" has a math prerequisite of a one semester introduction to calculus course (e.g., MAC 2233, "Concepts of Calculus" or MAC 2241, "Calculus for Life Sciences").

The Interdisciplinary Core

The interdisciplinary Ph.D. program in Modeling and Simulation will have a core of courses and seminars. The core will consist of four required courses, and two restricted courses. These six core courses and a research seminar will provide an interdisciplinary framework for all students. In addition, students are required to take three of the seven focus area cornerstone courses. Teams of program faculty will teach these core courses. A brief description of the proposed core courses follows:

Required Core (4 courses for 12 hours)

SIM 5XXX Introduction to Modeling and Simulation: Introduction to the theory and practice of modeling and simulation with an emphasis on multidisciplinary scientific underpinnings. Led by one instructor augmented by a team.

SIM SXXX Introduction to Quantitative Aspects of Modeling and Simulation: An introduction to matrix algebra and high level programming languages and other discrete mathematics topics for the M&S student who does not have a strong background in these areas. Students who have this background may select an elective instead.

EIN 6258 Human Computer Interaction: Computer task analysis, human-computer design guidelines and history, usability testing, next generation user interfaces, human- virtual environment interaction.

SIM 6XXX Research Methods and Practicum: Project course in which interdisciplinary teams conduct and manage research projects on fundamental and applied issues in M&S.

Restricted Core (2 courses for 6 hours)

EIN 5255 Interactive Simulation: PR: Post-Baccalaureate status or C.I. Introduction to significant topics relative to the development and use of simulators for knowledge transfer in the technical environment.

or

EEL 5891 Continuous System Simulation I: PR: EEL 3657 or C.I. Use of state-space techniques, numerical integration, and CSSL programs. Laboratory assignments.

ESI 5531 Discrete Systems Simulation: PR: STA 3032. Methods for performing discrete systems simulation, including network modeling, will be treated.

or

ESI 6532 Object-oriented Simulation: Object-oriented modeling and development techniques for building large process-based discrete event simulation models. Concurrency in discrete event simulation. Object-oriented simulation environment.

Focus Area Cornerstone Courses (3 courses for 9 hours)

Ph.D. students take at least three of the following cornerstone courses:

- CAP 5725 Computer Graphics Systems I
- CDA 5530 Performance Models of Computers and Networks
- EIN 5108 The Environment of Technical Organizations
- EIN 5255 Interactive Simulation
- ESI 5531 Discrete Systems Simulation
- EXP5256 Human Factors I
- MAP 5117 Mathematical Modeling

Courses for the focus areas including the cornerstone courses are listed below. Cornerstone courses should be taken before the restricted electives are taken.

Focus Area: Quantitative Aspects of Simulation (minimum requirement of nine hours)

Cornerstone Course: MAP 5117 Mathematical Modeling

Restricted Electives:

- EML 6062 Boundary Element Methods
- EML 6067 Finite Element Methods I
- EML 6275 Computational Fluid Dynamics
- ESI 6217 Statistical Aspects of Digital Simulation
- ESI 6358 Decision Analysis
- ESI 6529 Advanced Systems Simulation
- ESI 6546 Process Simulation
- MAP 5385 Applied Numerical Mathematics
- MAP 5407 Applied Mathematics I
- MAP 5936 Splines and Data Splitting
- MAP 6118 Introduction to Nonlinear Dynamics
- MAP 6207 Optimization Theory
- MAP 6408 Applied Mathematics II
- MAP 6445 Approximation Techniques
- MAP 6465 Wavelets and Their Applications
- MAP 6520 Fractal Image Compression
- STA 5285 Stochastic Processes and Applied Probability Theory
- STA 6246 Linear Models

Focus Area: Simulation Infrastructure (minimum requirement of nine hours)

Cornerstone Course: CDA 5530 Performance Models of Computers and Networks

Restricted Electives:

- CDA 5106 Advanced Computer Architecture I
- CDA 5501 Computer Communications Networks Architecture
- CDA 6107 Advanced Computer Architecture II
- CDA 6108 Selected Topics in Computer Architecture
- COP 6615 Operating Systems Theory
- EEL 5708 High Performance Computer Architecture
- EEL 5762 Performance Analysis of Computer and Communication Systems
- EEL 5891 Continuous System Simulation I
- EEL 6878 Modeling and Artificial Intelligence

- EEL 6785 Computer Network Design
- EEL 6893 Continuous Systems Simulation II

Focus Area: Simulation Management (minimum requirement of nine hours)

Cornerstone Course: EIN 5108 The Environment of Technical Organizations

Restricted Electives:

- EEL 6887 Software Engineering Life-Cycle Control
- EIN 5117 Management Information Systems I
- EIN 5140 Project Engineering
- EIN 5381 Engineering Logistics
- EIN 6322 Engineering Management
- EIN 6339 Operations Engineering
- EIN 6357 Advanced Engineering Economic Analysis
- ESI 5316 Operations Research
- ESI 5318 Military Applications of Operations Research
- ESI 6358 Decision Analysis
- SIM/EIN 5XXX Simulation-based Acquisition I (being considered for development)
- SIM/EIN 6XXX Simulation-based Acquisition II (being considered for development)

Focus Area: Computer Visualization in M&S (minimum requirement of nine hours)

Cornerstone Course: CAP 5725 Computer Graphics Systems I

Restricted Electives:

- CAP 5415 Computer Vision
- CAP 6411 Computer Vision Systems
- CAP 6412 Advanced Computer Vision
- EEL 5771 Engineering Applications of Computer Graphics
- EEL 5820 Image Processing
- EEL 5874 Pattern Recognition
- EEL 6843 Machine Perception
- EIN 6252 Human-Virtual Environment Interaction
- EIN 6258 Human Computer Interaction
- EIN 6541 Advanced Human-Computer Interaction

Focus Area: Simulation Modeling and Analysis (minimum requirement of nine hours)

Cornerstone Course: ESI 5531 Discrete Systems Simulation

Restricted Electives:

- EIN 6524 Simulation Modeling Paradigms
- EEL 5891 Continuous System Simulation I
- EEL 6878 Modeling and Artificial Intelligence
- EEL 6893 Continuous System Simulation II
- ESI 6217 Statistical Aspects of Digital Simulation
- ESI 6247 Experimental Design and Taguchi Methods
- ESI 6529 Advanced Systems Simulation
- EIN 6529 Simulation Design and Analysis
- ESI 6532 Object-Oriented Simulation
- ESI 6546 Process Simulation

Focus Area: Interactive Simulation/Intelligent Systems (minimum requirement of nine hours)

Cornerstone Course: EIN 5255 Interactive Simulation

Restricted Electives:

- EEL 5874 Expert Systems and Knowledge Engineering
- EEL 6875 Engineering of Artificial Intelligence Systems
- EEL 6876 Current Topics in AI in Engineering Systems
- EEL 6895 Current Issues in Real-Time Simulation
- EIN 5251 Human-Computer Interaction: Usability Engineering
- EIN 5317 Training Systems Engineering
- EIN 5602 Expert Systems in Industrial Engineering
- EIN 6645 Modeling and Simulation of Real-Time Processes
- EIN 6647 Intelligent Simulation
- EIN 6649C Intelligent Tutoring Training System Design
- EIN 6946 Simulation Practicum
- TTE 6270 Intelligent Transportation Systems

Focus Area: Human Systems in M&S (minimum requirement of nine hours)

Cornerstone Course: EXP 5256 Human Factors I

Restricted Electives:

- EIN 5248C Ergonomics
- EIN 6215 System Safety Engineering and Management

- EIN 6252 Human-Virtual Environment Interaction
- EIN 6258 Human Computer Interaction
- EME 5051 Technologies of Instruction and Information Management
- EME 6457 Distributed Learning
- EME 6613 Instructional System Design
- EXP 5208 Sensation and Perception
- EXP 5257 Human Factors II
- EXP 5258 Human Factors III
- EXP 6255 Human Performance
- EXP 6506 Human Cognition and Learning
- EXP 6541 Advanced Human-Computer Interaction
- INP 6528 Human Computer Interaction Design
- INP 6215 Assessment Centers and Leadership
- INP 6317 Organizational Psychology and Motivation
- INP 6605 Training and Performance Appraisal
- PSY 6216 Advanced Research Methodology I
- EXP 6XXX Team Training (under consideration)
- PSY 6XXX Skill Acquisition, Learning and Training (under consideration)
- SIM 5XXX Simulation Approaches to Crisis Management (under consideration)

## Comments on the Existing Simulation Literature Base

Both Drs. Pace and Page submitted extensive bibliographies from which the workshop bibliography was constructed. They also included the following commentaries on the existing simulation literature base.

### DR. ERNEST PAGE

This is a very brief treatment of "prior art" in the area of simulation as science. I haven't tried to be comprehensive, and only a few aspects of an admittedly narrow slice of simulation—i.e. discrete event simulation from a computer science perspective—are touched on. Certainly, more thorough treatments are possible, if warranted.

PART I discusses a few areas of simulation where science (i.e. theory, hypothesis, experiment, proof) seems to have a foothold. PART II is a data dump viz. the potential "body of knowledge" for simulation.

**Part I -- Some Areas of Simulation Where Science May Be in Play…**

The righteous clubbing of computer science—as a science—notwithstanding, the field has a number of theories that *arguably* provide a scientific underpinning for a reasonable portion of the work in the field. For example, we have…

- Computability theory
- Algorithmic complexity theory
- Formal language theory

Each of these theories is sufficiently populated to fully occupy undergraduate and graduate courses. Many texts, and thousands of papers have been published in these areas, so any attempt to summarize will leave lots of information out. By way of introduction to those unfamiliar with these topics, I'll just say something very brief about each here. Apologies for oversimplifying.

Computability theory (see, for example: H.R. Lewis and C.H. Papadimitriou. *Elements of the Theory of Computation*, Prentice-Hall, 1981.) provides a framework for describing the sorts of things computers can be made to do. Turing's Halting Problem, for example, illustrates that are some problems for which no algorithm can be designed. The theory is based on a model of computation, the Turing Machine, that actually predates digital computers. There is a thesis (Church's Thesis) that the Turing machines, Lambda calculus and recursive functions are equally powerful, and each fully capture anything we may regard as "effectively calculable". Recent work (see: Mark Burgin. "How We Know What Technology Can Do", *Communications of the ACM*, 44(11):83-88, Nov. 2001.) argues that there are more powerful models of computation than the Turing Machine.

Algorithmic complexity theory (see, for example, T.H. Cormen et al., *Introduction to Algorithms*, MIT Press, 2001.) is related to computability theory. Algorithms may be classified according to their complexities (in terms of both space and time), for example, a bubble sort has a time complexity of $O(n^2)$. That is, as $n$ increases, the time it takes to sort a list of $n$ items increases approximately proportional to the square of $n$. Complexity theory has enabled the classification of problems into two large bins: efficiently solvable (the class P), and not-efficiently solvable (the class NP). For example, given an expression consisting of arbitrary set of Boolean clauses, the problem of determining whether or not an assignment of truth values to each clause exists such that the expression is true has been shown to be in the class NP. Therefore it is believed that the problem does not have an efficient (deterministic polynomial time) solution. It is believed, but not proven, that the class NP <> the class P. If it is eventually proven that P=NP, the satisfiability problem (and many, many others) will be known to have efficient solutions, and (very likely) the construction of the proof will provide the solution.

Formal language theory (see, for example, A. Meduna. *Automata and Languages: Theory and Application*, Springer-Verlag, 2000.) is also related to the previous two theories. Formal language theory describes the degree of "expressiveness" and "analyzability" of a formalism. For example, the theory allows us to illustrate that recursively enumerable languages are more expressive than context-sensitive languages, which are more expressive than context-free languages, which are more expressive than

regular languages (the Chomsky hierarchy). The theory also shows that these languages are "recognized", respectively, by Turing machines, linear bounded automata, pushdown automata, and finite automata.

Looking at simulation, from the perspective of computer science, there are a number of areas that have evolved over the past 40 years in a manner that seems somewhat scientific in nature…

- *Random number generation.* A reasonable entry point into this literature is the article by L'Ecuyer in *Handbook of Simulation*. The evolution of RNGs has been the result of theoretical investigation (considerations and theory as to the *form* of RNGs, e.g. the relationship of prime numbers to RNG discrepancies) and empirical evaluation (e.g. statistical and spectral examinations of the *output* of RNGs). This is not my area (by a long shot), but it would seem that we have evolved from RANDU through the disciplined efforts of researchers employing both theory and experiment over the past several decades. It may be worth asking L'Ecuyer, or other luminaries in the area, to comment on whether or not the evolution of RNGs has been via science, alchemy or other.
- *Simulation performance*. I see three primary areas where performance has been studied in simulation: (1) time flow mechanisms for discrete event – fixed-time vs. next-event; (2) efficient event list management; and (3) parallel discrete event simulation (PDES). The most notable work in (1) is due to Nance (Richard E. Nance. "On Time Flow Mechanisms for Discrete Event Simulations," *Management Science,* 18(1):59-73, September 1971.) He provides formal constructive proof and empirical results that describe conditions for which a fixed-time TFM outperforms next-event. I haven't followed the literature in category (2) very closely, but it leans on algorithmic complexity theory. I am most familiar with the work in category (3). A reasonable entry into this area is the article by Fujimoto in *Handbook of Simulation*, or the text by Fujimoto. Much of the "science" in PDES has involved quantifying the nature of optimistic vs. conservative synchronization mechanisms. A great deal of empirical work has been published here, and there are number of interesting theoretical results as well. For example, Lin (I think; I need to go thru my files at home; or maybe David Nicol can correct this) shows that there are conditions within which optimistic methods may arbitrarily outperform conservative methods, but there are no conditions for which the reverse is true.
- *Simulation analyzability*. Dating to the early 1980s, there have been a few efforts aimed at formally quantifying the nature of automated support for analyzing model representations. This work is grounded in computability and complexity theory and illustrates, for example, that: (1) no algorithm exists to determine if two model representations are functionally equivalent; (2) no algorithm exists to determine if a collection of models, when composed, will satisfy a set of objectives, and so forth. A reasonable entry point into this literature is the article by Page and Opper (E.H. Page and Jeffrey M. Opper. Observations on the Complexity of Composable Simulation, In: *Proceedings of the 1999 Winter Simulation Conference,* pp. 553-560, Phoenix, AZ, 5-8 December 1999.)

[Note: I've intentionally left out a discussion of general systems theory and DEVS here; Bernie Zeigler can obviously say much more about that than I can.]

**Part II -- Data Dump: Texts, Journals, Conferences…**

A *comprehensive* collection of pointers into the field of simulation is probably not possible, nor useful, absent a cadre of librarians to maintain it and navigate it. The sheer ubiquity of simulation within the scientific and engineering disciplines means that one might discover *n* conferences and workshops that deal with simulation and biology, and *m* articles written on the subject of simulation and industrial engineering, where *n* and *m* are seriously large numbers. I entered "simulation" into my Lycos search engine this afternoon and got 7,258,355 hits….

Similarly, any attempt to capture a *definitive* source of simulation knowledge would seem to be folly. Simulation is inexorably diffuse. One could no more capture its essence in a small (or reasonably small) collection of all-things-simulation than one could capture all-things-medicine.

[Editor's Note: The references attached to this section have been included in the workshop bibliography.]

**DR. DALE PACE**

This [response] has a some what different perspective than that provided by Dr. Page in his June 28th email. A few comments stimulated by that email first.

- There are, as Dr. Page noted, a significant number of M&S publications and his annotations on some of the books will be useful for many people. At the end of my material is the M&S bibliographic materials that I provide Scott shortly after the SimScience Workshop. As discussed below, I think that acceptable introductory materials exist, advanced materials on a few particular subjects (such as pseudo-random number generation) exist, and acceptable guidance for selected application areas exist, but some of the more advanced general material needed for M&S professionals are lacking.
- There are, as Dr. Page noted, some areas related to M&S in which serious scientific methods have been applied, and fundamental limitations to logical capabilities identified – but these areas which have been explored rigorously, though important in my perspective, do not provide general guidance needed for M&S professionals.

My perspective:

Introductory level M&S textbooks exist. A number of books address mathematical techniques of special pertinence to M&S (e.g., queuing theory), software engineering practices and techniques germane to computer simulation, and simulation techniques and examples in particular application areas (e.g., CFD), but there are a number of significant M&S topics which are not adequately addressed in the current M&S literature. Development of a coherent set of books that dealt with topics not well addressed in the current literature and filled the gap between introductory level M&S texts and advanced guidance for use of M&S in particular application areas could lay the foundation for more

rapid acceptance of the body of knowledge needed by all M&S professionals, facilitate development of additional M&S courses in academic curricula, and provide a preliminary set of best practices in a number of M&S areas. This material could enable the quality workforce needed by the Defense M&S community.

Simple economics keeps the coherent core set of books needed from existing. Lack of M&S courses in academia eliminates an identifiable market for the set. Without subsidy for development of the core set of books needed, it is unlikely that they will be produced in a timely manner and offered at prices that would ensure their widespread distribution and use. However, with subsidy, the needed material could be developed and offered in an inexpensive format (such as a CD) that would enable it to be priced low enough ($25 or less) that every M&S professional (even part-time ones and students as well as M&S managers) could be expected to own and use the set. If such a vision were to become a reality, it could have a profound and positive impact on the quality of the M&S workforce and the consistency of adherence to best practices (even if best practices are only defined informally initially).

The idea suggested here, as described at the SimScience Workshop, is relatively simple. First, identify key lacks in the M&S literature and create an outline of books needed (a general suggestion of topics is included in this proposal). Second, identify potential authors to write the books, and establish contracts with them to produce the books. Third, develop the material and then prepare it in an appropriate format for publication. Finally, publish the materials.

Material suggested for the coherent core set of M&S books is shown below. The items in bold are topics that present M&S books do not treat adequately. The other material exists in the current M&S literature, though it may not fully satisfy everyone. Material in brackets [ ] is explanatory.

1. Simulation Precursors
    - **a. Problem Formulation for M&S** [common and distinct elements of problem formulation for M&S as functions of M&S variety and application domain]
    - b. **Modeling (abstraction process for M&S pertaining to intended applications & simulation design)**
2. Simulation Design
    - **a. Guiding Documents for Simulation Design and Implementation** [objectives, requirements, conceptual models, specifications, VV&A reports, code, user and analyst guides, etc.]
    - b. Simulation Design Implementation Options [principles for selection of architecture, hardware/software/liveware operating environment, software language, time management approach, visualization, distributed simulation, parallel processing, etc.]
    - c. Simulation Techniques to be considered in Simulation Design [OOD, formal methods, mathematical algorithms, HBR, adaptive processing, stochastic considerations, etc.]

3. Simulation Implementation (pertinent aspects of software engineering)
4. **Simulation Assessment (VV&A)** [policy and procedures exist; technical V&V guidance is expected to result from the Foundations'02 V&V Workshop and would provide the basis for this item]
5. **Simulation Management** [general principles, resource estimation, SMEs and their use, how management varies with M&S size and application, common M&S management problems and possible solutions, etc.]

**Technical Challenge.** The challenge lies in finding appropriately qualified authors to prepare the material in a timely way who are willing to comply with editorial guidance for the material so that the set of books will be coherent and provide a solid foundation to support a quality M&S workforce.

**M&S Bibliographic Materials**

There are a number of textbooks on modeling and simulation (M&S): some of which are designed to support a single introductory course at the undergraduate level, and others deal with a particular aspect of simulation (such as random number generation or stochastic aspects).

There are a multitude of M&S related conferences (or portions of conferences), not only sponsored by simulation-focused professional societies (such as the Society of Modeling and Simulation, International, previous the Society for Computer Simulation) but also sponsored by larger discipline societies (such as the AIAA or IEEE). Proceedings from these conferences and M&S-related journals/publications contain thousands of papers and articles each year. A few of these employ standard peer-review/refereed processes for the materials which they publish; most do not.

My impression is that:

a) Many involved in M&S development, modification/maintenance, management, and/or use have limited awareness of much of the material in this literature, and there is not currently a convenient way to plumb its riches (efforts like the 1998 *Handbook of Simulation* to provide such have not penetrated the consciousness of the general M&S world or are not perceived as being what is needed in that regard).
b) In the absence of formal best practices (guides, standards, etc.) from the simulation-focused professional societies, such guidance is being developed as adjuncts to M&S application domains (such as the 1998 AIAA V&V Guide for CFD Simulations). While such can be very helpful, such guidance usually does not address aspects of M&S fundamentals, and the different communities may introduce approaches that will conflict with one another and create unnecessary problems when M&S applications cross community boundaries.
c) Appropriate best practices are functions of M&S application (size, focus, domain, etc.). Our failure to provide clear guidance in such contributes to some of the inappropriate ways that M&S are developed, managed, and used.

**Acknowledgment**

Many of the items listed below may be found in M&S resource lists of Dr. Hossein Arsham of the University of Baltimore

Not only are many books not included in this table, but also web-based book equivalents are not included (such as the information on discrete event simulation modeling available from Dr. Arsham's website: http://ubmail.ubalt.edu/~harsham/simulation/sim.htm).

## An Additional Taxonomy of Simulation

Prof. Bernard Zeigler noted that others have proposed taxonomies of simulation and provided the following references to some of that work.

T.I. Ören, "Model Behavior: Type, Taxonomy, Generation and Processing Techniques," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp3030-3035.

T.I. Ören, "Simulation and Model-Oriented Languages: Taxonomy," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp4303-4306.

T.I. Ören, "Simulation Methodology: Top-Down Approach," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp4319-4323.

T.I. Ören, "Simulation Models Symbolic Processing: Taxonomy," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp4377-4381.

T.I. Ören, "Simulation Models: Taxonomy," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp4381-4388.

T.I. Ören, "Simulation: Taxonomy," Systems and Control Encyclopedia, M.G. Singh (ed.), Pergamon Press, Oxford, England, 1987, pp4411-4414.

## Comments on the Reviews of Modeling and Simulation

Prof. Bernard Zeigler wished to respond to the recommendation that a Journal of the Reviews of Modeling and Simulation be instituted. He said, "My comment is that we have too many M&S journals and not enough M&S diligent readers. As [President] of SCS, I would be happy to accommodate new forums within our existing publications.

## Post-Workshop Discussion on Science & Simulation

Dr. Paul Davis and Prof. David Nicol responded to the workshop's emphasis on traditional science.

### DR. PAUL DAVIS SENDS:

Despite our short dispute about philosophy, I rather imagine that we agree on most or all issues when things are specified in enough detail. I was probably being unnecessarily grumpy. Nonetheless, as follow-up, here are a few items:

1. A single source on scientific-method debate is the collection of essays by Lakatos (or Lakatos and Imre). It has chapters by Kuhn, Lakatos, Imre, Feyerabend, Popper, and others. I loathe most deconstructionists, but I like essential features of Feyerabend, such

as his conclusion that "anything goes," rather than there being a canonical method to real science. This collection also includes an essay in which Kuhn grudgingly iterates his positions in response to the many criticisms of his original book. I've used this collection in classes as an economical way to cover material while bringing out debate. It didn't seem fair to ask students to read the full-length books by all of these folks.

2. Personally, I distinguish between: creative and discovery processes; the way in which scientific assertions are packaged for communication, critique, reproducibility, and potential falsification; and the routine science in which we measure things, calibrate theories, etc.

It IS fundamental to science that the packaged work be reproducible and falsifiable. Freud, Marx, and astrologers all fail on these matters (as do religions). However, those who rail about pseudo science often rail against other subjects without knowing much about them. A good example here is acupuncture, which often works and aspects of which are both reproducible and falsifiable. Other aspects appear to be bogus, but alchemy was also a mix of good stuff and bad, but it laid the foundation for chemistry. There is a great deal of good stuff in the mind-body research business as well, but all of that has been claimed to be pseudo science by folks who want things to be more tidy.

3. Why did I grumble about the scientific-method stuff? The reason is that premature emphasis on hypothesis-statement stuff can stifle discovery activity and creativity. It can impose a kind of bureaucratic pedantry that gets in the way of progress. I have recently seen military organizations, after being bludgeoned about not being scientific, create the viewgraphs to show that they are forming hypotheses, experimenting to test those hypotheses, etc. Sometimes, they pull it off ok, but other times they end up focusing on trivial stuff (which can be readily tested) rather than exploring the frontiers. Influenced by history, I believe that a good deal of experimentation should be just going out and trying things. When one should be more organized, then, yes there are methods. My cut at that for JFCOM is at http://www.rand.org/contact/personal/pdavis/davis.online.html.

**PROF. DAVID NICOL RESPONDS TO DR. DAVIS:**

In response to what he just wrote, I'll chime in that I agree. I had my own level of grumpiness on Weds., always asking for the experiment that would test the hypothesis. That's science. Became clear to me from what Dell said his motivation for this is, that a pristine "scientific" approach is uncalled for, and at the end of the day is not really going to inform. Remember the "Null Hypothesis" from statistics? That is the statement that is SO obviously wrong from one's intuition about a problem that data can overwhelmingly refute it. What is needed in Dell's domain is not the formal framework to provide the refutation, but the insights into the problem that allow one to get to the Null Hypothesis. And by that time you don't need the formalism...the sort of thing you all were offering as hypotheses _could be made quantifiable, but only by stretching or bending a point. The relationship between the sorts of things identified as important, and the sorts of things science is best at (e.g., what is the relationship between pressure and temperature) is to my mind kinda scant.

I think what we were looking for is more Engineering of Simulations than Science. Engineering can be about methodology, without the rigor of the scientific method.

Engineering practices grow up as a result of experience, and working methodologies are established without a scientific understanding of why they work.

I am reminded of a church in England that recently had to replace roof beams. Despite recommendations to use steel, they choose to go (again) with old oak, on the grounds that the oak beams they were replacing had stood up for 800 years and they weren't yet sure of the longevity of steel. I digress, it's past my bedtime.

### MR. SCOTT HARMON RESPONDS TO THESE REMARKS:

Despite the criticisms, I remain a stalwart advocate of a scientific approach to understanding the fundamentals of simulation. Dr. Davis has cited several examples of science gone wrong. But, in actuality, these are simply examples of people saying they are taking a scientific approach when they really neither believe in nor exercise its most fundamental tenets. These examples, in no way, support his assertion that applying scientific discipline to a field like simulation will inevitably go wrong. He again cites the instance of good alchemy leading to good chemistry as an example of exercising undisciplined discovery leading to good knowledge. A little research reveals that alchemy did not precede a systematic study of chemistry. In fact, the chemistry from which we benefit today evolved much more diffusely from such interests as metallurgy, ceramics and cooking, usually through carefully controlled experimentation. Alchemy refers to a very narrow area of chemistry where people strived to replace precious metals with less precious metals for profit. The success of alchemists depended upon the strength of their understanding of the current tests for precious metals. Unsuccessful attempts led to imprisonment or execution. My reading of this history suggests that good alchemists were most likely to have practiced good scientific inquiry because their very lives depended upon the veracity of their knowledge. The whole notion of alchemy as magic appears to have been fabricated by the alchemists themselves because they needed their customers to believe in the magic of their techniques. Successful alchemists practiced good chemistry but preferred to keep their knowledge secret to discourage copycats that might lead to their unmasking.

We should not be deterred from applying disciplined scientific inquiry to understand simulation by any of these arguments. On the same hand, we should not apply sloppy inquiry techniques, preferring to call them discovery or creativity or the like, because we are too lazy or unimaginative to leverage the power of the scientific method on this problem. Easier paths will only lead to weak foundations upon which the pillars the simulation knowledge will stand.

## Interactions on the Session Narratives

### DR. PAUL DAVIS SUGGESTS:

Dr. Davis made several suggestions for improving the session narratives. These suggestions seemed more rebuttals for the material in the narratives and have been included here so that Dr. Davis' position is better understood.

**Is It a Science Stuff.**

Suggestion: Minimize discussion of what attendees thought about simulation as a science. It will be read as angels-on-heads-of-pin stuff. I might suggest language something like:

"Participants disagreed (and individually had mixed emotions) about whether simulation was best seen as a separate science, a specialty within existing larger sciences, or a kind of engineering specialty. Possible analogies were made to software engineering on the one hand (not seen as a separate science) and to computer science and biophysics on the other (originally seen as mere specialty subjects, but now, arguably, seen as fields of their own). It was agreed, however, that expertise in simulation does require specialized study and that the contents of such specialty study can and should be identified. Those hiring simulation experts want to know that the hirees have had such education and training in best practices."

**Simulation as Science and Engineering.**

I'd suggest language such as "A serious student of simulation needs a grounding in fundamentals, which can reasonably be called simulation science, even though the content is only one treatment of topics important in other sciences as well (e.g., system theory, complex adaptive systems, representation theory, issues of man-machine interface...). Much of a simulationist's study should be analogous to other specialty work in engineering (e.g., learning how to design, build, and operate large simulations)."

**Rigorous Scientific Method, Rigorous Experimentation, Etc.**

You say "Little of the theory underlying simulation has been rigorously validated." The context is one of lamenting the paucity of "rigorously controlled experiments." Hmmm. I'm skeptical and believe that this puts the emphasis on the wrong syllable.

The kinds of theory represented in Bernie Zeigler's work, for example, is not "validated" by running "rigorously controlled experiments" but by checking consistency with aspects of math, logic, and system theory. Similarly, the notion that one can build a big federation of distributed simulations, but that the result may be incomprehensible or unreliable, can be fully understood from theoretical considerations without "rigorous validation." And similarly yet for the work I've done on the theory of multiresolution modeling. What is being referred to under the phrase "rigorous validation"?

So, I have two points: (1) many fundamentals do have a good basis, (2) the terminology of "controlled experimentation" seems to me odd in this context. In retrospect, I believe that the workshop itself suffered from their having been too much relative emphasis on the aspects of science and scientific method that correspond to rigorous experimentation associated with laboratory-science measurements. Other aspects of science and scientific method involve repeatability and generation of insights and clarity (both of which are highly relevant to simulation). Theory is crucial. My background is primarily as a theorist, so perhaps I am a bit biased here, but I don't believe so and I sure spent plenty of time in the laboratories (and, in more recent decades, actually building models).

But maybe I don't understand. Are you talking about social-science-like experiments, where one collects data from n efforts to build a military simulation with and without object-oriented modeling and programming, and then makes comparisons, concluding

that "object oriented methods" took 45.6% less time and led to 57.3% more reuse, on average?" If so, then, ok, experimentation is certainly important, but it's not because of the "rigorous measuring," but because some things can't be understood without "doing" them. What would be important would be learning when object-oriented modeling pays its way and when it gets in the way. That's not usefully discussed in aggregate statistics, even if "rigorous." The learning gets recorded in case histories, lore, and the movement through society of those with experience. Much of engineering is that way, and certainly much of "management science" is that way.

**Separate Profession.**

You say "Most believe that simulation can and should exist as a separate profession." I don't. I am skeptical about specialties, because they can turn into narrow, rigid crafts. Furthermore, I believe that the right person, whether degreed in physics, computer science, economics, or engineering, could become a sound simulationist with perhaps 2 years of study and hands-on work. Simulation wouldn't be his "profession." however. Yes, I believe that it would be useful to have some number of specialists, just as it is useful to have SOME real software engineers. But if I were asked to build a big new DoD model of something or other, I can't imagine that I would want a software engineer to be in charge unless he were also "substantive," genuinely interested in the subject matter and application, very good at man-machine interface issues, etc etc.

Bottom line: it would be a mistake to characterize the consensus as anything remotely like "Only 'professional simulationists,' as defined by a new discipline, should be building DoD simulations." Certifications, standards, etc. are all great, but that's something else again. As a by the way, when I think of some people who made really important contributions to simulation, I think, for example, of one chap who later won the Nobel Prize in economics, another who is a highly esteemed chemical physicist, and some folks at the Santa Fe institute, who are all scientists or mathematicians who would never think of themselves as "simulationists."

**MR. WILLIAM WAITE REPLIES TO DR. DAVIS:**

Thanks for copying. Concur almost entirely, and appreciate your efforts to address nuanced points that otherwise will surely be misinterpreted and troublesome. As to the prospective existence of a 'simulation profession', while we are of opposite persuasion to some degree, I expect that we agree more than not. My own notion is NOT that ALL simulation should be done by professional simulationists (any more than that all mathematics be done by professional mathematicians or that all programming be done by professional programmers) but that there be SOME professional simulationists who earn a living focused on the specialization and serve together with other specialists (mathematicians, systems engineers etc.) to be productive. That this is not the case is patent to me and inhibitive of my own selfish interests ...but then why else would I care? ;-). I think that any expressions to the effect that simulationists should exclusively develop (or control development of) DoD (or anybody else's) simulations is of course prima facie absurd. That such expressions (if not their concomitant well-considered and strongly held opinions) exist at all, arises not unexpectedly I believe out of the frustration that 'software developers' having been allowed to do so with dire consequences - typically

a case of overreaction to redress a perceived wrong. In any event I appreciate your thoughtfulness; and as I am anxious that the case for simulation professional specialization and industrial development be phrased precisely and therefore more appropriately and effectively, I am pleased to have been motivated to reconsider and re-express my own views by way of self-tutelage and practice.

**MR. HARMON RESPONDS TO DR. DAVIS:**

I've put so much into the "is it science?" because that was one of the three questions that Dell wanted us to answer. I felt that it deserved more than a one sentence reply (e.g., the participants didn't agree). I also wanted to fairly convey where the different positions on the issue stood. Did my encapsulation capture your position? If not then I'll need to work on that summary.

I'll look at the science and engineering discussion. My recollection is that it's pretty short and vanilla flavored. One problem that I had during the workshop was the loose way that people defined science. Frankly, I don't consider much of computer science, systems science, and complex adaptive systems science as real science. These communities use the word but don't what it really means or the value of that strict meaning. These are all fields in which I've participated actively and am pretty familiar with the work. I know that that's my personal opinion but I was one of the participants. However, I tried hard not to let that bias influence what I reported in the paper. If you perceived such a bias then please let me know and I'll reconsider the recount. But, give me a few hints of where to look.

Yes, I know well that you were disappointed by the emphasis on disciplined science. In retrospect, I agree that that caused us to waste some time. If I were to do this again, I would handle it differently. But, don't worry. This has been a fantastically unprofitable and unrewarding endeavor to my company and to me personally. I'll never grab for this gauntlet again. I can fight this battle in much more productive ways. Anyway, I need to get this paper done to get out from under the burden of this workshop and it's probably not the best place for us to argue this issue. You've, once again, made some very insightful comments and I'll include them in the supplementary section of the final report where I've collected other things of this sort. That's the best that I can do at this late hour.

On the statement about validating theory, actually Bernie made that statement and I nearly quoted him directly. Others made statements supportive of that (including David Gross and Dale Pace). I tried to draw much of this paper from what people actually said with one exception, what I said. I figured that the paper risked enough inadvertent bias from me to try to represent my personal position anywhere in it. But since you've opened this can of worms, my opinion of rigorous validation doesn't exclude careful observations. However, they must be confirmed by many many people. We all know the danger from one person, even reputable a scientist, making observations to confirm their theory (e.g., Martian canals). Controlled experiments are good but they may not be possible or practical. Good science can come from observations alone (e.g., modern cosmology). I thought that I made that pretty clear in my discussion of these possibilities but I'll revisit that section to be sure that I've made the point as even handedly as possible.

Yes, I know that you don't agree on the simulation profession issue but, really, most other participants did to varying degrees. I looked at the record very carefully. If we all agreed then I tried to use terms like "unanimously" and the like. I don't know of any better way to depict a majority, but not unanimous, position. If the group was truly in disagreement then I tried to represent the different sides (as in the science issue). That happened very little. I'd welcome any better ideas. But, as I said above, I'll capture your position in the supplementary material and be sure that people reading the final report know about that section, its contents and its importance. This overview paper is not the place to represent everyone's individual positions on every issue. I tried to capture those ideas on which most agreed even though I don't believe that good science comes from democracies. Your points about nonsimulationists making useful contributions is a good one and shouldn't be lost. I don't believe that I reported that anyone believed that only certified simulationists should be doing simulation, in DoD or other places. Did I?

**DR. DAVIS REPLIES TO MR. HARMON:**

As for "disciplined science," I think of good theoretical work as being highly disciplined, but not in the same sense as rigorous scientific experiments, such as that of Millikan or Michelson and Morley. It is not clear to me where the role for rigorous experimentation is in simulation research. I'm not against it; I'm just don't know what people have in mind. And I know that much of what can be done is amenable to theory with the requirements for transparency, reproducibility, etc.

Since you don't see computer science or the study of complex adaptive systems as real science, I would think that you wouldn't see simulation as being science either, but I am personally happy to be ecumenical on such matters. This said, I would certainly agree with you that much of what is done in both domains doesn't look like science to me. But other parts do. For example, trying to represent cognition, develop robots, etc.

## Individual Opinion: On a More In-Depth View of the Body of Knowledge

Bernard P. Zeigler, University of Arizona
Tuncer Oren, University of Ottawa

The tone of the executive summary report intimates that our current state of knowledge about modeling and simulation is not as advanced as it really is. For example, the opening charge to the participants asks them to determine “if” fundamental knowledge about the field could exist, where as there is a half-century of literature that documents that such knowledge *does* exist. The first charge would be better stated as:

> *Elucidate* the fundamental knowledge elements that characterize the nature of simulation.

A useful starting point is the definition:

> *“Simulation is goal-directed experimentation with dynamic models.”*

This definition covers any type of simulation regardless of whether it is computerized or not. It allows top down decomposition of the entities and activities involved in simulation. Experimentation has been one of the key concepts in scientific thinking since it was surfaced by Francis Bacon. Hence, the definition also ties simulation to the origins of modern scientific thinking. Goal-directed experimentation stresses the advantages of performing the experiments on a model rather than on the real system. The separation of model and its implementation (the code that supports experimentation) is also critical to the definition. Much more could be elaborated about the nature of simulation from this definition, but for the present purposes, the point has been made.

Similarly, the second charge could be more positively stated as:

> Assess how a scientific approach can improve simulation.

A proper definition of simulation is a start toward a consistent set of concepts, techniques and tools that can support efficient and effective disciplined development of simulation applications.

SEI's "People Capability Maturity Model" <http://www.sei.cmu.edu/cmm-p/> is very important in assessing/raising the level of the quality of people. It is based on Carnegie Mellon Software Engineering Institute's (SEI) Capability Maturity Model for Software (SW-CMM) <http://www.sei.cmu.edu/cmm/cmm.html>. Vocational training alone does not replace a solid education and the flexibility it can allow. Bob Sargent had an interesting "advisory" tutorial to Ph.D. students at the WSC 2000. It may be referred to.

The code of professional ethics <http://www.site.uottawa.ca/~oren/pubs/D81_Code.pdf> may also be considered along this line.

Similarly, we can quarrel with the negative tones of many of the positions stated. It is instructive to suggest some reasons why some positions stated in the workshop are open to question.

> "Simulation is technology but not science …"

The American Heritage Dictionary gives the definition: "*Technology: The application of science, especially to industrial or commercial objectives.*" The Cambridge Dictionary has the following: "Technology: the study and knowledge of the practical, esp. industrial, use of scientific discoveries, such as *nuclear technology, space-age technology, manufacturing technology…"*

So this position states that simulation is based on science, but is not science itself. This seems to be, if not an oxymoron, very difficult to reconcile. It seems to imply that simulation is a totally ad hoc brew of component technologies without any coherent theoretical basis. It also seems to imply that this situation is intrinsic to it, so that no progress in this regard can ever occur (although the qualification "for the time being" softens this interpretation.)

> "Simulation consists of observable phenomena that the application of scientific method can explain."

This implies a rather narrow understanding of simulation activities, namely, those limited to those observable in model construction and execution. However, a wide variety of

different kinds of activities can be discerned and placed into two main divisions.(From: http://www.site.uottawa.ca/~oren/pres/2002-11%20D85-Shanghai.pdf )

There two types of [computerized] simulation activity:

1. **Stand-alone simulation activity:**

   ***(the simulation program runs independently from the system of interest)***

Four categories of purpose:

1. Decision making
2. Training to enhance decision skills (gaming simulation)
3. Training to enhance motor skills (simulators)
4. Understanding and education
5 Entertainment (simulation games, animation of dynamic systems)

**Use of simulation for decision making**:

*Prediction* of behavior or performance of the system of interest within the constraints inherent in the simulation model (e.g., granularity)

*Evaluation of alternative* models, parameters, experimental and/or operating conditions on model behavior or performance

*Sensitivity analysis*

*Engineering design*

*Prototyping*

*Planning*

*Acquisition*

*Proof of concept*

2. **Integrated simulation activity**:

   (An emerging area) ***simulation program operates together with the system of interest.***

   Two main purposes: to *support* or to *enrich* real system operation

   **Support of real system operation**: the system of interest and the simulation program operate *alternately* to provide *predictive displays*.

   **Enrichment of real system operation**, the system of interest and the simulation program operate *simultaneously*.

   Goals: - *on-line diagnosis*

   - *augmented reality* (enhanced reality) operation.

Such a larger horizon to grasp simulation activities would be needed to fully understand simulation and it would be a challenge to imagine observables for most of them. We may

underestimate the range of modern day modeling and simulation, by restricting our understanding of what science is to what it was in the past.

> "Simulation is a technology too underdeveloped to sustain productive application of rigorous scientific method.

This position seems like an extreme version of the first. So extreme that it not only calls into question a scientific basis for simulation, but also the viability of the technology (if one accepts the first position) itself.

> "Simulation is better considered as an engineering discipline. … than trying to explain it scientifically."

This position suffers from a similar objection as does the first. The American Heritage dictionary gives the following definition: "Engineering: The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems." Thus no engineering or technology can exist without science!

If simulation is considered as a model-based activity, one can also have symbolic processing of models which can have several practical applications such as computer-aided consistency checks as explained in Ören [1].

## Conclusion

High level government agencies are increasingly recognizing the importance of simulation. For example, the Department of Energy recently said that "Science in the 21st century rests on three pillars. ..as always, there's theory and experiments. But simulation is going to be the third pillar for scientific discovery" (pp. 52-60 of the

Technology Review - MIT's Magazine of Innovation, February 2003 issue). While at first glance simulation appears to be a technological brew of many different techniques and methods, a careful analysis reveals that there are deeper organizing principles and rigorous mathematical constructs that can drive progress toward a more coherent situation. Given the increasing influence on science, technology and business we are seeing, it is important not to sell ourselves short by underemphasizing the depth of our knowledge and allowing our hard-won theoretical advances to lie dormant only to be rediscovered over and over again in the future. Indeed, in the 1995 Summer Computer Simulation Proceedings, Tuncer Oren wrote "We do not move forward because we allow people to cycle through the same ideas over and over again." It is important for the field to recognize the existing body of knowledge in its full depth and to employ it for projects in the present as well as a basis to educate for the future.

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## Additional References

A few of the participants provided additional references for the bibliography after it had been completed and linked into the session narratives. Adding these few entries were not practical so they are included in this section.

### PROF. BERNARD ZEIGLER:

Prof. Bernard Zeigler provided the following reference of interest:

Modeling and Simulation in Manufacturing and Defense Acquisition: Pathways to Success (Available at <http://www.nap.edu/catalog/10425.html>.) (We have a quite extensive set of recommendations relating to best practices, research in M&S, etc that might be helpful. There is also an extensive set of references.)

### MR. WILLIAM WAITE:

Mr. William Waite supplied the following references:

**Programs for Lessons Learned:**

Programs available for lessons-learned recovery include:

- JSIMS
  - NASM
  - WARSIM
  - JSIMS Maritime
- JMASS
- JWARS
- EADTB
- Wargame 2000 now MDWAR

**Cognitive Science Abstraction Pointers:**

Popular examples are provided by Minsky and Pinker,

The Society of Mind, Marvin L. Minsky

How the Mind Works, Steven Pinker

Consciousness Explained, Daniel Clement Dennett

**Parnas Reference:**

Software Fundamentals: Collected Papers by David L. Parnas - David Lorge Parnas, et al

**Second Generation Certification Exam**

Second Generation Certification Exam for Certified Modeling and Simulation Professional (CSMP) being developed under auspices of Modeling and Simulation Professional Certification Commission, details not available for disclosure. For

information contact MSPCC@NDIA.org or see www.simprofesional.org or contact RADM (Ret) Fred Lewis at NTSA.

**MR. SCOTT HARMON**

Mr. Harmon found the following reference on the taxonomy of abstraction:

F.K. Frantz, A Taxonomy of Model Abstraction Techniques, Computer Sciences Corporation, Syracuse, NY, 29 November 2002. (Available at <http://www.rl.af.mil/tech/papers/ModSim/ModAb.html>.) [SH]

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[311] T. Toffoli, M. Biafore & J. Leao (eds.), Proc. 4th Workshop on Physics and Computation, New England Complex Systems Institute, Cambridge, MA, 1996. (This workshop was the fourth in a series, and last, that brought people together who worried about explaining information systems as physical systems.) [SH]

[312] W.H. Zurek (ed.), Complexity, Entropy and the Physics of Information, Perseus Books, Reading, MA, 1990. (This text captures the results of a workshop the addressed the fundamental nature of information and information systems from a physical perspective.) [SH]

## G. GENERAL REFERENCES

[313] R. Aris, Mathematical Modelling Techniques, Dover Publications, New York, NY. 1994. (This book contains a terse treatment of continuous modeling based on differential and difference equations.) [EP]

[314] B. Gower, Scientific Method – An Historical and Philosophical Introduction, Routledge, New York, NY. 1997. [EP]

[315] B.V. Koen, Definition of the Engineering Method, American Society for Engineering Education, Washington, DC, 1985. [DG]

[316] J. McLean, “The Algebra of Security," Proc. IEEE Symp. on Security and Privacy, Oakland, CA, April 1988, np. [RS]

[317] A.M. Olson, “Seven Rules in a Theory of Consistency,” Design of Computing Systems: Social and Ergonomics Considerations, M.L. Smith, G. Salvendy & R.J. Koubek (eds.), Elsevier Science, New York, NY, 1997, pp715-718. [DG]

[318] A.M. Pejtersen & J. Rasmussen, “Effectiveness Testing of Complex Systems,” Handbook of Human Factors and Ergonomics, G. Salvendy (ed.), John Wiley and Sons, New York, NY, 1997, pp 1514-1542. [DG]

[319] E. Tufte, The Visual Display of Quantitative Information, Graphics Press, Cheshire, CT, 1983. [DG]

[320] E. Tufte, Envisioning Information, Graphics Press, Cheshire, CT, 1990. [DG]

[321] W.A. Wallace (ed.), Ethics in Modeling, Pergamon Press, Oxford, England, 1994. (This book tells a cautionary tale on using model results in legal proceedings and public policy.) [EP]

[322] Webster’s II New Riverside University Dictionary, Houghlin Mifflin, Boston, MA, 1984. [DG]

[323] W.L. Wolfe (ed.), Handbook of Military Infrared Technology, Office of Naval Research, Department of the Navy, Washington, DC, 1965. [SH]

# II. Internet Sites

## A. PHILOSOPHY OF SCIENCE & TECHNOLOGY

[324] J. Bilton, What is Technology?, The UK Technology Education Centre, Trinity Church of England School, Escher, England, 2002. (Available at <http://atschool.eduweb.co.uk/trinity/watistec.html>) [DG]

[325] R. Feynman, Cargo Cult Science, Speech, California Institute of Technology, Pasadena, CA, 1974. (Available at <http://wwwcdf.pd.infn.it/~loreti/science.html>) [DG]

[326] M. Greenberg & A. Hough, What is Science?, Dept. of Biological Science, Wayne State University, Detroit, MI, 2002. (Available at <http://sun2.science.wayne.edu/~bio103/whatisscience.html>) [DG]

[327] J.L. Stanbrough, Hypotheses, Batesville High School, Batesville, IN, 2002. (Available at <http://www.batesville.k12.in.us/Physics/PhyNet/AboutScience/Hypotheses.html>) [DG]

## B. SIMULATION INFORMATION RESOURCES

[328] ARGESIM Simulation Links, 9 September 2000. (Available at <http://eurosim.tuwien.ac.at/hotlinks/>.) [EP]

[329] Arizona Center for Integrative Modeling and Simulation, Modeling and Simulation Sites, Tucson, AZ. (Available at <http://www.acims.arizona.edu/MSSITES/mssites.shtml>.) [EP]

[330] W. Braun & C. Roux, Systems & Simulation Links. ISIMA, Universite Blaise Pascal, France. (Available at <http://www.isima.fr/ecosim/simul/simul.html>.) (This page is a compilation of web links towards system and simulation links.) [EP]

[331] Defense Modeling and Simulation Office, Online M&S Glossary (DoDD 5000.59-M), Alexandria, VA, 14 March 2002. (More information is available at <https://www.dmso.mil/public/resources/glossary/>.) [DG, SH]

[332] F. Gomes, Simulation Bookmarks, University of Calgary, Calgary, Alberta, Canada. (Available at <http://pages.cpsc.ucalgary.ca/~gomes/HTML/sim.html>.) **[EP]**

[333] M. Green, Modeling and Simulation Acronyms and Web Sites, U.S. Air Force Agency for Modeling and Simulation, Orlando, FL, 22 March 2001. (Available at <http://www.afams.af.mil/doclib/doclib.cfm?AFAMS_RID_1000364>.) (This site points to an MS Word document that contains modeling and simulation acronyms and web sites. The information was current as 22 Mar 01, but has not been updated and will not be updated in the future.) [EP]

[334] Modeling and Simulation Information Analysis Center, M&S Website Directory, Defense Modeling and Simulation Office, Alexandria, VA. (Available at <http://www.msiac.dmso.mil/msosa-net/link_directory.asp>.) [EP]

[335] T. Nabeth, Systems: Modeling and Simulation, Centre for Advanced Learning

Technologies, INSEAD, Fontainebleau, France. (Available at <http://www.insead.fr/CALT/Encyclopedia/ComputerSciences/System/modeling.htm>.) [EP]

[336] E. Page, Publications, (Available at <http://www.thesimguy.com/publications.htm>.) (This site includes references to his paper on ALSP.) [EP]

[337] E. Page, Link to Chapter 5 of Dr. Page's dissertation that presents a pretty lengthy review of the CS and Overstreet's proofs. (Available at <http://www.thesimguy.com/ernie/papers/unref/dissert/node6.html#SECTION00600000000000000000 >.) [EP]

[338] S. Raczynski, Simulation Encyclopedia. (Available at <http://www.raczynski.com/pn/encyk.htm>.) [EP]

[339] A. Rizzoli, A Collection of Modelling and Simulation Resources on the Internet, IDSIA, Manno, Switzerland. (Available at <http://www.idsia.ch/~andrea/simtools.html>.) [EP]

[340] M. Roskothen, Simulation Software, California State Univ. Chico, Chico, CA, 1996. (Available at <http://www.ecst.csuchico.edu/~mcleod/software.html>.) (This is an (incomplete and never finished) overview of software for simulation development and application. Members of the McLeod Institute have experience with some of the products and are continuously testing and applying new ones.) [EP]

[341] Society for Computer Simulation International, Modeling and Simulation Archive, San Diego, CA. 2002. (Available at <http://scs.affinitycity.com/XRM/Main.asp?ID=51484>). [BZ]

[342] J. Swain, Simulation Software Survey, Operations Research and Management Sciences, 2001. (Available at <http://www.lionhrtpub.com/orms/surveys/Simulation/Simulation.html>.) (The information in this survey was provided by the vendors in response to a questionnaire developed by James Swain. The survey should not be considered as comprehensive, but rather as a representation of available Simulation packages.) [EP]

[343] University of Ottawa, Index of Publications: Simulation and Related Topics, Ottawa, Ontario, Canada, 2002. (Available at <http://www.site.uottawa.ca/~oren/11sim.htm>) [BZ]

## C. SIMULATION-RELATED ORGANIZATIONS

[344] Defense Modeling and Simulation Office, VV&A Recommended Practices Guide, Alexandria, VA. (More information is available at <http://www.msiac.dmso.mil/vva/default.htm>.) (The RPG describes the interrelated processes that make up VV&A from a number of perspectives. Different sections of the RPG cover the different roles and responsibilities of the various participants; discuss special topics associated with VV&A; identify tools and techniques, and provide reference material on related areas. This document continues with an informal discussion of the key concepts of VV&A – the principles, rationale, terminology, and general

approach to conducting VV&A for models and simulations. It provides an analogy from everyday life intended to demonstrate the practicality of VV&A and concludes with a summary of the costs and benefits and an introduction to the remainder of the RPG.) [SH]

[345] Grand Challenges Organization, Website on the Simulation Grand Challenges Conference. (Available at <http://www.grandchallenges.org >.) [EP]

[346] Military Operations Research Society (MORS) website: http://www.mors.org. (This site provides a link to the SIMVAL99 workshop.) [DP]

[347] Modeling and Simulation Professional Certification Commission, Arlington, VA. (Available at <http://www.simprofessional.org>.) (The Modeling and Simulation Professional Certification Commission (M&SPCC), under the auspices of the National Training Systems Association (NTSA), is responsible for the development and provision of professional certification to simulation specialists. Certification creates an identity for and builds cohesiveness across the modeling and simulation (M&S) community by establishing guidelines for determining professional competency. These guidelines cover three core competencies: model-based disciplines such as physics, engineering, human behavior, or biology; the use of empirical based methodologies such as statistics and experiment design; and computer technology and computer science. In addition to these core competencies, a professional must exhibit a degree of knowledge supporting a common basis for communications, cooperation and methodical exchanges across the diverse M&S community. This community includes discrete systems simulation, continuous systems simulation, and real-time systems simulation. ) [LA]

[348] National Training Systems Association (NTSA), Arlington, VA. (Available at <http://www.trainingsystems.org/>.) (NTSA provides the training, simulation, related support systems and training services industries a focused, formal organization to represent and promote their business interests in the market place. The Association provides a forum to communicate the full capability and broad characteristics of all of the elements of training systems and services to include associated support services.) [SH]

[349] North American Simulation and Gaming Association. (Available at <http://www.nasaga.org/>.) [EP]

[350] Simulation Interoperability Standards Organization, Orlando, FL. (More information is available at <http://www.sisostds.org/>.) (The Simulation Interoperability Standards Organization (SISO) originated over ten years ago with a small conference held April 26 and 27, 1989, called, "Interactive Networked Simulation for Training". The original conference attracted approximately 60 people. The group was concerned that there was activity occurring in networked simulation, but that it was occurring in isolation. The group believed that if there were a means to exchange information between companies and groups that the technology would advance more rapidly. The group also believed that once the technology begins to stabilize then there would also be a need for standardization. The technology and the consensus of the community would be captured in the standards as networking or simulation technology matured.) [SH]

[351] Society for Computer Simulation International (SCS), San Diego, CA. (More information is available at <http://www.scs.org/>.) (The Society for Computer

Simulation International is the principal technical society devoted to the advancement of simulation and allied computer arts in all fields. The purpose of The Society is to facilitate communication among professionals in the field of simulation. To this end, The Society organizes meetings of regional councils, sponsors and cosponsors national and international conferences, and publishes the monthly technical journal SIMULATION as well as the quarterly journal TRANSACTIONS of The Society for Computer Simulation.) [SH]

[352] University of Southern California Institute for Creative Technologies (USC-ICT), Marina del Rey, CA. (More information is available at <http://www.ict.usc.edu/>.) (In August 1999, the U.S. Army awarded a five-year contract to the University of Southern California to create the Institute for Creative Technologies (ICT). The ICT's mandate is to enlist the resources and talents of the entertainment and game development industries and to work collaboratively with computer scientists to advance the state of immersive training simulation. The goal of the ICT is the creation of the Experience Learning System (ELS), which provides the ability to learn through active, as opposed to passive, systems. In addition to specific military training tasks, the ELS will have applications for a broad range of educational initiatives.) [SH]

[353] Vis-Sim.Org. (Available at <http://www.vis-sim.org/>.) (This site is an independent visual simulation portal.) [EP]

## D. SIMULATION EDUCATION RESOURCES

[354] Academic Programs in Simulation, SOS Research Group. (More information is available at <http://www.sosresearch.org/simulationeducation/simprograms.html>.) [SH]

[355] Simulation Education Homepage, SOS Research Group, 2001. (More information is available at <http://www.sosresearch.org/simulationeducation/>.) (Initiated as a result of the NSF-Sponsored Simulation Education Workshop: Enhancing Teaching Simulation to Computer Science Majors held August 2-8 1998 at the University of the District of Columbia, Washington D.C.; workshop directed by Dr. Ruth Silverman. The Simulation Education HomePage was first officially announced at the Simulation Education Birds-of-a-Feather (BOF) Session at the March 1999 ACM SIGCSE Conferencein New Orleans, LA USA) [SH]

[356] University of Arizona, Tucson, Arizona Center for Integrative Modeling and Simulation, Tucson, AZ. (Access this site at <http://www.acims.arizona.edu/>.) [BZ]

[357] University of Central Florida, Institute for Simulation and Training, Orlando, FL. (Access this site at <http://www.ist.ucf.edu/>.) [RS]

## E. SIMULATION PROGRAMS

[358] ASCI Program, Department of Energy, ASCI program link. (More information is available at <http://www.sandia.gov/ASCI/apps/VNVext/vnvframes.html>.) (Note that this site is restricted to authorized users). [DP]

[359] Functional Area 57, Army Model and Simulation Office, Arlington, VA. (More information is available at <https://www.fa-57.army.mil/>.) [SH]

[360] Janus, Constructive Simulation Branch, Ft. Benning, GA. (More information is available at <http://www.benning.army.mil/SimCntr/JanusA.htm>.) (Janus is a warfighting simulation that challenges commanders to plan and interactively fight battles against real world opponents. Janus can see the opposing sides, but the players cannot; they only see their forces in Janus. Janus is an interactive, two-sided, closed, stochastic, ground combat simulation featuring precise color graphics. It also models weather and its effects, day and night visibility, engineer support, minefield employment and breaching, rotary and fixed wing aircraft, resupply, and a chemical environment.) [SH]

[361] Joint Conflict and Tactical Simulation (JCATS), Constructive Simulations Branch, Ft. Benning, GA. (More information is available at <http://www.benning.army.mil/SimCntr/JCATS.htm>.) (JCATS evolved from a merger of the Joint Tactical Simulation (JTS) and the Joint Conflict Model (JCM). All were developed by the Conflict Simulation Laboratory at Lawrence Livermore National Laboratory. JCATS is a multi-sided, interactive, entity level conflict simulation used by Government organizations (military and site security, for example) as a tool for training, analysis, planning and mission rehearsals.) [SH]

[362] Joint Semi-Automated Forces (JSAF). (More information is available at http://www.mstp.quantico.usmc.mil/modssm2/InfoPapers/INFOPAPER%20JSAF.htm.) (JSAF is a simulation system that generates entity level platforms such as infantrymen, tanks, ships, airplanes, munitions, buildings, and sensors, which interact at the individual level in a robust synthetic natural environment. The individual entities are task organized into appropriate units for a given mission and can be controlled as units or single entities. The synthetic environment is a representation of real world terrain, oceans, and weather conditions that effect the behaviors and capabilities of the synthetic forces.) [SH]

[363] Joint Simulation System (JSIMS), Orlando, FL, 15 November 2002. (More information is available at <http://www.jsims.mil/>.) (The primary purpose of JSIMS is to support training and education of ready forces by providing realistic joint training across all phases of military operations for all types of missions. JSIMS will provide for Joint training as well as Service specific training. A distributed, constructive wargaming simulation, JSIMS is designed to create a single, seamlessly integrated Joint Synthetic Battlespace (JSB)1 providing a common environmental and operational picture of the battlespace. It will interface with command, control, communications, computers, and intelligence (C4I) functions and equipment in the field, thus providing the interface between the JSB and the training audience. The resulting effect is a training environment indistinguishable by the training audience and the real world.) [SH]

[364] PM CATT Close Combat Tactical Trainer (CCTT), U.S. Army PEO STRI, Orlando, FL. (More information is available at <http://www.peostri.army.mil/PM-CATT/CCTT/homeflash.jsp>.) (The Close Combat Tactical Trainer (CCTT) is the first virtual simulation trainer developed under the Combined Arms Tactical Trainer (CATT) Program. CCTT trains tank and mechanized infantry units from platoon to battalion task force including cavalry scout platoons and heavy cavalry troops on ARTEP-MTP collective tasks. CCTT offers commanders the opportunity to develop and tailor structured exercises based on mission, enemy, troops, terrain, and time available (METT-T) to meet the unit's training plan and objectives.) [SH]

[365] U.S. Army Experiment Program. (More information is available at <http://www.tio-armytransformation.net/aepublic/previous_ae/default.htm>.) (This site discusses the Army experiment program that provides the context and details of the Synthetic Theater of War (STOW).) [SH]

[366] Warfighters' Simulation 2002 (WARSIM), U.S. Army National Simulation Center, Ft. Leavenworth, KN, 17 April 2002. (More information is available at <http://www-leav.army.mil/nsc/warsim/> and <http://www.stricom.army.mil/PRODUCTS/WARSIM/>.) (WARSIM 2000 is a computer based simulation with associated hardware and is the Army's next generation command and control training environment.) [SH]

## F. EDUCATIONAL RESOURCES

[367] Accreditation Board for Engineering and Technology, Inc., Baltimore, MD. (More information is available at <http://www.abet.org/>.) (The website for the organization that accredits engineering education programs. The vision of ABET is to provide world leadership to assure quality and stimulate innovation in engineering, technology and applied science education.) [SH]

[368] National Technological University. (More information is available at http://www.ntu.edu/.) (The National Technological University Corporation offers nearly 1,400 graduate-level courses, and through the PBS: The Business and Technology Network NTU broadcasts nearly 500 interactive short courses and workshops via satellite, the Internet, and CD-ROM. National Technological University is accredited by the Commission on Institutions of Higher Education of the North Central Association of Colleges and Schools.) [SH]

## G. SIMULATION PRODUCTS

[369] Analytica, Lumina Decision Systems, Los Gatos, CA, 05 December 2002. (More information is available at <http://www.lumina.com/>.) (Lumina's flagship software product, Analytica® , is a quantitative decision-support environment that helps people visualize problems with a clarity and power far beyond what is possible in a spreadsheet. Existing applications of Analytica include strategic planning, R&D management, decision analysis, and risk analysis in finance, healthcare, energy, environment, aerospace, and telecommunications.) [SH]

[370] Mathematica, Wolfram Research Co., Champaign, IL, 2002. (More information is available at <http://www.wolfram.com/>.) (Whether you need a sophisticated calculator or an integrated technical programming environment, or a means to deploy technical computations and information throughout your organization, Mathematica provides you with a complete solution. You can perform a single task, such as analyzing data or solving a tricky differential equation, or develop an entire solution, prototype, or application.) [SH]

[371] SimCity, 2002, Electronic Arts, Inc. (More information is available at <http://simcity.ea.com/>.) (SimCity's basic idea as a game is to simulate the ongoings in a city, covering all the basic problems, dealing with infrastructure and people's needs and

demands. In SimCity you take control as the mayor of your newly founded city and start out with nothing but a small amount of money and piece of land. Hopefully you'll end up with a bustling metropolis with great fun on the way there.) [SH]

[372] K. Schmucker, A Taxonomy of Simulation Software, Apple Computer, Inc., 2002. (More information is available at <http://www.apple.com/education/LTReview/spring99/simulation/>.) (The focus of this article is simulations that could reasonably be used on a computer in a K-12 classroom or a home computer. Multimillion dollar immersive flight simulators or complex simulation codes that run only on supercomputers, while arguable extremely useful and cost effective in certain environments, are generally beyond the scope of this work. Likewise, at the other end of the spectrum, board games like Monopoly could be considered low-fidelity simulations of small economic systems, but for the purposes of this paper, we will only consider computer-based simulations whose complexity is reasonably beyond what could be done by hand.) [SH]

## H. RANDOMNESS RESOURCES

[373] P. Hellekale, PLAB, Mathematics Department, University of Salzburg, Salzburg, Austria (Available at <http://random.mat.sbg.ac.at>.) (This site provides a server on the theory and practice of random number generation.) [SH]

[374] Random.org (More information is available at http://www.random.org/.) (This is an independent site that provides information about random number generators and related topics.) [SH]

## I. HISTORY OF CHEMISTRY

[375] J.R. Fromm, Chemistry, A History, April 1987. (Access this site at <http://www.nidlink.com/~jfromm/history2/chemist.htm>.) [SH]

[376] Thomson Brooks/Cole, The Story of Chemistry, 2002. (More information is available at <http://www.brookscole.com/chemistry_d/special_features/time_line.html >.) (The earliest record of man's interest in chemistry was approximately 3,000 B.C, in the Fertile Crescent. At that time, chemistry was more an art than a science. By 1000 B.C, chemical arts included the smelting of metals and the making of drugs, dyes, iron, and bronze. Iron making was also introduced and refinement of lead and mercury was performed. The physical properties of some metals such as copper, zinc, silver, and gold were understood. Many groups of people contributed to these developments--among them were ancient Egyptians, Greeks, Hebrews, Chinese, and Indians.)

## J. GENERAL RESOURCES

[377] American Association for Artificial Intelligence, Innovative Applications of Artificial Intelligence Conferences, Menlo Park, CA. (More information is available at <http://www.aaai.org/Conferences/IAAI/iaai.html>.) (Innovative Applications of Artificial Intelligence (IAAI) Conferences traditionally consist of case studies of deployed applications with measurable benefits whose value depends on the use of AI technology. In addition, many IAAI conferences augment these case studies with papers

and invited talks that address emerging areas of AI technology or applications. IAAI is organized as an independent program within the AAAI National Conference, with schedules coordinated to allow attendees to move freely between IAAI and National Conference sessions. IAAI and the National Conference often jointly sponsor invited talks that fit the theme of both programs.) [SH]

[378] R.R. Colwell, Beyond Barcodes: Wisdom in the Age of Information, Speech, National Press Club, Washington, DC, April 29, 1999, (Available at <http://www.nsf.gov/od/lpa/forum/colwell/rc990429npc.htm>) [DG]

[379] Defense Information Systems Agency, DoD Joint Technical Architecture (JTA), Washington, DC, 29 November 2002. (More information is available at <http://www-jta.itsi.disa.mil/>.) (A technical architecture is a set of rules, or "building codes", that are used when a system engineer begins to design/specify a system. These rules consist primarily of a common set of standards/protocols to be used for sending and receiving information (information transfer standards such as Internet Protocol suite), for understanding the information (information content and format standards such as data elements, or image interpretation standards) and for processing that information. It also includes a common human-computer interface and "rules" for protecting the information (i.e., information system security standards). The Joint Technical Architecture (JTA) is a document that mandates the minimum set of standards and guidelines for the acquisition of all DoD systems that produce, use, or exchange information. The JTA shall be used by anyone involved in the management, development, or acquisition of new or improved systems within DoD.)

[380] J. Pike, National Image Interpretability Rating Scales, Federation of American Scientists, Washington, DC, 16 January 1998. (More information is available at <http://www.fas.org/irp/imint/niirs.htm>.) (The aerial imaging community utilizes the National Imagery Interpretability Rating Scale (NIIRS) to define and measure the quality of images and performance of imaging systems. Through a process referred to as "rating" an image, the NIIRS is used by imagery analysts to assign a number which indicates the interpretability of a given image. The NIIRS concept provides a means to directly relate the quality of an image to the interpretation tasks for which it may be used. Although the NIIRS has been primarily applied in the evaluation of aerial imagery, it provides a systematic approach to measuring the quality of photographic or digital imagery, the performance of image capture devices, and the effects of image processing algorithms.) [BZ]

# III. Other Pointers

## A. PERIODICALS

[381] American Physical Society, Reviews of Modern Physics, College Park, MD, 2002. (More information is available at <http://rmp.aps.org/>.) [SH]

[382] Annals of Operations Research (More information is available at <http://www.kluweronline.com/issn/0254-5330/>.) [EP]

[383] Association for Computing Machinery (ACM) Transactions on Modeling and Computer Simulation (More information is available at <http://www.acm.org/tomacs/>.) [EP]

[384] Game Developer magazine (More information is available at <http://www.gdmag.com/>.) (This magazine publishes lessons learned in the gaming industry.) [WS]

[385] INFORMS Newsletter (More information is available at <http://www.informs-cs.org/newslet.html>.) [EP]

[386] Journal of Artificial Societies and Social Simulation (More information is available at <http://jasss.soc.surrey.ac.uk/JASSS.html>.) [EP]

[387] Military Operations Research Society (MORS) Journal (More information is available at <http://www.mors.org/mor_journal.htm>.) [EP]

[388] Simulation Practice and Theory (More information is available at <http://www.elsevier.nl/locate/simpra/>.) [EP]

[389] Society for Computer Simulation (SCS) Simulation (More information is available at <http://www.scs.org/pubs/simulation.html>.) [EP]

## B. CONFERENCES & WORKSHOPS

[390] ACM Annual Parallel and Distributed Simulation Workshop (PADS) (This workshop represents a good mix of theoretical and empirical studies, studies largely aimed at improving the runtime performance of discrete event simulations. PADS began as an SCS-sponsored conference called "Distributed Simulation" in 1985. And was held again, under the same title in 1988, 89 and 90. It became PADS in 1991 and has been held annually since. The majority of PADS papers follow similar lines: (1) you start with a mathematical understanding of parallel computation, and one of two basic approaches to synchronization, (2) you suggest a modification of the basic synchronization approach and estimate its effectiveness using the math model, (3) you conduct experiments varying parameters like message density, network topology, etc. and (4) you say something about cases where your approach works well and cases where it works less well. (Proceedings are available online going back to 1993 on the ACM digital library at <http://www.acm.org/dl> and information on the workshop is available at <http://www.pads-workshop.org>.) [EP]

[391] AIAA Modeling and Simulation Technologies Conference (More information is available at <http://www.aiaa.org/calendar/index.hfm?cal=5&lumeetingid=573>.) [EP]

[392] Huntsville Simulation Conference (More information is available at <http://www.scs.org/confernc/coninfo.html>.) [EP]

[393] IASTED International Conference on Applied Simulation and Modelling (More information is available at <http://www.iasted.org/conferences/2002/greece/asm.htm>.) [EP]

[394] IASTED International Conference on Modelling and Simulation (More information is available at <http://www.iasted.com/conferences/2002/marina/ms.htm>.) [EP]

[395] Indian Modeling and Simulation Society Conference (More information is available at <http://www.cmmacs.ernet.in/ismmacs/conf_brochure.html>.) [EP]

[396] SCS Advanced Simulation Technology Conference (More information is available at <http://www.scs.org/confernc/coninfo.html>.) [EP]

[397] SCS Summer Computer Simulation Conference (More information is available at <http://www.scs.org/confernc/coninfo.html>.) [EP]

[398] SCS Western Multiconference (More information is available at <http://www.scs.org/confernc/coninfo.html>.) [EP]

[399] SCS Winter Simulation Conference (More information is available at <http://www.wintersim.org> and <http://www.informs-cs.org/wscpapers.html>.) [EP]

[400] SISO Simulation Interoperability Workshop (More information is available at <http://www.sisostds.org/>.) [EP]

# APPENDICES

# Appendix 1: Initiating E-Mail Thread for the Workshop on the Scientific Exploration of Simulation Phenomena

Over a year before the workshop actually occurred, Mr. Lunceford initiated an e-mail discussion on the topic of science of simulation. This discussion formed the nucleus around which the workshop eventually crystallized. This discussion is presented in its raw and unedited form to preserve historical accuracy.

The last section of this appendix contains the material used to prepare Mr. Harmon's final response. Eventually, this response became a short guest editorial in Simulation.

## W. Lunceford – 05/14/01:0800

For about six months now I've been kicking around the subject idea. It initially came from a comment that Dennis McBride made to me about four years ago about M&S not being a science and was re-stimulated by a conversation with Ernie. The basic question is this, is there a science of M&S? If you take my field (Electrical/Electronic Engineering) there is a small core set of knowledge that can be used to create a sound foundation for almost any design effort. Start with E=IR, P=IE, the concepts of serial and parallel resistance and a few other basics and most of electrical engineering falls into place (ok so that is a little simplistic). The important part is that no engineer starts designing a stereo without building up from these basics. As important, no one starts out on an education in EE without starting with an understanding of these principles.

In M&S however I don't think we have the equivalent, at least not defined in such a way that once can recognize them as such. This is why, at least in part, we get so much junk in the M&S world. People build simulations based on a casual knowledge of techniques such as DES but not from fundamentals.

So the question is this. What do y'all think about the idea of holding a small workshop focused on defining the first order principles of M&S and possibly our current state of understanding of the principles? If nothing else we might end up with a couple of interesting dissertation topics, but we might also be able to define the scientific (and practical?) foundations of M&S that would be the base course everyone would take before launching off into rules of thumb and OJT design practices.

Thoughts?

## W. Waite – 05/14/01:0800

- Is there is a core body of knowledge for M&S? Yes.

- Is it a science or an art? ...don't know, don't care.

- Could / should we know what the core BOK is? Yes.

- Could knowing what the BOK is significantly contribute to the maturation of the profession / industry / market and consequently to the quality of products and services? Yes.

- Could / should we have a workshop? Yes.

- Is there ample opportunity to use the professional societies to support this? Yes.

- Could we add a working meeting to the SCSC to address this? Yes.

- Could / should this topic persist above and beyond any one event? Yes,

but in deference to your style of 'run it up the flag pole and see if anyone salutes", I'd like to see us do SOMETHING now.

- Will I help (even if uninvited)? Absolutely.

I'll be in DC (with Ernie and for the NDIA SBA Conference) most of the week 703.578.3494. Let me know if there's anything I can do on this.

## R. Fujimoto – 05/14/01:0900

My initial reaction is I don't think M&S is a science, in the way we think of Physics or Chemistry as sciences (EE is based on fundamentals of electricity & magnetism in Physics).

M&S is more a "science" in the sense that "computer science" is a science. I think we've heard a zillion times that any "science" that has to put "science" in its name isn't one, but let's put aside that discussion for now.

The physical sciences are based on some fundamental laws of nature (gravity, for instance) which we have empirically observed not only to be true, but are the basis for explaining how things work in the physical world. Why the world should be based on a few (one?) laws is a philosophical question I won't get into. I can only say that that seems to be how the universe works, whether by accident, or someone's grand plan.

By contrast, M&S, like fields such as CS, is fundamentally a human created activity. M&S is based on humans' abstraction of the world. Different people can look at the same thing and come up with entirely different ways of looking at it.

M&S is an activity limited and constrained more by one's imagination and ability to abstract than any underlying physical laws of nature.

Thus, I am skeptical that there are fundamental laws that can be defined that explain the rest of the M&S field. Having said that, I can see the value of addressing Dell's question from a curriculum perspective, as consensus within the community on "the basics" of M&S can shed some light on how M&S educational programs should be constructed. While Computer Science (perhaps arguably) isn't a science, there are certain bodies of knowledge widely accepted as forming the core of the field.

## W. Lunceford – 05/14/01:1000

Richard, you make a good point about contrasting basic laws of physics (E=IR) vice a 'human endeavor' such as CS or M&S. I could counter argue that even as a human endeavor, there are a few rules of the universe that still apply...conservation of energy being a good one. This however may be more esoteric than most can deal with however and perhaps not what I was thinking about.

Something I left out of my four years of casual musing about this topic is some work that Scott did back in the pre-HLA days, which is where we met BTW. Scott was using formal methods as a way to define the distributed simulation problem. This work was never finished but what I did see in his equations was a way for 'formally' characterizing the problem and possibly just as important, in working through them it was helping (at least me) to better understand the fundamentals from which we needed to build HLA upon.

We of course through out all this work since it got into the way of actually building something, but I've always wondered how bad a mistake that was.

Perhaps M&S isn't a science, but there should be a core set of knowledge that we should define and from which everyone should build their simulations (everyone?). If we did this, would it help the VV&A issue (or at least the second V)?

## E. Page- 05/14/01:1100

I don't know that M&S in-and-of-itself ought be considered a science. The collective "M&S" is a tool that a scientist employs in practicing the scientific method within a given field: biology, chemistry, economics, politics, architecture, engineering, etc.

Modeling is arguably more art than science--it is, after all, the general discipline within which activities like painting and sculpting fall.

Simulation is no more than a technique that "exercises" a model in some fashion.

There are certainly first principles of building good simulation models--which I've seen be ignored with impunity in the DoD training sim world--and these relate to creating the simplest abstractions possible that satisfy a set of well-reasoned and well-formulated modeling objectives.

But the under-representation of SCIENCE in the M&S community, I believe, is the failure of M&S types--who are tool builders--to appreciate the disciplines within which their tool is employed. The science of M&S lives in the CONTEXT of its application. As a community, we are so "tool focused" that we think M&S is an end and not a means. It is absurd, really. Take a look at the folks who brought you SIMNET, DIS, ALSP and HLA (especially the core architects) and find out how many of them actually ever built and used a simulation model to analyze a system. Even a toy problem. You probably won't believe the answer. I'm not 100% sure about BBN and Lincoln Labs, but I know where the bodies are buried at MITRE on this one....

But the decline and fall of science is not singularly the fault of the M&S community. It certainly appears rampant within the DoD at large. Consider our live fire friends. In what universe does 8-10 shots against a piece of equipment constitute a statistically significant sample? And here we have a community that resists the use of models--which could help them with their statistical significance problem (albeit with the acceptance of an error term introduced by the level of "sufficiency" of the models' validity).... which reminds me, we ought to include Dr. Dietz in this discussion.

## W. Lunceford – 05/14/01:1200

The problem is that we must separate training from analytical. Training simulations have a lot of latitude to 'get things wrong'. You could build SIMNET with little understanding of the problem. Analysis tools were very different, but were as a rule held closely by a small group.

That said, a few misc. thoughts come up:

- As we move more towards the application of SBA the blending of training and analysis tools will make the need for more formality more important
- Systems like JSIMS get into trouble because (1) the application pushes the technology enough that first principles must be applied and (2) lack of understanding of first principles by the practitioners got us into this in the first place
- As M&S continues to infiltrate new domains of use and finds new less experienced folks to build/use them, it is very important that we start thinking about how we train/educate the M&S community or we will end up with JSIMS ++ before long
- Where we are today (a reference to the life fire test) is as much a part of the limitations of simulations in the past vice a lack of applied science. That is, where we all need to balance dollars, time, tools and a lot of stuff to get a job done. What happens over time is that people forget WHY they do something and it becomes culture/organizational practice. This is why documenting fundamentals is important to a maturing field.

Call is science or whatever, I think documenting first principles and thinking about fundamentals would be good for the community. It would be nice to talk to someone about what they are building that actually understood what they were doing :-(

## S. Harmon – 05/16/01

To any traditional scientist, the thought of a "science" of simulation at best appears misinformed and at worst grates on the scientific sensibility worse than fingernails dragging across a chalkboard. So many have misappropriated the word science that the union of all definitions for that moniker defines a bloated and grotesque monster causing even nonscientists to flinch at its sight. The previous responders to Dell's prodding have aptly captured many of the sensible reasons for discounting the existence of a separate science of simulation. But, my respect for Dell as a careful thinker gave me the incentive to shuck the stuffy preconceptions of a fervent scientist and explore his question scientifically.

The hypothesis I want to test is whether a science of simulation could exist. I think that we all agree that no such science currently exists. I began by looking at scientific definitions of science to identify its salient characteristics. This search was frustrated by the surprising lack of definitions for science in my repository of scientific publications, including a couple of dictionaries of science and technology. Further exploration of the

web resources and my local nonscientific sources proved fruitful. This survey delineated two senses of the word science, one referring to the activity and another referring to the knowledge that the activity produces. Here are a few of the definitions that I found for the activity of science:

- The systematic study of the structure and behavior of the physical world, involving experimentation and measurement and the development of theories to describe the results of these activities (Cambridge Dictionaries Online).
- The observation, identification, description, experimental investigation and theoretical explanation of natural phenomena (Webster's II New College Dictionary)
- The systematic observation of natural events and conditions in order to discover facts about them and to formulate laws and principles based on these facts (Academic Press Dictionary of Science and Technology).
- The study of the material universe or physical reality in order to understand it by making observations and collecting data about natural events and conditions, then organizing and explaining them with hypotheses, theories, models, laws, and principles (Biotech Life Sciences Dictionary).

These definitions show an amazing consistency considering the past liberal applications of the term science to various nonscientific activities. They suggest that a science has a few essential properties:

- Science is a study.
- It deals with the natural or physical world.
- That study takes place through experimentation and development of theoretical explanation.
- Its theoretical explanation (stated in terms of hypotheses, models, laws and principles) arises from and is confirmed by observation and experiment.

These definitions and their essential properties certainly conform to my personal views of science. In this experiment, I tested the nature of simulation against each of these properties reasoning that its failure to meet any one of these criteria distinctly shows its lack of the qualities necessary to make its scientific study possible. Here are my findings in this experiment.

(1) One could certainly study, in the broadest sense, simulation. Many stately bodies of higher education offer courses and even entire curricula purporting to teach simulation. These observations lead me to conclude that the study of simulation could exist in some form. That conclusion meets the first criterion of being a science.

(2) Certainly many simulations deal explicitly with the physical or natural world but are simulations actually part of the physical or natural world themselves? A quick trip to the Cambridge Dictionaries Online (the scientific dictionaries also avoid defining the natural world) reveals that the natural world is the one NOT constructed by people (as opposed to the man, or more politically correct, person-made world). So, Richard is right! The study of simulation might not be science because people create simulations. But wait, the

property states natural OR physical world. The Academic Press Dictionary of Science and Technology defines (and other sources agree) the physical world as synonymous with the material world. The material world (from the Cambridge Dictionaries Online definition) contains physical objects rather than emotions or the spiritual world. Judiciously avoiding the circular arguments associated with the physical world composed of physical objects as much as possible, simulations, the objects in the simulation world, do not generally contain emotions nor do they represent the spiritual world (at least as far as I know). Further, the development of simulations does not necessarily need reference to emotional or spiritual objects (although I'm sure that some program managers would argue this). Therefore, simulations must be part of the physical world and so do meet the second criterion to be subject to scientific study.

(3) Experimentation, according to the Academic Press Dictionary of Science and Technology, involves a procedure carried out under controlled conditions in order to discover, demonstrate, or test some fact, theory or general truth. This definition implies that a system subject to experimentation must

- Exhibit observable behavior, and
- Respond to controls of its behavior.

Thus, experiments cannot really be performed upon systems that either are not observable or are not controllable. This, in fact, is a very strong condition because much science involves observation of uncontrollable systems (e.g. the observable universe). One could conclude from this that a system need only be observable. But, let us consider the strongest condition for the moment. Most of the artifacts of simulations (e.g., designs, software, computers, results) are observable. I do not believe that we could construct simulations without many artifacts that would facilitate observation. This suggests that both simulations and their development are observable. As Richard argues, people are inextricably involved in simulation development and often in their execution. Where people are not involved, computers perform most operations. Both of these elements are controllable. The field of psychology has repeatedly demonstrated controlled experiments involving people and computer science has repeatedly demonstrated controlled experiments involving computers. The success of these demonstrations that controlled experiments could be formulated and executed upon simulations to examine their behavior and the behavior of the processes involved in their creation. Admittedly, simulation project managers might argue against the controllability of the simulation development process but we, like most others, will ignore those pleas. Therefore, study of simulations could realistically involve experimentation. Some would even argue that some of those experiments have already been performed. The ability to develop theoretical explanations of the experimental results clearly exists since many people have proposed theoretical explanations of various aspects of simulation without the benefit of experiments. Therefore, simulation satisfies the third criterion to be subject to science.

(4) The final criterion remains untested in simulation and presents the major challenge in realizing the science of simulation. No clear physical barriers appear to exist to prevent the systematic study of simulation suggested by this criterion. However, only trying to execute this study can prove or disprove its assertion. So, the jury remains out on this criterion.

In summary, the final answer to whether a science of simulation could exist awaits someone brave enough to begin performing a systematic study of simulations and the processes for realizing them. No doubt, many physical and cultural hazards face any such individual, Perhaps, these will deter many. Hopefully, human curiosity will prevail and someone will gallantly ignore the naysayers and try.

Bill Waite hinted at a good question. Why should we care about a science of simulation? I interpret that question as "What value does knowledge derived from scientific study possess over knowledge derived from any other form of study?" To me (unarguably a science zealot), science reaches for the surest truth, truth that applies broadly and persists over time. Science creates the most powerful form of knowledge. The assurance that real science provides founds much of the engineering practice that has created the world we know today. Scientific study has even permeated the justice system to some extent (e.g., genetic evidence) and I am confident that it will continue to do so. Over the few thousand years of its development, science has evolved into a very robust and consistent source of knowledge unsurpassed by all other sources. This type of knowledge about simulation would surely provide tangible benefits beyond our meager imaginations as it has in many other fields. Dell and Richard suggested yet another important benefit, science provides the knowledge that we could confidently teach to improve the capabilities of the practitioners in the field. So, in my mind, Bill, you SHOULD care if the core body of knowledge comes from scientific study or from other less reputable sources.

My little informal study of Dell's question stands for your criticism and confirmation.

Scott

P.S. Yes, I vote for a small workshop in some relaxing place ... say the Florida Keys.

## Background Research for SYH Response

Webster's II New College Dictionary defines phenomenon as "an occurrence or fact directly perceptible by the senses" or "an unusual, unaccountable, or remarkable fact or occurrence" or "that which appears real to the senses, regardless of whether its underlying existence is proved or its nature understood"

The New Penguin Dictionary of Science does not define science but does define physics as "the study of systems and their interactions with one another. Physics attempts to characterize these interactions in terms of simple laws.

The New Penguin Dictionary of Science defines system as "that part of the world to which a particular physical model is applied. As the model becomes more sophisticated, more components are added to the system to simulate reality more closely.

Interestingly, the McGraw-Hill Dictionary of Physics does not define physics. There must be some phenomenon at work here.

Elementary Classical Physics, by Weidner and Sells, says, "Physics is the fundamental experimental science. Its purpose is to make sense out of the behavior of the physical universe. Physics begins with controlled observation, or experiment, in which some one phenomenon is examined quantitatively through measurements. The relations among the

physical quantities observed in experimentation are expressed with precision and economy in the language of mathematics. When a relation summarizes many experiments with reliability so great that it can be said to reflect universal behavior in nature, then it is said to be a "law" of physics. Happily, the laws of physics are few and the whole variety of physical phenomena is comprehended in a remarkable small number of fundamental laws.

Theory and experiment both play essential roles in the development of physics. Experiment discloses the facts of nature; theory makes sense out of them."

Introduction to Modern Physics, by Richtmyer, Kennard and Cooper, quotes Galileo as saying "Science can advance only so far as theories, themselves based upon experiment, are accepted or rejected according as they either agree with, or are contrary to, other experiments devised to check the theory."

They also provide the following definitions:

1. The organized body of knowledge that is derived from such observations and that can be verified or tested by further investigation. The organized body of knowledge that is derived from such observations and that can be verified or tested by further investigation.

2. Any specific branch of this general body of knowledge, such as biology, physics, geology, or astronomy. (From the Latin word meaning "knowledge.")

3. The organized body of knowledge about the material universe that can be verified or tested.

Academic Press Dictionary of Science and Technology defines physical (science) - 1. Of or relating to matter or the material world. Of or relating to matter or the material world. 2. Of or relating to physics or another physical science.

A procedure that is carried out under controlled conditions in order to discover, demonstrate, or test some fact, theory, or general truth.

The Organon – EASG Dictionary defines physical – of material nature

Cambridge Dictionaries Online defines physical - existing as or connected with material things that can be seen or felt; not spiritual or mental; natural – anything not made by people; material - Material means relating to physical objects rather than emotions or the spiritual world.

# Appendix 2: Proposal for a Workshop on the Scientific Exploration of Simulation Phenomena

## 1. PROBLEM:

The accumulation of information through scientific exploration has given humankind the largest and most stable descriptions of natural phenomena ever possessed. This knowledge base has contributed to numerous engineering revolutions that have changed society irreversibly.

While simulation has contributed substantially to science, the understanding of its basic nature has come largely from application experience and limited engineering studies. Relatively few have applied rigorous scientific discipline to characterize and understand the phenomena associated with simulation. However, until we take a serious scientific approach to answering the predominant questions plaguing the advancement of simulation, it will remain an art with only a few tenets to guide its practitioners who can never guarantee the results of their work.

## 2. OBJECTIVE:

The objectives of the proposed effort are to

- Conduct a workshop exploring the possibility of scientifically characterizing the phenomena underlying the development and use of simulation and
- Produce a permanent record of this workshop's proceedings, conclusions and recommendations.

More fundamentally, the objectives of this workshop will be to seek the answers of the following questions:

- Could there be a science of simulation?
- What is our state of understanding that might contribute to such a science?
- What do we need to do to improve that understanding?
- What difference will a science of simulation make to the world?

The answers to these questions will help to guide those seeking to improve the ways we currently develop and use simulations.

## 3. APPROACH:

This workshop will formally initiate the exchange of current ideas about the phenomena underlying the development and use of simulation. Even though its attendance will be limited to 10-15 individuals, all invited, these participants will come from a broad range of scientific disciplines as well as mathematics, computer science and engineering. All will have built or used simulations for a variety of purposes.

The workshop will span two and one half days. It will begin with two keynote presentations, one from an eminent beneficiary of simulation science and one from an eminent scientist. Following these presentations, the participants will each give brief

statements summarizing their individual positions on the scientific study of simulation. The participants will pose their own answers to the objective questions in their position statements and in the short position papers they submit for inclusion into the workshop record.

Working sessions will cover the next one and one half days. During these sessions, its participants will

- Characterize what is currently known about the nature of simulation and summarize past efforts to study it scientifically and the results of those studies;
- Identify a set of candidate phenomena that could be studied scientifically and a set of observable properties that could characterize these phenomena;
- Formulate a set of testable hypotheses describing these phenomena in terms of relationships, mathematical if possible, between their observables, and propose a set of experiments to test these hypotheses;
- Describe the rationale for scientifically exploring simulation phenomena and the implications of possessing such knowledge; and
- Recommend promising paths for future scientific exploration of simulation.

In the last working session, the participants will evolve the consensus recommendations of the workshop.

This workshop is proposed to take place during the summer of 2002 in the Washington, DC area. The specific venue will be determined in the course of its organization but the candidates include National Defense University and the Defense Modeling and Simulation Office.

## 4. DELIVERABLES:

A formal workshop record will document the proceedings of and results from this workshop. This record will contain

- Keynote papers and presentation materials,
- Position papers of each participant and their presentation materials,
- Summaries of the discussions in the working sessions,
- Graphics and tables developed during the working sessions,
- Consensus recommendations of the workshop,
- Short point papers describing the positions of any participants at variance with the consensus recommendations, and
- Bibliographic material suggested by the participants.

In addition, an executive briefing summarizing the results of this workshop will be prepared and presented to the sponsors and a technical paper describing the workshop's results will be prepared for, submitted to and presented at an appropriate technical conference. Further, periodic reports describing the progress made in organizing the

workshop and producing its record, as well as the financial status, will be submitted as required.

**5. RELEVANCE:**

Why study simulation scientifically? In other words, what value does knowledge derived from scientific study possess over knowledge derived from any other form of study? Science reaches for the surest truth, truth that applies broadly and persists over time. Science creates the most powerful form of knowledge known to humankind. The assurance that real science supplies founds much of the engineering and medical practice that has created the world we know and enjoy today. Scientific study has even permeated the justice system to some extent (e.g., genetic evidence) and, as legal trends show, will continue to do so. Over the few thousand years of its development, science has evolved into a very robust and consistent source of knowledge unsurpassed by all other sources. This type of knowledge about simulation would surely supply tangible benefits beyond our meager imaginations as it has in so many other fields. Furthermore, science generates the knowledge that we can confidently teach to improve and unify the capabilities and knowledge of all practitioners in the field. These promises make a science of simulation worth pursuing.

Any scientific study of any set of phenomena is a long journey. This workshop will create a single stepping stone from which the journey to scientifically characterize the fundamental nature of simulation can begin.

**STATEMENT OF WORK**

**1.0 Task Order Title**

Workshop on the Scientific Exploration of Simulation Phenomena

**2.0 Background**

The accumulation of information through scientific exploration has given humankind the largest and most stable descriptions of natural phenomena ever possessed. This knowledge base has contributed to numerous engineering revolutions that have changed society irreversibly. While simulation has contributed substantially to science, the understanding of its basic nature has come largely from application experience and limited engineering studies. Relatively few have applied rigorous scientific discipline to characterize the phenomena associated with simulation.

## 3.0 Objectives

The objectives of this effort are to

- Conduct a workshop exploring the possibility of scientifically characterizing the phenomena underlying simulation development and use and
- Produce a record of this workshop's proceedings and conclusions.

## 4.0 Scope

The contractor shall provide support to the DMSO in accordance with the above objectives to include workshop organization and management, and preparation of the workshop record.

## 5.0 Specific Tasks

The contractor shall accomplish specific tasks as follows:

5.1 Provide workshop organization and management support: The contractor shall provide support for the organization and management of the workshop. Tasks include:

5.1.1 Coordinate the invitation of the workshop participants including identifying participant candidates, determining their availability and interest in participating and formally inviting those that do express interest in participating.

5.1.2 Coordinate the invitation of the workshop technical and user keynote presenters including identifying presenter candidates, determining their availability and interest in participating, and formally inviting the keynote presenters chosen.

5.1.3 Manage the workshop preparations including keeping the sponsors and participants informed of the workshop organization progress, interacting with the sponsors to ensure that their needs are met, and managing the workshop details.

5.1.4 Manage the workshop participant submissions including preparing and distributing submission guidance, creating the submission schedule, ensuring that the participants submit their material according to the schedule.

5.1.5 Conduct the workshop including developing the workshop schedule, identifying working session leaders, managing the workshop proceedings to optimize the working session discussions, managing the workshop proceedings recorders to optimize the quality of the workshop record, and leading the session to develop the consensus recommendations.

5.1.6 Participate in the workshop discussions.

5.2 Provide workshop documentation support: The contractor shall provide support for the documentation of the workshop. Tasks include:

5.2.1 Prepare the workshop discussion summaries from the recorders' notes and the graphics developed during the discussions.

5.2.2. Organize the participants' submissions including putting them into consistent formats as needed.

5.2.3 Locate the references to outside sources mentioned in the workshop discussions.

5.2.4 Manage the submission of the point papers dissenting the consensus recommendations including developing a schedule for these submissions, interacting with the participants to ensure their submissions follow that schedule, and putting the point paper submissions into a consistent format as needed.

5.2.5 Assemble the workshop material into a coherent record of the workshop proceedings.

5.2.6 Submit the draft workshop record for sponsor review and comment including modifying the draft record to reflect those comments and submitting the final workshop record.

5.2.7 Prepare and present a briefing to the workshop sponsors summarizing the workshop results.

5.2.8 Prepare, submit and present a technical paper summarizing the workshop results.

## 6.0Key Personnel (Skill Requirements)

The contractor shall provide personnel with the appropriate skills and qualifications to perform this task. All contractor personnel proposed shall be required to provide quality and professional products and services.

The contractor shall provide personnel with the following skills sets:

6.1 Senior Scientist to act as the workshop manager. The individual shall organize and lead the workshop. The individual interacts with both the workshop participants, observers and sponsors. Develops the workshop format and schedule. Develops the guidance for the participants. Coordinates the workshop briefing preparations and position paper submissions. Appoints the workshop session leaders and coordinates the workshop's proceedings. The minimum education requirement shall be a graduate degree from a certified college or university in engineering or physical science. Minimum professional experience required is 25 years general scientific background, 15 years project management with ten or more years of modeling and simulation experience. The individual must have organized and managed scientific workshops. Desired skills include workshop organization, project management and simulation technology.

6.2 Senior Scientist to prepare the workshop record. The minimum education requirement shall a graduate degree from a certified college or university in engineering or physical science. Minimum professional experience required is 25 years general scientific background with ten or more years of modeling and simulation experience. The individual must have prepared the records documenting the results of scientific workshops as well as scientific technical publications. Desired skills include abstraction of detailed workshop proceedings, assembly of workshop record, and presentation of workshop summary.

## 7.0 Place of Performance

Primary place of performance will be the Zetetix facilities at 6547 Bayberry Street, Oak Park, CA 91377. Occasionally, the contractor will meet at the Defense Modeling and Simulation Office, 1901 North Beauregard Street, Suite 500, Alexandria, VA 22311 to coordinate and review ongoing activities. The contractor will also participate at the workshop location in the Washington, DC area.

## 8.0 Security Clearance

This work will require only unclassified access.

## 9.0 Government Furnished Property / Government Furnished Information (GFE/GFI):

No additional GFE/GFI is required at this time. If the contractor determines that additional equipment and/or software is required to support this task, the contractor will present a list of required equipment and/or software, with a justification and impact statement, to the Associate Director or Deputy Director for Technology for approval and acquisition. All equipment and software purchased by the contractor in support of this task will become the property of the DMSO, upon contract completion and must be obtained, inventoried, maintained, and returned in accordance with published DMSO property management procedures.

## 10.0 Travel

All travel required during the performance of this task order shall adhere to the Federal Travel Regulations (for travel in 48 contiguous states), the Joint Travel Regulations, Volume 2, DOD Civilian Personnel, Appendix A (for travel to Alaska, Hawaii, Puerto Rico, and U.S. Territories and possessions), and if required by the SOW, the Standardized Regulations (Government Civilians, Foreign Areas), Section 925, Maximum Travel Per Diem Allowances for Foreign Areas (for travel not covered in the Federal Travel Regulations or Joint Travel Regulations). Local travel is required. All travel will be coordinated and approved by the DMSO Deputy Director of Technology, or her designated appointee, prior to actual travel.

## 11.0 Materials

The contractor may be required to furnish material is support of this task, when directed and approved by the COTR.

## 12.0 Period of Performance:

The period of performance shall be 12 months from the date of contract award.

## 13.0 Deliverables

The contractor shall provide the following deliverables:

13.1 Monthly Status Report – The contractor shall deliver a monthly status and technical report by the close of business on the **10th** of each month. This report shall summarize: work accomplished during the reporting period, to include the results of meetings, and resources consumed to accomplish the work (labor, travel and overhead costs); work planned for the next reporting period and an estimate of resources required to accomplish that work (detailing labor, travel and overhead costs); an overall status of resources; PCO approved equipment/materials procured; and status of all deliverables.

13.2 Workshop Record - The contractor shall deliver a copy of the workshop record for review 60 days after the workshop's completion and the final workshop record 90 days after the workshop's completion. This report shall contain the keynote papers and presentation materials, position papers of each participant and their presentation materials, summaries of the discussions in the working sessions, graphics and tables developed during the working sessions, consensus recommendations of the workshop, short point papers describing the positions of any participants at variance with the consensus recommendations, and bibliographic material suggested by the participants. The final submission shall reflect the changes suggested by DMSO reviewers.

13.3 Workshop Executive Briefing - The contractor shall deliver and present a briefing summarizing the results of the workshop. This briefing shall contain overviews of the working session results, the workshop consensus recommendations and the individual position papers dissenting the consensus views.

13.4 Technical Paper Summarizing the Workshop Results – The contractor shall prepare, submit and present a technical paper summarizing the workshop's results to an appropriate technical conference.

The government has ten (10) working days to review and accept all deliverables.

The contractor shall have twelve (12) working days to correct any changes made by the Technical Director for Technology or the COTR.

The contractor's monthly reports will highlight any potential problems with respect to completing the work as contracted (e.g., potential resource shortfalls).

All reports shall be in formats approved by the Deputy Director for Technology or his/her representative. All reports shall be submitted in electronic and hardcopy and prepared using a Microsoft Office application.

# Appendix 3: Participants at the Workshop on the Scientific Exploration of Simulation Phenomena


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# Appendix 4: Session 1 Notes

The notes contained in this appendix refer to the participant making a statement by a two or, in one case, three letter code. Table 1 connects these codes to the participant speaker. These notes also sequentially number the statements, sometimes consisting of several sentences, from each of the speakers. The session records in the main body of this report refer to these numbers to correlate the record statements with the actual statements from the participants. This numbering begins with the first statement made in the session. Thus, a statement number higher than another signifies the utterance of that statement AFTER the lower numbered statement. A sequence of numbers is associated with the particular transcriber source. A new sequence begins with a change in transcriber source. In most cases, the two transcription sources worked simultaneously in workshop time. Letter prefixes were assigned to each source in the session records (e.g., a citation of [A046] refers to transcriber source A (in this case, Mr. Harmon) and the 46th statement). The assigned letter prefixes are shown with the transcriber source heading.

**Table 1.** Codes for the Participant Speakers.

| Code | Speaker |
|---|---|
| **BZ** | Bernard Zeigler |
| **DG** | David Gross |
| **DL** | Dell Lunceford |
| **DN** | David Nicol |
| **DP** | Dale Pace |
| **EP** | Ernest Page |
| **LA** | Larry Alexander |
| **MR** | Marc Raibert |
| **PD** | Paul Davis |
| **RS** | Randall Shumaker |
| **SH** | Scott Harmon |
| **SN** | Susan Numrich |
| **WS** | William Swartout |
| **WW** | William Waite |
| **WWh** | William Whelan |

In general, the transcribers attempted to capture the speakers' comments as accurately as possible where those comments clearly pertained to the workshop topic. Some discussion occurred between the participants that was not relevant (e.g., idle banter, jokes, references to the lack of coffee in the morning). That discussion was not recorded in these notes. The nature of spoken discourse made identifying individual sentences difficult so the transcriber made no attempt to do more than make a casual distinction.

### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **DL:** how do I get a well-trained workforce and quality from them? that's the single biggest issue; most problems can be tracked back to the workforce; he's got a couple of issues: what does he have to surround that workforce with to get them to perform quality work? he wants to decompose that set of questions; what makes a quality workforce and what to surround it with? he'd like to believe there is a science but that may not be the right question; there may be no science but just a set of first principles; he doesn't need

the answer necessarily; answering the quality workforce problem helps give him some vectors; it might take a couple of years to fashion a science

002. **DP:** we must put a time dimension on that question; does he mean a couple of years or many years?

003. **DL:** yes, he wants a quality workforce within 2 years but doesn't think that will happen; he doesn't want to focus too closely because that may compromise the longer vector; but, we must do something near term

004. **WW:** is he concerned with the quality of leadership?

005. **DL:** that's going to happen anyway because of the value of simulation; the question is how many false starts must we make? can we make it move faster and cleaner? everyone wants to do this but no one understands the value of it so they won't put any money in it

006. **MR:** is there enough value to this? what are the defects in the value proposition?

007. **DL:** that's good question to answer but that may sidetrack us from how to get a quality workforce

008. **DP:** does the quality of workforce substantially change the value of simulation? that determines how much quality to invest in; our blundering has produced results

009. **WS:** there are lots of fields where there is a quality workforce; what factors have led us to where there is a quality problem in simulation? there's not the opportunity for a cottage industry of prima donnas; number of factors influence this: what are the training programs, standards, etc.?

010. **SH:** what is an example of a quality workforce?

011. **DP:** the medical profession

012. **Group:** laughter

013. **DL:** part of my problem is our business model; commercial industry has a different business model; maybe it's a government problem; he can't weed; he has a bunch of people to whom he pays a mediocre wage and then when they don't deliver he just gives them more money

014. **WS:** other things are going on in the Government that are pretty high quality

015. **BZ:** there are other professions that produce quality work that don't depend upon science

016. **WS:** physics produces quality work

017. **BZ:** they're engineers

018. **WW:** we have a customer who wants to select from a labor pool; you can get a good doctor or lawyer if you want to

019. **DL:** you can select a good mechanic; a certification process helps; lots of us select by organization; we assume that the organization will produce quality work

020. **SH:** you can't make those assumptions with mechanics

021. **DL:** how about in larger organizations?

022. **SH:** large organizations just provide the infrastructure for customer service

023. **SN:** the peer review process helps; lots of professional organizations provide peer review

024. **DP:** SCS has a peer-reviewed journal, how many people get that journal?

025. **BZ:** they had two journals, one popular and one archival; the popular publication was converging to the archival one; they combined the two and created another general interest publication; the archival journal has 700-1000 subscribers

026. **DP:** the few places that do serious publications related to simulation have small distributions; the simulation community tends not to read peer reviewed journals

027. **WW:** we must decide what considerations are important

028. **DL:** assume that there is a foundation of principles and that the workforce lives in environment where they can do good work; if he was going to hire an electrical engineer, there are questions that he won‘t need to ask (IR, gains, etc.)

029. **DG:** that's because a codified body of knowledge exists that is taught

030. **DL:** there should be things that he can assume when he knows that someone has a degree; he'll then ask about experiences, more vocational stuff; what are the questions that he should ignore? that will tell him about what the fundamentals are; in the next step, he hires a person and gives him a job: his expectations are that he'll have a set of practices that he'll use to do his job; he might have a certain understanding about how to define user requirements and turn those into design; he should know something about building a quality simulation engine or selecting a good commercial engine; so, what are those things, practices? ... a path of best practices; he will try with DMSO to create a set of best practices; they will cobble something together for the short term then build up from a peer review process to get a quality set

031. **DP:** that sounds like the books we discussed

032. **DL:** what if a guy was doing research then I should have a different set of questions?

033. **DP:** SIMVAL99 had 100 leaders in simulation attend; the ignorance of V&V technology and practices was astounding; he wouldn't expect people to keep up

034. **RS:** there are two levels of specificity: their specialty plus math and physics; do you have the expectation that they understand software and systems engineering? almost anyone can declare themselves a simulationist

035. **DL:** that's part of the question that we need to answer; he believes they must have understanding of math, abstractions, turning algorithms into software

036. **DP:** a third of the people who he has taught do not have that understanding

037. **DL:** how can you be a simulationist without popping out some JAVA?

038. **WW:** what's the body of knowledge that should be held and what processes and practices should be competently executed?

039. **DG:** and, what is the body of literature in which you could expect someone to be knowledgeable and stay current?

040. **DL:** in old days, we trained people in the journeyman process, starting in an apprenticeship; today we call that mentorship

041. **WS:** that's what happens in CS graduate school; it's very much an apprenticeship process

042. **BZ:** most of our students leave after a BS

043. **WS:** that's the difference between a researcher and a practitioner?

044. **DL:** you will ask different people and jobs different questions; a third point is related to the issue of not trying to treat it as an engineering problem; why would he hire someone to do a research project who does not have a publication list and history of success?

045. **WS:** in the beginning in computer science, there weren't undergraduates; there were typically PhDs and MSs; in simulation, it's almost the reverse; there aren't many PhD programs focused on simulation; that's the reverse of what went on in computer science; there just isn't the academic or scholarly tradition; that may explain our current state

046. **DL:** is simulation a technology itself or something that is strapped into everyone else's technology? simulationists must have three skill sets: simulation, software and the domain being simulated; how do you solve that problem? put simulation into the domain or teach communications between the fields?

047. **WW:** in medicine, do you ask doctors to learn simulation? no, they reach back to the specialists; first teach them to be simulationists then send them off to their specialties

048. **WS:** the people who did medical expert systems, the CS people, needed to learn medicine and the doctors needed to learn expert systems; that happens in other fields; mechanical engineering has changed radically; in past few mechanical engineers used computers and now they build expert systems

049. **WW:** but, expert systems people keep their domain; simulation doesn't have that center; it's too hard to run an industry where you must assume the guise of another field

050. **WS:** it's a really bad idea for expert system people to pretend to be physicians at medical conferences

051. **SN:** Disney doesn't want CS people; they want the artists; they feel that anyone can program a computer; what are we looking at in simulation, people who can design systems? the people who we are hiring that can do everything only because they can produce code

052. **DL:** why do we hire code poppers to build simulations?

053. **DP:**

054. **MR:**

055. **RS:** the guy running a simulation project doesn't write code but does design the architecture

056. **DL:** let's take the basics and turn them into formal definitions (e.g., interoperability); after someone publishes an experiment there are those who wax philosophically and a group who repeats the experiments; we don't do that in the analytical community; no one repeats the processes; can someone else get the same results?

057. **DP:** we used to have that when we had multiple simulations doing the same thing

058. **DL:** that's not the same thing

059. **DP:** it confirms that the simulations are doing the right thing

060. **WS:** each tool will have implicit assumptions; we want to know that those assumptions don't have a significant influence on the outcome

061. **WW:** he addresses congruence in repeatability in science

062. **WS:** we want to see how close the simulation is to the real world; we must prove that the implicit assumptions don't make that big a difference; each party can construct an experiment that produces similar results; in this example, assumptions are like contaminants in chemistry experiments

063. **DL:** they're the uncontrolled variables in experiments; we don't do that in DoD/Army analytical processes

064. **DP:** a large part of simulation community does repeat experiments, it's called benchmarking, e.g., different operating systems or checking a modification to a simulation to see that it hasn't corrupted the results; repeatability goes under that name

065. **DL:** what could you expect the core set of knowledge that a simulation person has?

066. **BZ:** that's the core question that the certification people are asking; it's referred to as a body of knowledge; some work has been done; it would be better to see the results of that work and start from there

067. **DL:** is there an expected set of practices (skills) that a person knowing simulation has? is there a core set of things in the form of a science or foundation that could be used as the basis for the previous two? also, we should explore issue of how you gain this domain expertise ... specialties within simulation; also we need to answer what the step forward is? he hasn't been following the certification efforts

068. **BZ:** they brought together the top people; there will be a process and certificate; it will also result in a compilation of core knowledge; what can we do better than that?

069. **SH:** is there a core knowledge?

070. **DP:** they have a good way to find out

071. **BZ:** yes

072. **WW:** no

073. **DL:** if he hires a BS in electrical engineering from a credible university then can he assume that they have certain knowledge about what it means to be an engineer and an electrical engineer especially?

074. **DG:** if it's an ABED accredited university then yes

075. **WS:** there would be a certain set of things that if he didn't know them then you'd be surprised

076. **DL:** as the next question, if he hires a simulation guy who claims to have a degree from a reputable school could he make the same assumption?

077. **WW:** no

078. **BZ:** it doesn't exist, an undergraduate degree in simulation; maybe there's a program in Sweden

079. **RS:** UCF has an associate degree then an MS and a PhD; there is a hole there; the issue is that there's lots of overlap with computer science; there doesn't seem to be a huge difference between computer science and simulation at the BS level

080. **DL:** why couldn't someone come from the mathematics department; most simulation people can't turn algorithms into simulations?

081. **RS:** which is weakest, system design stuff or algorithms?

082. **DL:** both, we can't advance simulation technology until we have people who can collect data and turn that into algorithms then turn those algorithms into a working simulation

083. **WS:** simulation is primarily an add-on to another degree; it's not identified as a separate body of stuff

084. **BZ:** he knows 5-6 universities who have pursued that, they started a PhD then are trying to go down to an MS; there are difficulties in establishing a specialty because the current cores are packed with existing stuff; we don't teach people modeling; there are very practical problems for why we can't start a discipline; we need the motivation from the Government for instance

085. **DL:** shouldn't the path of simulation be at MS level?

086. **DP:** law, theology and medicine don't have undergraduate levels; people start after that

087. **RS:** you must get a general degree then specialize

088. **WW:** is there or should there be a body of knowledge and the answer is yes, absolutely; is there one now, absolutely not

089. **LA:** we need to go to a testing services and have them build a SimCAT; students must meet certain criteria then go on to another degree

090. **DL:** can I assume that simulation can evolve as a subspecialty?

091. **BZ:** the problem is putting a modeling course into an existing curriculum

092. **WW:** it's everyplace but it's no one place; that situation fundamentally undermines establishing a presence of M&S across domains; you can stick it into other curricula

093. **DL:** a BS cannot claim to be a simulation person

094. **WW:** we should want that within 5 years

095. **DL:** are there any assumptions that you can make when a person presents themselves as having studied simulation?

096. **DG:** you can assume that they know some specialty

097. **SN:** the problem set that we're considering is inherently multi-disciplinary so no one can represent that

098. **WW:** that demands a comprehensive knowledge of simulation; other areas are demanding as well

099. **DL:** should I ask the question "are you a simulationist?" part of this is being able to create algorithms; those people have different skill sets than someone who creates simulation engines

100. **WW:** that's true of general practitioners and brain surgeons; will you pay for it? if you have a need then everything else should follow

101. **DL:** after a general degree in engineering, the first job gives the focus

102. **WW:** ten years from now you want a person to come out with the ability to say they are a simulation person

103. **WS:** it will start out as a PhD or MS

104. **WW:** that doesn't matter

105. **DG:** is there a body of knowledge?

106. **RS:** our associate degree trains people to fix simulators; two more years gives them a BS in mathematics, computer science or engineering; they can then go back to simulation at the graduate level; is there enough unique stuff to make it a separate BS?

107. **DL:**

108. **RS:**

109. **DL:**

110. **RS:** is there enough body of knowledge to fill two years?

111. **BZ:** there's plenty of knowledge to fill two years

112. **WW:** there is and it's needed

113. **DP:** for the short term, short courses are the only way; an academic solution is ten years away

114. **BZ:** yes, there should be a BS in simulation but there are the culture and people problems

115. **MR:** there's also a marketing problem; when do we get to the point where people will hire these people?

116. **DL:** there is consensus; whether it's right today or not, it is reasonable to have a BS in simulation and have an equivalent view as people do in engineering

117. **EP:** that's not true unless there's a market outside DoD

118. **BZ:** there is a market

119. **DL:** he wants to hold that; do we agree? MR and EP don't; derailing someone from electrical engineer might be the right thing to do now

120. **WS:**

121. **DL:** if he trains a guy as a simulation person then he must believe that he has a job when he finishes; a basic degree in engineering gives a lot of mobility

122. **MR:** they must believe that they have a job and that they have pride in that; it might take two generations; we must have people that have been in that program hiring people

123. **SN:** she wants domain experts and an interdisciplinary crew

124. **DL:**

125. **DG:** what's the demand? graduating someone in simulation is like graduating someone in circuits design

126. **WW:** he wants a simulation person to support their range of problems; they need identity, integrity and persistence

127. **DL:** if there was pride in the profession and there were people to hire them then there would be a market for people in simulation

128. **BZ:** being a generalist may be true only by default; simulation people would be very flexible and able to fit into a wide variety of contexts; they could specialize with minors; they would have the modern skills that people do not get in any orderly manner now

129. **MR:** at CMU, they proposed not to teach calculus to make room for other things; he was horrified; a program like this at the undergraduate level will have those pressures; what will you give up?

130. **BZ:** starting fresh leaves room for methodological courses

131. **DL:** is it unreasonable to assume that someone would enter college with goal of being a video game designer?

132. **BZ:** yes, it's reasonable

133. **DL:** then why not a simulationist? they could build flight simulators for American Airlines

134. **RS:** most people entering college don't have that a specific idea

135. **BZ:** the goal of a job is often the motivator; 2 years ago, they had tremendous flood of students interested in video game design

136. **DL:** a degree in simulation is good and could go down to BS level; a degree program requires a core body of knowledge for that; we need a willingness of commercial industry to hire these people; we need academics willing to teach it and we need people willing to do it; as the next question, if he hires an experienced simulationist then watched that person executing his craft, are there procedures, understanding and practices that he could expect?

137. **EP:** a simulationist equals a simulation scientist; what would he expect a scientist to do?

138. **DP:** A. Law has taught simulation and comes from the industrial engineering world; he never personally was involved in simulation that had more than 6 man-months in it; the expectations should include large systems as well as small; Law has very narrow base

139. **WW:** a degree in simulation should mean that he could do what is expected

140. **DL:** a 6 man-month project vs. a large project should exercise the same discipline

141. **DP:** they involve different skills and processes

142. **DG:** an apprentice works under masters or is given very small tasks; Boeing has apprentice, journeyman and masters levels and sets of tasks that can be assigned to each level

143. **DL:** if he was hiring a journeyman to masters, could he expect an observable set of practices indicative of good work?

144. **WW:** it's like a body of knowledge; they are not well defined today nor are practices well accepted today

145. **DL:** we all would expect this to occur; he should be able to get requirements from users, track requirements and turn requirements into simulation needs; he should understand HLA and its services and implementation if in the DoD; he would expect that

146. **WW:** what's the difference between this list and the list in the body of knowledge?

147. **DL:** DP mentioned that ... what happens over next five years to achieve that? DP said that will come from non-university processes and OJT

148. **WS:** there may be short courses but another answer is the apprenticeship model, a PhD and MS in academia; a short course gives knowledge but no hands-on experience; people with experience will need to lead these efforts

149. **WW:** think about it as a coordinated campaign; things at the level of profession, getting courses in place, in industry, establish standards and body of knowledge; marketplace where customers establish presence; there are activities that fit into all of these areas; we must do at all levels; it's doable but we must be careful

150. **DL:** yes, he wants an MS in simulation but he really wants one good 3 hour course; can the university system create courses focused on simulation technology? he could drive people to that program; it must be online because his practitioners are all over the country; he can't send them off to do 3 hour course (unless it's in the summer); he's developing a program to develop M&S officers; they will spend their 1st year learning the

Army domain; then they'll spend their 2nd year learning the practice of simulation; he could add to this the university component

151. **BZ:** there is a mechanism called the National Technological University; it makes course material available throughout the country; that means that there must be a broad demand for it

152. **DL:** I can create that demand; the advantage of the university is that he'd get other people as well

153. **BZ:** they do have courses at the graduate and undergraduate levels on basic modeling and simulation; it's gaining popularity; that can be available online but there are difficulties associated with that, implementation issues

154. **DL:** he has thousands in Army with that interest; there are two types of people: simulationists and people who must understand simulation, e.g., program managers; they currently know software development and program management but not simulation; the new program manager for WARSIM doesn't understand simulation; it would be nice if he could get that knowledge

155. **BZ:** he will give course at Ft Huachuca for managers to give them a broad familiarity in simulation; this should motivate them to take an MS at UofAZ

156. **DL:** in Functional Area 57, they're going to train by putting them through a 16 week program; they are trying to define that program now; he wants to do it in an academically acceptable way so that the hours are transferable; he's had some success in pursuing that

157. **BZ:** we must ease them into taking the proper level of courses; we should help them answer where they could specialize

158. **DL:** is there practice that I can expect them to perform; basic good research practices are well understood; we don't practice them in my domain

159. **SH:** we know what they are but consistency is a pervasive problem throughout science

160. **DL:** we agreed that there is a body of knowledge upon which to base an academic program

161. **WS:** how do we move forward to get a set of practices established?

162. **DL:** he wants to see a couple of things to move forward; yes, there is a body of knowledge; we want a degree program; we want a set of practices for engineers and scientists; yes, we want a set of processes in place to support that; in the short term that may be a set of courses that teach current best practices; we may want a set of best practices documents as well; he'll attack establishing a set of courses within Functional Area 57; he's also pushing people back into quality publications; it's hard to separate good work from bad work, especially for new people; he hopes that we end with a set of actionable steps, perhaps the content of new workshops

163. **DL:** is there a set of ...; we accept there's a core body of knowledge; is there a science or formal discipline underlying that? is there a need to create formal definitions for parts of our knowledge?

164. **SH:** we want to get at fundamentals; what are the fundamentals associated with simulation? we want to get at that through the scientific discipline; through that we create science; this is somewhat consistent with all the definitions; part of that are repeatable experiments; science also has a theoretical component; science is not just controlled experiments but encompasses astronomy and cosmology; that includes repeatable observations

165. **WW:** using scientific methods to understand simulation and does fundamental knowledge underlying simulation involve science, those are two different things; we're after the latter

166. **DL:** the answer has two components; the answers that belong to other people and the answers that belong to simulation itself

167. **WW:** is there anything that is irreducibly modeling and simulation?

168. **DL:** part of the science of simulation is mathematics and part is something else; with that we don't have to create everything; let's find the pieces that belong only to modeling and simulation; is there something that's just modeling and simulation?

169. **BZ:** I wrote the answer to that question in my book (35 yrs ago); he can define something unique to modeling and simulation; we do have a core set of principles that are mathematical in nature; you don't really know what you're doing until you can state it in a mathematically consistent way

170. **DL:** we don't have to start from scratch

171. **BZ:** he can list chapters from his book; these exist

172. **DL:** some of those things are not necessarily a science

173. **BZ:** they are theory

174. **WS:** there's plenty of content there but it sounds more engineering than scientific activity; how do you take things in the world and create a model? engineering is concerned with creating things; it sounds more engineering than science

175. **BZ:** addressing a viewgraph, we are talking about both science and engineering; if it can improve practice then it becomes engineering; you need core knowledge to do that; the ability to predict the motion of stars and planets gave us the ability to codify other practice

176. **DL:** my question is do these four boxes exist?

177. **BZ:** that's my session

178. **WW:** if the referent is not something that has existence then it's engineering

179. **SH:** if it doesn't proceed to utility then it's not engineering

180. **WW:** both science and engineering do useful things; does it have an objective referent is the question; theory could be one place to make investment; it doesn't matter whether it's science

181. **MR:** is physics the right model? it is the theoretical thing that drives everything else; there are lots of other areas where big systems problems are more central and lots of other things are in play; is the science the most important thing about it?

182. **BZ:** to get to the theory, what is the end state of science? that may not be where we are now; we start with a central theory then do the empirical stuff

183. **DL:** I said, I want the people who are building current simulations to have the fundamentals of building simulations; we can't go back to the fundamentals (first principles) today to get to WARSIM; we're making it up as we go along and what we think the practice is; let's say that time management is uniquely simulation, can I show that the five time management schemes in HLA are derived from first principles? that's a fundamental question

184. **DP:** we're missing the heuristics that bridge builders gained from many failures

185. **DL:** he likes the alchemy and chemistry thing; JSIMS wants to turn lead to gold and they never got it; let's not drive this analogy too far; chemistry has its foundations in alchemy; a lot of good things came out of the search for the secret of turning lead to gold; maybe from these projects we learned a good deal about simulation

186. **DP:** but they're not documenting these lessons

187. **DL:** we must change the current mindset for documenting the efforts of large simulation projects

188. **DP:** the lack of archival literature is a problem; that must include both failed and successful experiments because of all the reasons for publishing candidly

189. **DL:** that's why I'm pursuing the peer-review process; watch over the next 6 months to get peer-reviewed papers from MC02; he wants to understand what happened and doesn't want it quantified by the people trying to justify a program

190. **SN:** you can get some of that at a low level but you will not get anything at a higher level

191. **DP:** Pat Sanders tried to collect a series of lessons learned from a set of projects and it never saw the light of day

192. **WW:** the Canadian systems engineering office is writing into the contracts they issue that lessons learned must be captured; they offer that we'll help you but we'd like to see the lessons learned

193. **DL:** I would like to see the wording for that

194. **MR:** will you send the message that this program was a great success because this is what's different from what we got and what we wanted; you must get a culture to reveal lessons learned by making sure that people are winners if they do that

195. **DL:** yes

196. **BZ:** what if a JSIMS-like thing, that didn't meet its goals, if we'd gone back to the literature (like my book), could it have met the goals? we don't know that if they'd had the existing knowledge then they would succeed as opposed to not having the background knowledge

197. **DP:** we don't do the review/assessment of existing programs to analyze failure modes

198. **WS:** that's because the failures are not so obvious

199. **DL:** STOW was a failure because it didn't meet its goals; but it wasn't because it created a huge body of knowledge; no body at Congress wants to know you spent a lot of money and failed

200. **WS:** the goal was to acquire a better understanding of how to use these simulation tools and techniques; but that wasn't the real goal

201. **DL:** that's not what happened at STOW; DARPA programs should always fail to some degree; STOW got enormous visibility and the test case was a joint training event; that way it violated the tenets of research and couldn't fail because that's how it got its money

202. **SN:** it became a technology demonstration as opposed to a research program

203. **SH:** we should revisit these issues

END OF SESSION

**NOTES TRANSCRIBED BY B. BAILEY & L. ALEXANDER (B PREFIXES)**

**Introduction**

001. **DL:** Mr. Lunceford opened the session by asking, "How do I get a well trained workforce and what do I need to surround the workforce with to support it? Also, we might possibly need to address the "science of M&S" as part of the problem."

Factors bearing on the problem:

- Training
- Business practices
- Education
- Certifications
- Peer review process

**Question 1:**

002. **DL:** Are there skill sets or a core body of knowledge that an M&S professional might be expected to have?

003. **BZ:** At the bachelors-level there is no degree qualification for M&S. Several schools are starting the process in reverse order (i.e., PhD, Masters…with the bachelors degree yet to be implemented.

004. **RS:** There is not a core body of knowledge at this time to justify the initiation of a bachelor's degree in M&S.

005. **DP:** An M&S undergraduate degree is probably a decade away.

006. **SN:** A multi-disciplined background is extremely important as an entry to an M&S career field.

007. **DL:** Then I should look at a Masters-level degree in the M&S professional context?

008. **Group:** Numerous members came to the consensus that the answer was "yes" because M&S is an additional skill that is adopted as a specialization to other educational functional disciplines.

009. **WW:** M&S should not be placed as a sub-specialty in EE, BS, SE, etc. These don't provide the cross-domain visibility required.

010. **DL:** What are the M&S skill sets/core body of knowledge?

011. **DG:** Boeing has a documented process for professional skill applications (i.e., apprentice, journeyman, and masters).

012. **DL:** After much discussion, I think we have consensus that it would be realistic to expect that a similar knowledge-based system could possibly be implemented for the profession of M&S along with a core body of knowledge. In the short-term, he would be interested in being able to have a series of courses available (online) to send Army M&S personnel to as part of a training program.

013. **DP:** Employer supported short courses are only a near term solution.

014. **BZ:** The University of Arizona has a basic entry-level graduate course for M&S that could possibly be offered online. Also, the National Technical University is set up to offer discrete event courses.

015. **Group:** A degree program in M&S is a good thing. Working down to the BS level in the future is desired. Need to develop a core body of knowledge. Industry will want to hire a qualified simulationist. The degree program must be broad enough so as not to unnecessarily limit recipients.

**Question 2:**

016. **DL:** What are the core fundamentals (educational/skills/sciences/etc.) of an M&S professional? Is there a need to start creating a set of core definitions that address the issue? [I got the question as:] What are the practices and procedures that an experienced simulationist would use? – Solicit requirements. Develop simulation needs from requirements. Research COTS / GOTS. Understand the existing standards.

017. **BZ:** As outlined in my book, we already have a set (though probably not complete) of the fundamental principles that provide the definition of the science of M&S.

018. **DP:** There is not a body of literature that documents the lessons learned of developing M&S products. In other words, there is no record of "what works and what doesn't".

019. **WS:** To build simulations you need to understand simulation, understand computer science, understand the domain.

020. **DL:** He is considering possibly conducting a workshop addressing peer review and lessons learned for the M&S community.

021. **Group:** The group recommended: 1) that successes should be highlighted as a component part of the program to balance the negative aspects of the program; 2) that the peer review committee would be extremely important to the success of the workshop; 3) that there was reasonable cause to pursue the workshop because participants would likely be motivated to submit papers.

022. **NOTE:** The group did not provide input/answers that addressed the question above.

023. **DL:** How do we define the core knowledge to get at the fundamentals?

024. **SH:** Through the scientific method – develop the science.

# Appendix 5: Session 2 Notes

The notes contained in this appendix refer to the participant making a statement by a two or, in one case, three letter code. Table 1 connects these codes to the participant speaker. These notes also sequentially number the statements, sometimes consisting of several sentences, from each of the speakers. The session records in the main body of this report refer to these numbers to correlate the record statements with the actual statements from the participants. This numbering begins with the first statement made in the session. Thus, a statement number higher than another signifies the utterance of that statement AFTER the lower numbered statement. A sequence of numbers is associated with the particular transcriber source. A new sequence begins with a change in transcriber source. In most cases, the two transcription sources worked simultaneously in workshop time. Letter prefixes were assigned to each source in the session records (e.g., a citation of [A046] refers to transcriber source A (in this case, Mr. Harmon) and the 46th statement). The assigned letter prefixes are shown with the transcriber source heading.

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In general, the transcribers attempted to capture the speakers' comments as accurately as possible where those comments clearly pertained to the workshop topic. Some discussion occurred between the participants that was not relevant (e.g., idle banter, jokes, references to the lack of coffee in the morning). That discussion was not recorded in these notes. The nature of spoken discourse made identifying individual sentences difficult so the transcriber made no attempt to do more than make a casual distinction.

### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **BZ:** he didn't come to this workshop convinced that there was a simulation science and became more convinced that there is and that it's worth doing; take the mother of all sciences, physics, and backtrack to understand how that evolved; then try to identify where we are and put names down; physics has both phenomena and practice; he's talking about astronomy; then directed observation and controlled experiments that created the data describing the phenomena that could be used over again; then there's data mining that's trying to find the relationships; but, you don't influence practice until

you have theory that goes beyond data mining; it hypothesizes entities that are not directly observable; these enable predicting behavior; hypothesis generation, guessing the underlying cause and testing that by making and testing predictions; ability to predict, ability to confirm or falsify predictions; that leads to practice but only if the theory is applied; what was the killer app?

002. **SH:** mechanics is a pretty good example; it depends upon which of Newton's laws you're talking about

003. **WWh:** artillery

004. **DL:** engineering lags physics by 100 yrs and physics lags math by 100 yrs

005. **WS:** engineering precedes

006. **SH:** that's not true now since engineering doesn't precede the science; nuclear engineering is an example of science preceding the engineering

007. **DL:** we never would have had skyscrapers without Newton

008. **BZ:** there were guilds that were very successful

009. **SH:** well, they only got to a certain point

010. **BZ:** we have lots of observations but no controlled experiments in simulation

011. **DP:** we do have controlled experiments; every time you try to compile a simulation and when you compare the results with the real thing

012. **BZ:** there is a theory for hypothesis generation but they're not well connected to the empirical part; we have some confirmation (His theory) that it works; but, we never discuss falsification; we have lots of practice and application but it isn't connected well to the theory and the data: he can list references for these things

013. **SH:** you'll send those to me?

014. **BZ:** we do have data but not the use cases; lots of the articles are small cases that don't scale up; we do have some discussion of the phenomena like fidelity

015. **DP:** the problem with experiments is that there are established methodologies and simulation experiments don't report experimental conditions rigorously; it's not the same experimental description and you can't replicate and experiment from what is described

016. **BZ:** what are some references where that has been done? we can't say what's been bad or what we should do

017. **WW:** he asserts that BZ has cited things on the periphery but nothing that's specific to simulation; that makes it thin and shallow because most of these things are at the margins of other disciplines; we're trying to solve a problem, not understand simulation; therefore all the examples are domain activities and not the scientific conduct of experiments

018. **SN:** observations or experiments always work the instance

019. **DG:** STOW exists and, in theory, things should have been learned; is STOW a source that we could data mine

020. **BZ:** its data may not exist in a form that we could use

021. **DG:** these programs have existed and they produced artifacts; are we listing these programs?

022. **SH:** will you send me lists of the things that we've done (DG and WW)

023. **WW:** building bridges that fall down is engineering and not science; most of what we do in M&S is more like building bridges

024. **SN:** can we look at the bridge or JSAF as phenomena and probe/observe them?

025. **BZ:** maybe we could do controlled experiments

026. **DG:** what do you want me to do, fund two WARSIMS?

027. **WW:** as an example of a failed attempt to get more information, they sent a proposal to Hollis to assess the last 6-8 simulation projects and they were told that the EXCIMS was too busy; it's not in the culture to do this kind of thing; we must find ways that it can be acceptably received

028. **DL:** consider running a lessons-learned peer-reviewed workshop; we would ask the people involved in simulation programs to generate post mortems; for example, how hard it was to set up multicast groups in STOW? the bulk of work in creating an exercise was that

029. **DP:** software engineering does studies that identify the effort associated with each phase of development; we don't do that for most simulations; in small simulation efforts 10-20% is spent on actual simulation issues and >50% on interfacing with the people; how you allocated what you're representing in the simulation is interesting

030. **BZ:** can you give a reference to a software engineering text that talks about gathering that sort of data?

031. **DP:** the NIST software study has some of that information and I'll send that reference

032. **BZ:** Rainey and McLeod did go through these various aspects and did cover a lot of this ground

033. **DG:** where's that book? how about the VV&A RPG? the data thing is more observation and McLeod's book is more data as is the RPG

034. **SN:** what are experiments?

035. **BZ:** experiments test theories; there is a theory about using discrete event vs. classical things and it describes what is provably better; we should check whether that theory applies; is it right enough for some applications? that could be a controlled experiment

036. **EP:** we have groups that do that well like the distributed simulation people; they've done a lot of controlled experiments (e.g., optimistic vs. conservative synchronization); they've also done a lot of theory (time warp could outperform Misra); lots of examples of science applied to simulation phenomena; he'll send pointers but what phenomena?

037. **BZ:** Fujimoto's book is a general reference to that

038. **SN:** do you want to use existing simulation instances to derive observed data in the absence of theory? what's the stuff to generate data?

039. **RS:** every implementation tests existing theory; some work perfectly, some not

040. **SH:** that depends on where you are; if you're just using a heuristic to build something then you're just testing that heuristic

041. **RS:** a heuristic is a theory too

042. **BZ:** I made a distinction because a theory is where you're trying to explain the rules of thumb; that's a deeper characterization

043. **RS:** you don't use quantum mechanics to design bridges

044. **BZ:** at Newton's time, it wasn't clear that there were masses and forces

045. **RS:** failure should send you back to the theory to modify it; there were theories before Newton

046. **BZ:** we don't have examples where we're really testing the theory

047. **RS:** STOW tested the theory that I have enough information to build

048. **EP:** a posteri, you could propose these things

049. **DG:** all that stuff is things that could be considered

050. **BZ:** any more references?

051. **DG:** fidelity is the only phenomenon uniquely associated with simulation; other things are not unique to simulation; and, I can give you references

052. **WW:** the core part of M&S is the abstraction bit; the theory for that may be evident or coherent but that is an appropriate part; we should go looking for more information on that topic (e.g., cognitive science); there we may find stuff about abstraction that's relevant

053. **BZ:** references for abstraction in cognitive science?

054. **SH:** you'll send me pointers; WW knows them and WS can help

055. **DL:** why I am not able to make more effective progress in HBR is because it's not really a simulation problem; it's an HBR problem;

056. **SN:** it's better if you articulate a problem and stay out of the solution space; go to the right phenomenologist but with the right problems

057. **DP:** let's move to something more basic; we do not have unambiguous processes for identifying what we need to represent or at what fidelity; there's a fundamental modeling problem; we don't have theory developed for deciding what level of fidelity is appropriate for a particular application

058. **BZ:** he used the imagery interpretation domain because they do have a scale and that should be a reference

059. **MR:** are there simulations abstracted from those applications?

060. **SN:** how do we do this across a broad range of systems?

061. **DL:** he believes that simulation technology has been stalled for 3-5 yrs; no different today than 5 yrs ago and the things that we can simulate are still the same; one of the reasons we don't move forward is that we allow people to cycle through the things that we can do; no rigor in the system so we can't make progress

062. **EP:** we've been working on the same systems for the last 5 yrs

063. **DL:** we might want to include the apparent rediscovery of distributed simulation; he'll send reference

064. **DG:** new materials and experience provide the grist for science; when they ask why things happen they created science

065. **SH:** got to this point because we don't have a formality or science and can't go further without that

066. **BZ:** take microelectronics; we couldn't have gone anywhere close to where we are now without M&S; it's almost automatic that has become part of the process; it can succeed

067. **DL:** do they apply general practice to be successful in a limited domain? can we use what they've learned?

068. **WW:** we see that all the time when we sell a product to different domains (automotive and pharmaceutical); that's characteristic of M&S and why we need a generalized body of knowledge; there's a huge margin to applying it in DoD

069. **DG:** it's like English because lots of people use it for a lot of different things

070. **BZ:** there are distinct levels of abstractions that relate to general principles that are not associated with application

071. **WW:** Parnas had simple criteria for modularizing software (had to do with semantic self consistency); that's almost theoretical guidance that had huge implications; this might be an example of a path with great application

072. **EP:** understanding abstraction is about where you're going to get; the military has a pretty good hierarchy that's flexible

073. **WW:** you can always find an example that challenges the application; is there any theoretical basis for thinking about the problem in a systematic way and then devolving that to a practice?

074. **EP:** there is nothing inherent in science that codifies the creativity that drove Newton

075. **WW:** we can find ways the codify abstraction in ways more usefully

076. **BZ:** his book describes homeomorphisms as part of abstraction

077. **EP:** it's undecidable to take two descriptions and prove they're equivalent; Mike Overstreet proved that

078. **DL:** how do I build a representation to move forward? you may or may not be able to automate that

079. **WW:** you can't automate much of physics and that's not a good criterion

080. **DG:** send references to BZ or SH?

081. **DL:** we are thinking about running a peer-reviewed workshop on lessons learned; we ought to do this regularly; he can't get the Government to pay for capturing lessons learned; if I did this call for papers, would I get more than two papers?

082. **RS:** maybe one or two would be enough

083. **WW:** you must frame the question carefully so there is a reward for exposing the real problems; that could be done but it would take an articulate and well managed announcement

084. **MR:** showing outtakes, I'm very uncomfortable with showing this before showing the successes; people remember failures

085. **WS:** people do remember failures

086. **SH:** failures arouse your emotions

087. **MR:** failures also emphasize your success

088. **DL:** everyone at this table considers failures success

089. **DG:** you'll get a mix of papers but we must get these observations on the table; generating useful observations is different than abstracting theory from those observations

090. **DL:** can I make publication in such an environment rewarding? for example, maybe I should give a monetary award for the best lessons-learned paper

091. **WW:** what form of implementation would work?

092. **SH:** your review committee composition is going to be really important; failures might be rejected

093. **WW:** we control lots of stuff in SCS and SISO and can communicate with everyone; we can make this happen

094. **DL:** look at the Grand Challenges Conference; the rejection rate was 40%

095. **WS:** you don't find a lot of negative results in simulation literature

096. **DL:** results shouldn't be characterized as positive or negative; look at multicast groups, it's hard; how do we do it?

097. **WS:** video game magazines include articles that talk about lessons learned; it might be interesting to look at that

098. **EP:** he talks about his paper on ALSP; he'll send a reference

099. **DL:** we can let people say "let me tell about my little piece to achieve success and how hard that was"

100. **BZ:** what can we do now that we couldn't do before your contribution? that view puts it in a more neutral way

101. **WS:** they created a sub conference on innovative applications of AI; they had strict reviewing criteria and tried to get people from industry to publish; everyone who got paper accepted got an award and the proceedings were published in a book so it could go into your resume; they didn't give just one prize for best paper

102. **DL:** take lessons learned workshops and say what organization published the most then give them an award; it then becomes an organizational competition

END OF SESSION

**NOTES TRANSCRIBED BY B. BAILEY & L. ALEXANDER (B PREFIXES)**

001. **Note:** The purpose of the session is to identify references that illustrate the scientific functions for M&S initiatives/products.

002. **BZ:** he introduced the session by outlining/discussing the following:

- That he is convinced that there is a "science of M&S".
- He outlined the broad "science of M&S" by depicting (via PowerPoint) the "Mother of All Sciences – Physics" as an illustration of the parallels of how the science of "physics" (i.e., phenomena, data, experiments, theory and practice (as the engineering application)) could possibly be related to the circumstances for M&S.

003. **Group:** they agreed to forward literature which illustrate examples of M&S applications to "phenomena, data…etc.

004. **DG:** regarding data describing simulation – McCloud's book and VV&A Recommended Practices Guide

005. **DG:** regarding fidelity, he agreed to specifically forward fidelity references.

006. **BZ:** regarding theory, he stated that the references related to microelectronics would be a good recommendation and agreed to relay the references to the group.

007. **BZ:** he outlined observations for the following scientific fundamentals (via PowerPoint):

- Observation
- Recording, generalization, data mining
- Hypothesis formation, deep generalization
- Confirmation, falsification
- Application

008. **DL:** he summarized the session discussions as follows:

- It would be extremely valuable to have a paper written which describes how to manage a "multi-task" management process for software/large M&S development programs.

- Simulation technology has been stalled for the past 5 years. The M&S community appears to be repeating its application development focus without actually having to tend to the science of M&S.

009. **Group:** they agreed to forward literature references which illustrate examples of M&S applications to "phenomena, data…etc.

# Appendix 6: Session 3 Notes

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### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **PD:** has simulation been characterized in terms of its applications? cannot characterize it without asking what it's good for and what questions you're going to ask of it

002. **WW:** that means establishing both the appropriate metric and the value of the metric

003. **WS:** thinking about fidelity for simulations with analytical uses has a different set of attributes associated with them than thinking about fidelity from a training perspective where such attributes as immersiveness might play an important role

004. **DG:** believability

005. **SN:** is there a common definition of fidelity?

006. **SH:** there is a definition of fidelity but it's not very common

007. **WW:** the SISO definition is not bad; when people have this debate they invariably confound the definition of fidelity

008. **PD:** is fidelity a super set of resolution and the other things?

009. **DG:** yes, resolution plus other things

010. **SH:** fidelity is a way of describing the representational capabilities of a simulation

011. **WW:** but that doesn't discriminate it from scope which is another way of describing the capabilities of a simulation

012. **DG:** the elements of fidelity include resolution, error, precision, sensitivity, capacity; there are probably more components

013. **WW:** are they subsets of fidelity?

014. **DG:** it isn't useful to describe fidelity as a roll up term

015. **PD:** so this is a way of describing the goodness of a simulation?

016. **SH:** no, it's a way of describing what a simulation can represent; goodness has to do with a purpose

017. **WW:** if the referent is a fair die then one can have different representations of it; one highly detailed representation would be Newton's equations of its motion; that is a highly detailed representation and that could be high or low fidelity depending upon how good the equations are; another would be a random number draw from the set of integers between one and six; that is a high fidelity but very low detailed representation

018. **SN:** we can argue this forever; you just described high fidelity in geometry and the other is high fidelity to the behavior when rolled

019. **DG:** detail is part of resolution

020. **DP:** the phenomena are language, runtime, and code?

021. **WS:** some aspects are considered part of computer science

022. **DP:** some of the phenomena regarding simulation are whether it's only software, whether it's hardware, visualization, a whole set of things like looking at a person's appearance; those phenomena are part of the description of the simulation

023. **WWh:** you're separating the model from the simulation

024. **DP:** a model is part of algorithms that are in software but HWITL or HITL is more than just code

025. **WW:** the distinction between implementation and representation domains is significant

026. **SN:** yes

027. **WS:** and how it's presented; whether it's an immersive environment or whether just a bunch of numbers comes out

028. **SN:** the representations are phenomena

029. **WS:** is a phenomenon a behavior or an entity?

030. **PD:** are we trying to characterize the simulation input and output and comprehensibility? representation is related to comprehensibility and application

031. **SH:** phenomena are the things that make the observables change over time

032. **PD:** then you're talking about the model

033. **SH:** the phenomena are the causes and the literature supports that view

034. **DL:** is the ability to turn a set of data into a set of models part of this problem? who owns that?

035. **SH:** it's owned by scientists

036. **DG:** fidelity describes the phenomena that are uniquely associated with simulation; the kind of modeling is also our problem; the choices about detail and resolution is our problem; other people drive their models down to where they think they've approximated reality

037. **DL:** the techniques by which I build models from core data are a simulation phenomenon

038. **WW:** that's all there is that distinguishes M&S from other stuff, abstraction and conceptual modeling

039. **SH:** the execution of representations is also very important

040. **WW:** by the time you've done the abstraction in an implementable way then the rest is software

041. **SH:** no, time management is completely independent of that

042. **WW:** that's part of the abstraction

043. **WS:** a counter example, in training a big concern is immersion, does the person feel immersed? that can be measured in a number of ways and that's a function of the model and the displays and other things, not just the model

044. **WW:** it's a consequence of how you do the job that influences the success

045. **WS:** that's sort of a tautology

046. **WW:** how you do the job matters

047. **WS:** but that's one of the things you can observe

048. **WW:** I said that of the fidelity, part of the process of abstraction and definition of the conceptual model is absolutely part of M&S and the stuff that follows are important but without the modeling part the rest can be done by software and system engineers

049. **WS:** we should include things that are not just modeling and I would put immersion

050. **DG:** I would too

051. **EP:** time is a characteristic of simulation; that should include the speed at which its simulation clock is moving relative to real time; that's an observable phenomenon but I don't know if that's part of fidelity; lots of experiments have been performed related to that

052. **WW:** time evolution

053. **DG:** put it on the list

054. **DP:** do we want to pocket the idea that good software engineering is necessary and go from there? interoperability isn't just a software problem

055. **WW:** depends upon what kind of mistake you think people are going to make; the people that I run around with think that if you get the software right then you can forget the other part, that's the likely error; if you think about how the simulation is built then time model, time advance model, implementation mechanics, production of the artifact are all in scope and should be kept in the debate; implementation includes time representation, mechanization of the simulation (analog, etc), implementation, language choices, biomechanics, operator interfaces and other things

056. **DG:** interactivity is different than immersion in an important aspect

057. **WS:** someone could be immersed in a passive system; interactivity is not part of implementation, it's a first level bullet

058. **PD:** man-machine interfaces is larger than interactivity

059. **WW:** there are controller modes and other modes

060. **BZ:** the relationship between the model and the real world is the underlying concept for validation; the relation between model and simulator underlies verification; we must capture those relations

061. **WW:** is the relation between the referent and the simulation different than fidelity?

062. **SH:** that's error

063. **WS:** immersion is a relationship

064. **SN:** there are a whole bunch of relations; between the simulation and the human, between the models and the simulation

065. **WW:** we need to use UML to represent this

066. **SH:** do it and send it to me

067. **WW:** a theory that doesn't admit to this representation is not sufficient because you don't understand it

068. **DL:** can any mathematical representation that can move forward in time be a simulation?

069. **EP:** the data base people would argue that

070. **SH:** and they're right

071. **DL:** that's no because if I have a data base with data that I've collected from a number of sources then it doesn't represent anything

072. **MR:** how about observability?

073. **PD:** that's comprehensibility; you need it

074. **DL:** why do we to separate modeling and simulations

075. **PD:** simulation is a subset of models

076. **EP:** the military world is the first place that seems to distinguish between models and simulations; the rest of the world doesn't make that distinction

077. **BZ:** is something written in FORTRAN just the code itself?

078. **EP:** there are different versions of it

079. **BZ:** you can have a model expressed in FORTRAN in 1960, C in the 70s and JAVA in the 90s; you have to make that distinction to discuss what are aspects of the whole are related to the real world, the model, and how it's executed and that's the simulation

080. **DP:** the Sargent circle makes the distinction so SCS considered that

081. **WS:** would changeability or maintainability be part of it?

082. **SH:** what is immersion?

083. **WS:** ask subjects "how much were you engaged by the simulation?"

084. **DG:** immersion is very soft in the literature

085. **WS:** another aspect is to look physiological responses

086. **SH:** would you send me a short description of immersion?

087. **DG:** that's my dissertation

088. **SH:** would you send me another list?

089. **PD:** another missing thing is connection to other things, the real world, other simulators, video clips, audio tapes; what the simulation is connected to is part of its characteristics; connectability to other types of equipment and simulations

090. **DP:** that's an expansion of the MMI to the machine etc interface

091. **PD:** the ability of this simulation to fit into a larger picture

092. **WS:** that includes a bunch of architectural issues

093. **PD:** connectability to reality and other things

094. **WS:** that could include interfaces to other simulators

095. **PD:** BZ's book covers a lot of these things although immersion is not as well covered there; we don't want to rewrite his book but rather make sure these other things are added

096. **EP:** where does lumped models go?

097. **PD:** that's part of abstraction; I like abstraction better than resolution

098. **WS:** what do we want to do with connectability

099. **DG:** a whole category of things including cost, life cycles, and applications are not included

100. **WW:** those are implementation domain things; there are meta things

101. **WS:** cost and development time are attributes

102. **DG:** change implementation to program management stuff; DL didn't think immersion was an attribute of the simulation; I have a fully elaborated taxonomy of that stuff

103. **DL:** all simulations are immersive but they all give a different feeling of immersion; can't disagree if immersion is immersion into some part of the problem; immersion is like going to the movies; that is not a phenomena of simulation but something that you can do with simulation; the simplest of simulations is immersive

104. **WS:** it's a question of degree, how much and what kind and that's observable

105. **DL:** why isn't that a fidelity question?

106. **DG:** that's an interesting question and fidelity will lead to a certain level of immersion

107. **EP:** it's also a function of the interface

108. **WS:** there's something else; I don't see the elements of story in fidelity; you can observe how much you engaged in the experience

109. **SN:** I may want a very high fidelity simulation of chemical warfare; and I may not want to be immersed

110. **DL:** story is component of fidelity

111. **SH:** that's an interesting perspective

112. **DL:** story line is a new view and in some simulations the story line is part of fidelity

113. **WS:** a good story line may create an experience that is less faithful to the real world but it increases immersion

114. **DL:** a simulation is not an absolutely faithful representation of the real world; it's only as good as you need; in training I might not do real world things to increase the training experience

115. **MR:** those are reasons why fidelity is not synonymous with the utility of the simulation and it gives room to say that the story can go somewhere else than the real world

116. **DL:** story is part of fidelity

117. **SN:** story and immersion are usability factors

118. **DG:** story is an interesting argument that should be a hypothesis

119. **BZ:** models with respect to objectives; there must be a relationship between model and objectives

120. **DG:** you mean models and uses

121. **SH:** how the simulation gets used and then objectives are separate

122. **RS:** what's being immersed

123. **WS:** a measure of how much people are immersed

124. **RS:** why isn't that an MMI issue? if I run this and no one is present then there's no immersion

125. **DL:** but someone is always there because he looks at the results; that's not a real time immersion

126. **PD:** the other word is performance

127. **DN:** add capability; that's the problem associated with how large the model is

128. **MR:** objectives were originally the relationship between objectives and simulation design

129. **WS:**

130. **SN:** anything that refers to usability

131. **WS:** that's an issue

132. **SN:** maintainability

133. **WW:** how about availability; we're identifying the attributes of a system; only some of these are simulation specific issues and the rest are systems engineering problems

134. **DL:** think about the phenomena part

135. **DG:** is one observable the algorithms used?

136. **DL:** problem formation for M&S; how do I formulate, abstract and validate the problem?

137. **WW:** those are all developmental activities manifest in the artifact; only manifest in performance, utility

138. **SH:** we must get to the phenomena that underlie these things; like relationship between cost of the simulation and usability; another is the relationship between cost and fidelity

139. **DG:** these are the correlations between these observables

140. **DL:** what do you teach as fundamentals in M&S?

141. **BZ:** we start with three entities: model, simulation and the real world; then go from there

142. **PD:** always characterize the model with regard to what you want to do and what data is available

143. **DL:** courses of simulation basics might embody the basic phenomena; we might need to sample a few courses

144. **PD:** systems engineering covers a lot of ground; think of the concept of what you want your simulation to do; that's more than implementation; we should keep our mind on the relationship between reality and the model; we must recognize the creation of the conceptual model and build that into the implemented version and separate that from systems engineering and program management

145. **WW:** the utility of having those bins is that the concept of operation and the utility of the system are represented by systems engineering and the representation issues; we would like to keep those things modular

146. **SH:** some phenomena cross those two boundaries; interoperability for instance

147. **WW:** yes, that's a good one

148. **SH:** we should realize that relationships will cross those boundaries

149. **WS:** are the headaches related to M&S describable in these terms?

150. **DL:** no

151. **EP:** science won't help you make good funding choices

152. **DL:** WARSIM – wrong simulation to start with; the use doesn't need that level of detail; desiring a large general purpose simulation may drive you down that road; that may not be necessary; if I were crafting simulations for the training event efficiently then I wouldn't build WARSIM

153. **PD:** in the 80s we built a big wargaming system and it took a lot of effort; it was designed to be composable; nobody outside of Rand ever did anything with that other than put the data into it a push the button; the descendent of that system is now in use and run by contractors of modest capability; a characteristic of the way DoD does business; you can't do what you're describing unless you go first class; that's not just a technical question but also a management one

154. **DL:** that's driven by need but not by desire to drive to lowest possible level; there could be phenomena there;

155. **PD:** two reasons: some problems are just hard and provide learning experiences; another is more characteristic of the analysis community; the analysis is just useless because the models and data have become so complex that you can get any answer you want; there is no concept of using the simplest and fastest models then looking at more detailed representations only when needed

156. **SH:** what is it that makes simulation too hard?

157. **PD:** this stuff is generally harder than mere mortals can learn; it's too complex

158. **DP:** there are two basic problems: lack of adequate knowledge about the phenomenology modeled and complexity of the relationships and the number of parameters and interactions involved; it takes a long time to learn those; complexity and ignorance make it too hard

159. **DL:** what's wrong with WARSIM; trying to build too big a thing? we don't train very well; running simulations with 5000 people doesn't train too well except communications; JCATS is an interesting simulation; it represents mounted and dismounted exercises; it has a poor interface; built by Livermore; the Europeans love this thing; it's easy to use and set up; you can get it set up the way you want; ModSAF vs JCATS is very unsatisfying; people want to use JCATS

160. **MR:** ModSAF wants to use automation and JCATS allows you to do it yourself

161. **DL:** JSIMS asked what people wanted and they're building exactly the opposite; nobody seems to care or understand that the analysis and requirements people didn't agree; WARSIM has reached the technology breakpoint where they can't make it work

162. **PD:** bright people can put a quick model together that's very useful for a specific job but not generalizable; you can build an infrastructure with enormous flexibility that you can put something together really quickly but he's never seen that approach work, even within Rand; people didn't want to turn parts of the model off that they didn't need; how can we train people better? it's a generational issue, training issue, set up issue;

163. **WS:** set up is not on the list

164. **DG:** accessibility

165. **DL:** the intended training audience is the joint task force commanders; there were five levels between the simulation and the commanders; it was a $400M board game

166. **MR:** how painful do people find stove pipe solutions: adding such things as reusability and interoperability adds a lot of cost and challenge

167. **DL:** most people don't understand simulation; so they don't understand the fundamental flaw in building general purpose solutions for people trying to do very specific things; if people actually looked around at what else existed and were willing to use that; building your own thing is really not very efficient; that leads to general purpose solutions; he wants to put tools in people's hands quickly and efficiently; he'd much rather have a solution where a guy describes his problem then pushes a button for the solution; we have a mantra that simulations need the same fidelity as the real world to avoid people gaming the system

168. **MR:** building institutions that create effective simulationists is the opposite of trying to make simulations that solve every problem

169. **DL:** he doesn't want engineers to build simulations; they should use simulations in their job; at some point, they'll need to customize a simulation for their problem

170. **PD:** JWARS has really good technology; what could be done with the tools and infrastructure they built? the reality is that you can't just move things around because things are dependent on low level representations; Janus is a success story; suppose that we took a new look at what JWARS has done

171. **WS:** there is a tension between allowing people to build ad hoc simulations vs giving them a large infrastructure that takes effort to answer their problem; that's the fundamental dilemma

172. **DP:** the majority of money to develop simulations isn't going into infrastructure; it goes toward developing the models of the entities; this is an entirely different approach and more successful; we're focusing on one aspect of simulation as if it were the whole thing

173. **DL:** building a general-purpose model or a specific model still depends upon the same underlying phenomenology

174. **WW:** look at the considerations at what is fundamental then we won't have gone too far astray

**END OF SESSION**

# Appendix 7: Session 4 Notes

The notes contained in this appendix refer to the participant making a statement by a two or, in one case, three letter code. Table 1 connects these codes to the participant speaker. These notes also sequentially number the statements, sometimes consisting of several sentences, from each of the speakers. The session records in the main body of this report refer to these numbers to correlate the record statements with the actual statements from the participants. This numbering begins with the first statement made in the session. Thus, a statement number higher than another signifies the utterance of that statement AFTER the lower numbered statement. Letter prefixes were assigned to each source in the session records (e.g., a citation of [A046] refers to transcriber source A (in this case, Mr. Harmon) and the 46th statement). The assigned letter prefixes are shown with the transcriber source heading. However, only one transcriber took notes of this session, Mr. Harmon.

**Table 1.** Codes for the Participant Speakers.

| Code | Speaker |
|---|---|
| **BZ** | Bernard Zeigler |
| **DG** | David Gross |
| **DL** | Dell Lunceford |
| **DN** | David Nicol |
| **DP** | Dale Pace |
| **EP** | Ernest Page |
| **LA** | Larry Alexander |
| **MR** | Marc Raibert |
| **PD** | Paul Davis |
| **RS** | Randall Shumaker |
| **SH** | Scott Harmon |
| **SN** | Susan Numrich |
| **WS** | William Swartout |
| **WW** | William Waite |
| **WWh** | William Whelan |

In general, the transcribers attempted to capture the speakers' comments as accurately as possible where those comments clearly pertained to the workshop topic. Some discussion occurred between the participants that was not relevant (e.g., idle banter, jokes, references to the lack of coffee in the morning). That discussion was not recorded in these notes. The nature of spoken discourse made identifying individual sentences difficult so the transcriber made no attempt to do more than make a casual distinction.

All of this session's notes were transcribed from a videotape of the session proceedings. Unfortunately, the soundtrack of the videotape was lost midway through the session for some reason. As a result these notes only represent part of the session's proceedings.

### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **DG:** working from his charts: (1) showing a view of the scientific method: he threw in directed observations to account for where formal experiments may be difficult; (2) showing the properties of hypotheses: a good hypothesis is testable; it can be answered with a small set of variables; but, he doesn't agree with that constraint; his point is –

some good hypotheses come from what we think is true but have never been actually verified either by some derivation or experimentation

002. **DP:** you mean my first law of simulation that no simulation works perfectly all of the time

003. **DG:** that might be a good hypothesis; it feels gut-level true but I've never verified it but may be you have

004. **DP:** i haven't found an example to the contrary

005. **DG:** you're still getting to the truth by exhaustion

006. **WW:** he asserts that that is unfalsifiable

007. **EP:**

008. **SH:** astrologers haven't found any counter examples for their hypotheses

009. **DG:**

010. **DP:** what are the properties of a statistically valid sample size?

011. **DG:** these are examples of good experimental design; can we estimate the variance of a population from the sample size?

012. **DP:** is a sample of one statistically significant?

013. **DG:** no, because it gives me no sense of the variance of the population from that sample size

014. **DP:** a lot of the simulation validation experiments have a sample size of one or close to one

015. **DG:** when I think about a classical experiment, I think of repetition and repetition by independent sources; so I added directed observation because I don't believe that we can conduct experiments like that for some of the kinds of problems that we're interested in; for example, if the problem had something to do with a hypothesis about the construction of WARSIM, we're not going to build a second WARSIM to validate this by repetition of experiment, it's not going to happen

016. **DP:** i was thinking of a missile flight experiment; for example, the ground-based mid-course missile defense simulation where you may have one or a handful of experiments at most or test flights that you're trying to correlate with your simulation results so you can have some level of confidence in your simulation for other conditions; in many cases you're at a sample size of one for the experimental correlation there

017. **DG:** could be and I would term that an observation of the real world rather than a repeatable experiment because you're not going to repeat it

018. **SH:** with those missile tests they really do collect a lot of data so it's more than a single sample; it's more a single event from which many observations are taken

019. **DG:** it's my objective to pull some hypotheses that might be subjected to some kind of observation or experimental program

020. **SH:** i'd like to add to experiment where you have elimination of bias, characterization of error

021. **DG:**

022. **WW:** someone mentioned carrying the error bars earlier

023. **SH:** that's one aspect of characterizing error, the statistical character of the error; I'm trying to understand the sources as well

024. **WW:** that's a reflection of the discipline

025. **DP:** the work that's being done in the DoE ASCI program where they are quantifying the uncertainty of both the simulation codes and the experimental data; he encourages us to get familiar with that; this is the first serious step at using a fairly comprehensive scientific approach with a reasonable degree of rigor for the simulation community

026. **DG:** validating simulations based on small sample sizes is the root of a hypothesis; i don't believe that that's been shown to be a valid approach for doing business; but, people are still doing it

027. **EP:** i don't believe that any statistician in the world would be willing to say you could shoot the missile one time and from that can tell what the next 100 shots are going to do

028. **DG:**

029. **DP:** part of what's going into the V&V of computational solid mechanics code says that correspondence between simulation and test data for singular or small number of events has no meaning or very little meaning; it doesn't insure validity

030. **SH:** that depends upon what the small number is

031. **WWh:** there's a subset of statistics called small number statistics; the ICBM people have to deal with that

032. **SN:** when we talk about statistically valid sample sizes, are we talking about the sample sizes of the real world measurements or are we talking about the sample sizes of the simulation runs?

033. **DP:** an example of the missile flight simulation, before you fire a test missile you run a batch of simulation runs that you think are going to represent that flight to make sure that you understand what's expected to happen; then after you fire that flight, you go back and rerun those simulation runs correcting for the environmental factors that you made original assumptions about for which you may have better data; then you have some set of simulation runs to compare with that one flight test; so the question is how do you compare the results from multiple simulation runs with that one flight test and consider whether or not that simulation has concurred or not; do you compare it so that the actual flight for any of the parameters that you're looking at does not vary from the mean of all those more than some specified amount does not fall outside any of those runs or do you measure it by the difference between the actual flight and the run that seems to be closest to that flight? that's a very difficult question of how you compare many simulation runs with that one set of data for the flight

034. **WS:**

035. **DG:**

036. **PD:** what is your intention? are we asking what do hypotheses about simulation look like and what might some of those be?

037. **DG:** yes

038. **PD:** there are two basic questions; one is the hypothesis about whether the simulation is any good and the other is the hypothesis about the real world phenomena that you're using the simulation to investigate

039. **WW:** there are also hypotheses about the science of simulation which may be made and I don't care which ones we discuss but I think it prudent...

040. **PD:** can you give me one?

041. **DG:** yeah; i'd like to add one; fidelity is somehow directly associated with the phenomena of simulation; so I would like to propose that fidelity is somehow related to interoperability; differing levels of fidelity affect interoperability

042. **PD:** interoperability is a matter of degree; it depends upon what you're doing

043. **DG:** sooner or later that's what's going to prevent it

044. **SH:** in the limit that's what's going to happen

045. **DG:** the limit is where I regard what is testable

046. **WW:** what is the referent? two simulations having different levels of fidelity will be difficult to make interoperable?

047. **DG:** that's clearer

048. **DN:** when you're talking about hypotheses and testing hypotheses and the like you're ultimately talking about numbers, statistics; how are you going to test interoperability?

049. **SH:** no, you do it by evaluating validity; you have criteria for validity for a particular application that you define in the fidelity terms; then you measure the fidelity of the two simulations and then execute them and look at the fidelity of the combined output

050. **DN:** but haven't you made the assumption that you haven't been very smart of about gluing these things together?

051. **SH:** what is smart?

052. **DN:** there's another component of modeling that has to do with the glue between models that are operating at different levels of fidelity; consider fluid models of traffic; these are described in terms of rates and then I want to have that interact with packet models of traffic; or, maybe I want to turn it into packet level traffic; it's my choice to say what comes from this simulation whether it's a specified constant rate or whether I use random numbers; these are two different models

053. **PD:** another example, I'm sensitive to the notion that high resolution is good; if you have a simulation that there are times that the ground forces are represented at the entity level then there are times that they're represented as units; the validity of the simulation does not depend on the resolution with which you have the movement because how they disperse depends upon doctrine and local terrain and not on how they march; that's a case where the same simulation has different levels of resolution

054. **SH:** DN and PD are talking about the same thing; i'd assert PD is talking about representing the same thing at two different levels and that may or may not be a functional dependence problem but it is certainly a manifold representation problem and you must have the transforms that take you across the levels of resolution;

055. **PD:** there are also constraints on where you can use things

056. **SH:** yes, and those become the interoperability criteria and they're very specific criteria, like invertability

057. **PD:** consider going to lower resolution then going back to higher resolution, the invertability may or may not depend upon the history

058. **SH:** yes, it turns out that there are entry and exit criteria for resolution changes; but, this is an open question; we have only done a small amount of work on this area; the functional dependency stuff is very specific and very near necessary; to DN, i'm not sure whether you're trying to represent systems at two different levels of resolution or whether they're interacting; that's a different problem

059. **DN:** when you're talking about hypotheses then you must have something quantitative; I didn't understand that you had specific criteria

060. **DG:** creating testable experiments may be difficult

061. **DP:** let me suggest a couple of hypotheses; simulation development is limited by phenomenology knowledge/domain knowledge

062. **WW:** of the referent?

063. **DP:** yes; a second one is simulation fidelity/validity is limited by domain knowledge; those are two testable hypotheses

064. **EP:** I don't understand the first one; but, the second one says that you can't represent what you don't know about

065. **DP:** the first one says that you can't represent what you don't know about and the second one says you can't tell how good it is until you have knowledge of the domain

066. **EP:** I don't know anything about how the brain works but I can build a simulation of the brain, complete wrong

067. **DG:** so you would dispute the second hypothesis

068. **EP:** the first one; nothing will stop me from building a model of the brain

069. **DP:** you could make certain representations of the brain without knowing about it but you're limited to what you can represent about the brain if you know nothing about the brain; and, how good your representation is is what the second one is about

070. **WW:**

071. **DN:** it would be helpful to offer a test of any hypothesis that we propose

072. **DG:** i can certainly offer a test of the first hypothesis

073. **EP:** if i have an exponential distribution of traffic and a detailed model of a bank teller then those two models will interoperate perfectly to tell me what the utilization of the teller is even though they are at completely different levels of abstraction; that's falsifies the fidelity and interoperability hypothesis

074. **WW:** in fact they're different levels of detail but at the comparable levels of fidelity because the representation of the world is correct at the semantic level that you care about; detail and resolution are the same and fidelity is different from both of them; that's why I think that detail and fidelity are semantically significantly

075. **EP:** ok, i have a bad exponential distribution; the fidelity is obviously poorer

076. **DG:** that doesn't have anything to do with poorer or good; it has to do with difference; a hypothesis should not be a tautology

077. **PD:** some critics of simulation will say that some attempts to simulate complex adaptive systems is hopeless because the results are so sensitive to the initial conditions; to what extent should we even try to simulate complex adaptive systems especially if we're going to run them with only one run

078. **EP:** you cannot propose a hypothesis without also proposing a test

079. **PD:** a narrower hypothesis, it is useful and somehow legitimate, at least for analytical purposes; it's useful because it's predictable enough to be useful; take the program from one computer and put it on another computer and see whether you draw the same conclusions about the legitimacy of the force structure; some people argue that you get such different answers that it clearly has shown that this is not the right way to do your work

080. **DP:** all models are wrong but some models are useful; that generalizes your hypothesis

081. **PD:** building simulations of complex adaptive systems that run far forward in time is a bad thing to do; we are fooling ourselves and we're fooling our clients

082. **DG:** so simulations may be useful if not predictive

083. **PD:** that's what DP said and I agree with that

084. **DP:** simulations of adaptive systems should not be extrapolated very far in time

085. **PD:** you get into serious problems when you do that

086. **DG:** simulations may not be useful even if they're not predictive

087. **WWh:** does that say that there's some limit of error that makes them useful?

088. **DG:** that's an interesting assertion because there are all kinds of guys in the analytical community that have a problem with that; how many times have you been told that no analytical simulation has ever been verified against real combat data; lots of

people say that that simulation is junk; so that says that there's actually utility even thought it doesn't predict the outcome of the Gulf war

089. **DP:** all models are wrong but some are useful; did Fisher say that?

090. **EP:** you couldn't empirically test that all models are wrong

**SOUND TRACK LOST FOR THE REST OF THE SESSION**

# Appendix 8: Session 5 Notes

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### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **WWh:** i've become convinced that simulation is not a science; models or simulations are epistemological things; they underlie all of science; he uses models and simulations as a path to understand the real world

002. **PD:** there are so many special features of simulation that it at least qualifies as an engineering discipline; whether it's a science is arguable

003. **WWh:** i'm using simulation in the context that it's the model passing through time

004. **DP:** he's not talking about the implementation; the implementation is certainly a kind of engineering sub-discipline

005. **PD:** we were talking about systems science; in practice, most systems work is in engineering and it isn't mere implementation; systems engineering is a real field in itself; there are an awful lot of things that we should include in digital simulation (e.g., implementation issues like software engineering)

006. **WWh:** digital simulation is one category of simulation; dropping the apple off the tower is another form of simulation

007. **PD:** experiments are simulations

008. **WWh:** i had difficulty putting my hands around the hypothesis to prove or disprove the validity of this hypothesis; two elements of experimentation have bothered me for a long time; on experimental design, people have waxed about this for a long time but I see very little of it done; people seldom think of simulation as an experiment itself; it can help define what you're going to do and what sort of problems you'll encounter; a good scientist would work in designing experiments for simulation; all simulations are giving you indirect information

009. **PD:** you can have experiments about how do you build simulations (e.g., hypotheses that say like modularity is good, multi-resolution modeling is feasible and doable); you could have controlled experiments in this area; the other subject is how do you test whether simulations are any good, the validity thing; these two things confused the previous discussions; if you're asking about whether a simulation is valid, it looks like a lot of other stuff that's out there; if we're trying to learn about how to build simulations well then that is a worthy subject in itself; the roots are perhaps in systems science; is there anything left out? that's something you can find; the techniques that people use are testable; part of our discussion is professionalism and best practices; that's a separate class;

010. **DP:** what WWh had said before is all oriented toward simulation validity; i can think of a number of experimental areas about simulation technology; one that is most critical, because it's being used most flagrantly, is visualization without critical understanding; visualization can be used for the analysis of output and/or the control of the process while it's going on; it's used for all kinds of things; as far as i know there's nothing in the literature on how you can, should or don't use visualization; there's lots in the literature about what visualization you need for training purposes; that work largely regards the validity part but nothing discusses the technology aspect; if we're moving toward a science, the experiments we ought to be concerned about should relate to the simulation technology; we have a unique opportunity here because no one else is looking at the experiments that would advance the simulation technology

011. **SN:** there's another marriage there too; you have the marriage between the content, the models, and the structure, the simulation infrastructure; they're not independent

012. **WW:** regarding the admonition to be careful to know what the referent is, i concur; we could be talking about the simulation itself or the V&V of the simulation and that's something else; we can talk about how we do it, the practices and process; i think that's

not what you're asking; we could talk about the technology of the science itself; i think that's the null set

013. **PD:** when you say null set you're thinking in terms of uniqueness and so forth, it's not that there isn't science in the technology there; it's just whether it rates a separate field

014. **WW:** my opinion is that it's technology there and not science the way we think about it wherein there's an objective reality that we come to understand; although there may be stuff that we can tease out; let's think about simulation as a technology because that's where there's the challenge

015. **SN:** a science is something where there's an objective reality that we're trying to learn more about; hence, computer science is not a science?

016. **WW:** in my opinion, yes

017. **WWh:** is there a general feeling that simulation is the easier part to address?

018. **DP:** i think that it's the part that's untouched

019. **WWh:** i agree but i think that we know how to do it

020. **PD:** WARSIM is not working; big systems are failing

021. **DP:** i don't know of scientific efforts that can tell us how to decompose the subject that we're representing or how to select the decomposed items to put into compositions, any of those process/technology issues; i don't know how to choose the best implementation of various models; nothing exists beyond people's experiences and prejudices in making these choices;

022. **WWh:** we do know how to address those issues; we just have not addressed them yet

023. **DL:** let's go back to the why for the workshop; it's really a question that I don't have a gelled practice and that's because I don't have a set of underlying principles upon which to build a gelled practice; what i really need is that set of practices; they come from a wide range of sources; but, they're mostly built upon some fundamentals; it would be nice if there's a science here because i could build tiered products; discovering that there's no science here is ok; maybe what i should do is identify how to apply scientific discipline to uncover those fundamental principles;

024. **SH:** there are two proven ways to improve a practitioner's knowledge; one is far older than science, the journeyman practice; the other is to define the underlying principles; both are effective ways of improving workforce quality; the guilds taught people how to do it; the apprenticeship path is far less efficient; a professor could teach 30-80 students and teach them the fundamental of physics; an apprenticeship program is much more one to one where an apprentice works side by side with a single journeyman; even in those cases where it's better than one to one, then it's highly inefficient; the efficiency of the transfer of knowledge gets very thin; we are looking at one way, identifying the underlying principles; the other way, the guild model, may deserve another workshop;

025. **WS:** i think that you actually need both; which approach that's the right one to take depends upon the maturity of the codified knowledge; so, a guild approach works if the skills are not that well understood; if there's a set of engineering practices, e.g., for beginning bridge design, that's pretty well codified; you give the class a homework assignment and they go off and design the bridge; where you need to get into a guild approach is where you're building a new kind of span that's never been done before; then, the way you understand how to do it is to work with someone who's a master; that's how you get to be a very advanced bridge builder; it's the same way with medicine, school then internship then residency; it becomes more and more guild-like as you move closer to actual practice and specialization; there's a transition that occurs as you move from an apprentice to expert; it's not that there's one strategy but that the strategy changes depending upon the degree of expertise and how well understood the knowledge is

026. **SH:** the only aspect that we're looking at in this workshop is the building of the fundamental knowledge

027. **DL:** if you make a decision that there's no science of simulation then i would like for you to tell me what the bottom rung is and make a series of recommendations about what we could do in the future, e.g., additional workshops; at the end of the day, if you've found the science but there's nothing that we can do with it, that hasn't helped me

028. **SH:** the question i was trying to answer is what things are in this science; we probably would find a very small set of literature on the scientific understanding of simulation; the result is that we agree that there is merit in pursuing the scientific exploration of simulation

029. **PD:** whether or not it is a small area

030. **WW:** to get a concrete set of pointers that are actionable is what you want; we must operate as if we're dealing with a partially populated page; those become the blocks that are the things that we're going to do; the fundamental thing that we'll get is an enumerated set of topics and their relationships that could be explored

031. **WS:** i agree; we would get what would be the chapter headings for a textbook

032. **SN:** we've said that there isn't any foundational research in this area and that we'd like some; i have a problem with that; i'm constantly talking about foundational research to people that have a traditional scientific education and they don't see this as foundational anything, at best an applied piece of CS; i'd like a list of basic research topics because we'd like to get some foundational research investment in this area and i need good foundational topics

033. **WW:** there was recently a workshop for affordable manufacturing; the sponsor wanted a list of research topics; there's a need for that and an institutional way to use it

034. **WWh:** we're scrapping the side of improving the professionalism of the simulation community; which element should we concentrate on, the education, the basic tenets? you must do all of them

035. **SH:** we, at this workshop, are focused upon of those ways

036. **PD:** a fundamental distinction is physical systems that you're trying to simulate and the other is complex adaptive systems; the first one looks like engineering; the second one is really a researchy subject; most of us who know the field say this is a profoundly different thing; on textbook elements, i would go to John Holland's book called Hidden Order; it's readable

037. **SH:** send me the reference

038. **PD:** he talks about multiple levels in complex adaptive systems that have their own laws; building up from the bottom will not capture everything; another fundamental is that they have things that adapt; a world with people or where species evolve is really different; the concept of doing experiments is different because they cannot be controlled; there are parallel but overlapping paths; control people reinterpret everything as control theory; apprentices from guilds that teach simulation of type one will not be able to represent complex adaptive systems because they've been trained wrong; we need a core curriculum that teaches where you take different approaches and point out overlaps and that these are interdisciplinary areas that may make you uncomfortable; a third fundamental is the view that computational approaches are a different way of codifying knowledge and learning and doing experiments; much of the future is going to be about computational experiments to discover the world; we used to do build simulations and compared them with the real world; but, there are increasingly computational experiments to figure out what's going on in the real world; this relates to complex adaptive systems; these are things that you'd want in the first couple of courses in addition to systems engineering and object oriented modeling

039. **WWh:** are you arguing that there's not a set of underlying principles that apply to all models and simulations?

040. **PD:** no

041. **WS:** there are a set of core things that you need to know when you go into simulation: how to deal with time, how to manage time, how to manage events; there are a variety of things that make the simulation work; on top of that, simulation is a very interdisciplinary study so if you're going to look at people then in addition to dealing with the computer science issues you must talk to people who understand human behavior and how it works; if you're simulating weather phenomena then you must talk to a different group of people; someone coming from a simulation program should have some acquaintance with these areas

042. **WWh:** that's the educational point of view; is there something inherently fuzzy about complex adaptive systems?

043. **PD:** no, i said that a big portion of the world consists of complex adaptive systems and they are different

044. **WS:** the methodologies for experimenting with those systems are different than what you'd use for systems where you can limit it to a couple of free variables

045. **WWh:** i don't agree that number or complexity of variables really changes the fundamental issues; we're talking about going from classical theory to quantum theory; the experimental tenets are the same

046. **PD:** look at simulations representing a 100K entities; some people believe that you punch a few buttons and everything will work out; take traffic models for instance: LANL did some models; they built detailed models and couldn't get them to look right; then, they represented traffic behavior as complex adaptive models governed by a few rules and got something that looked better

047. **WW:** both LANL's experience and a lot of others are how representation, abstraction and conceptual modeling are a matter of fundamental import to simulation; the qualities of the referent are really influential; that topic ought really to make the list;

048. **EP:** that's an experimental basis from which you can draw a conclusion about representational effectiveness to solve a class of problems

049. **DL:** what was the problem with striking to 100K entitles? we had a lot of guys that had a great vision of what they wanted; then, we allowed the mantra to overtake the reality; we didn't have a group of people who understood that a 100K tanks didn't make a corps; it only made a 100K tanks; the people didn't understand how to architect this thing and understand the constraints, limitations and values of not only the mechanics of simulation but how to apply simulation to get whatever you're trying to get at; i quit because we saw that the initial vision wasn't practical for a lot of reasons but we didn't understand about how to execute the field and shift the mantra when we needed to shift; we're not any better today

050. **DP:** in the system world there's a similar kind of thing; the thing that hasn't happened in simulation world is we have been advancing our understanding of the principles, like how to do the conceptual model; we don't have any experiments exploring how to determine the decomposition, practices or interrelationships, how you pick out the features without corrupting yourself so that you can deal with different complex systems; we haven't been doing the structured experiments to advance our knowledge so that we understand what's worked and keep building on what's been done;

051. **SH:** so what experiments do you think we ought to do?

052. **DP:** there are about half a dozen areas; one is visualization in terms of its ability for simulation control and its analysis of simulation results; another is the representational aspects for how you decompose for a purpose and how you select features in that decomposition related to purpose; another is how to decide what level and approach of representation (e.g., object oriented) to achieve purpose; also, we want to know how to select operational or implementation environment (choice of language or architecture or computational style); those are the kinds of areas where we need to make progress; there was an evaluation of a large number of basic science codes and they discovered there were about 10 significant errors per 1K lines of code; they also found that it takes 2X code in Fortran than in C; we haven't looked at things in the simulation world with that kind of approach

053. **WW:** we need to know about abstraction for intended purpose (different techniques and processes); conceptual model specification has not been solved; also, architectural design; simulation systems have architectures and our capacity to specify them is pretty pathetic; our ability to implement architectures is about as slipshod as our ability to specify them

054. **SH:** where is our capacity to choose our architectural approach?

055. **WW:** architecture design is a significant topic

056. **DL:** an example, what's one of the biggest challenges of WARSIM? i gave it to a bunch of guys who know how to build CCTT to build

057. **WW:** does it look like CCTT?

058. **DL:** it looks a lot like CCTT; i tried to take a visually-oriented implementation and turn it into a command and staff simulation

059. **DP:** you are suggesting that the architecture should go higher than the Joint Technical Architecture (JTA)?

060. **WW:** yes; JTA is a certain class of answers for a certain set of problems; simulation is an application domain where there are architectural considerations, ways to specify architectures and ways to choose among architectural features that is not very well understood and people doing JTA are not likely to produce solutions to those problems; it's a systems engineering class approach

061. **DP:** if people got at least as far as JTA effort they'd be at least ten steps ahead of where we are now in simulation

062. **SH:** sounds like an experiment o me

063. **EP:** we mentioned the performance aspects of the artifacts of simulation that execute; there's a lot of theoretical and experimental work in a lot of different areas on that, e.g., conservative vs. optimistic time flow, event list management schemes; people have been doing a lot of work on efficient event list management schemes; the folks doing Monte Carlo simulations have been trying to figure out how to make them converge; there's a lot of scientific work ongoing, both theoretical and experimental; in random number generators, for thirty years people have been working both experimentally and theoretically on how to make good random number generators; for performance, there's a lot of good science; from the representation stand point, there has been a lot of work in computability theory and complexity theory; these are pretty good bodies of theory that have been employed over the last 10-15 years to look at simulations from a point of analyzability vs. expressiveness; i can recommend 30-40 citations in that area; you can say things like the validation problem is fundamentally undecidable; you can say that it's fundamentally undecidable whether i can take two models and determine if they're equivalent; there are lots of things that i can say about how i analyze these representations; this is theoretical work based upon Turing's argument on the halting problem; on expressiveness, lots of people have looked at efficient algorithms from a complexity theory perspective; regarding expressiveness, i can compare different formalisms, formal language theory and complexity theory, to answer which is more expressive and which is more analyzable; there's lots of both theoretical and empirical work in the context of model representation and what are the limits of that and what can i do with that and what is the automated support for looking at representation; i claim that this is part of the basis of scientific knowledge

064. **SH:** let's not confuse mathematics with science; i'm loosely familiar with complexity theory but don't know of much experimental work in that area

065. **EP:** tons of experimental work has been done related to heuristics; every bit of that work is experimental in nature; i come up with heuristics experimentally

066. **WW:** the existence of formal notations and their power of expressiveness is hugely useful; we need to drag as much of it that applies and let it find its way into practice

067. **EP:** people have done quite a bit on that

068. **WS:** another area where there's a lot of experimental activity is looking at how various phenomena in the world work and how they can be simulated; take the behavior of light; people have done lots of work on how to depict things so they look photo-realistic in simulation; similarly for sound, three dimensional sound fields

069. **SH:** the perception of sound and light

070. **WS:** there's solid experimental work there; for human behavior, they've done a lot of experimental work; it's like understanding the physics

071. **SH:** very little of the human stuff tries to understand the physics

072. **SN:** there are two parts; the participant believes that they're in the real situation; at other times, under different circumstances, that same depiction must be effective in other parts of the simulation; like sensor systems that work in consonance with what the human is perceiving if that is appropriate at the time; it's not always appropriate; but our ability to choose the portal through which we're seeing the world and understand the relationships between those different portals, the relationship between the visual portal and the sensory portal, is important

073. **WS:** you mean automated sensors? making sure that they're consistent?

074. **SN:** yes, when they need to be; they don't always need to be; when do they need to be?

075. **DP:** there is a lot of work as EP described but it's very much like formal methods but they have splinter level application as far as the simulation community is concerned

076. **WS:** i don't think that's true; look at training systems; all of the things i mentioned are important there

077. **DP:** take random number generators; we've had those since computers were invented; none of the problems from them have prevented any advance in simulation; there are an awful lot of effective training simulations without advanced representations; we must keep these things in the perspective of the problem of getting a quality workforce; we have lots of things going on around this big core

078. **SH:** you'll send me references on the work that you cited?

079. **DL:** one could build an argument that there is not a science of simulation; we should apply good scientific practice that is looking at the piece parts; if i parse the simulation problem and use formal structured inquiry then we've gotten somewhere

080. **PD:** ask instead if there's a realm of activity that has coherence then it is clear that there is such a thing and we could call that simulation science or technology and there are underlying foundational areas that they should know; we can agree on that; we have the system science that BZ has talked about; i don't know how to characterize Paul

Fishwick's work but that should be counted; there's lots of fundamental stuff that we know; interdisciplinary stuff should put you above these boundaries

081. **DL:** is there a field of military science?

082. **PD:** if you use the words such as systematic body of knowledge then yes; the Soviets had that but screwed it up; there is something to it; military science should involve things that our officers are not trained in

083. **DL:** you can apply science in strict thinking that comes from the Greeks or is a science when it becomes a body of scientific knowledge; maybe that 's what simulation science will be

084. **PD:** science is not what the philosophy of science people talk about; science is much more about discovery; another part is people theorizing that may not have much to do with the real world; the scientific method can get us into a lot of trouble; physics and chemistry didn't grow from that nice neat stuff

085. **SH:** there's a lot of soul searching being done in the scientific community today; people have gotten fast and loose and everybody will agree that those people were not doing science; the very thing that gives us the strength of science is the discipline that was executed

086. **PD:** where we are in simulation is not where we should be concerned about rigorousness of experiments and we are still in the discovery stage in simulation

087. **SH:** the discipline is not that constraining

088. **PD:** social scientists have done a lot of experiments in social science; the scientific method has terrible effects; they end up looking where the lamppost is

089. **SH:** people can take a perfectly good methodology and turn it into crap

090. **WS:** that's not where the argument is; taking the scientific method and applying it inappropriately may miss the boat; the survey people get numbers so they look respectable but they miss the underlying story of what's going on; a story may come closer to what's really going on

091. **SH:** science isn't just numbers; you can take a perfectly good method and make it look perfectly bad by doing the wrong things; people may have perfectly good intentions but that doesn't make it right

092. **SN:** there must be lots more observation that goes on before doing controlled experiments; there's a lot of nosing around asking what's happening here; we didn't have a notion of atomic theory first, just lots of systematic observations; the nosing around is not scientific; i think that we're at the nosing around stage in simulation

093. **PD:** take alchemy and chemistry; in the beginning, they didn't do rigorous experiments but they produced useful knowledge; there was lots of sloppiness there

094. **SH:** saying that you adhere to the discipline doesn't say that you don't use any creativity

095. **DG:** part of science is nosing around; one of the difficulties in simulation science is the lack of data; in astronomy, anyone can look up at the stars; we don't have the data

through which to nose around; the only phenomena uniquely associated with a simulation is its correspondence with the real world; let's get a bunch of graduate students to generate lots of data for us

096. **PD:** if we look at programming, there is lots of data; we want to build models and simulations that are comprehensible and we don't know how to do that very well and we don't verify any observations about that collected experimentally

097. **DG:** the random number people have tended to publish their generators or their numbers and that enables us to test what they have; there are all kinds of reasons why we don't have those observations in the public domain; it would be neat if DL could sponsor a workshop on MC02

098. **PD:** when we do studies on diseases, there's often hard data; DL could ask for such things from the simulation people but may want to obfuscate the exact source, like the social science people do; we probably need those techniques to protect the companies that built the code; there's a data collection concepts that could produce what you're talking about

099. **DG:** i'm nervous about the social science analogy; he proposes the experiment of a model competition where a bunch of guys develop models of the same phenomena and submit them and we could pick one as a winner and award a prize; this would give us a 1K models that we could then analyze

100. **DL:** you don't actually have to build the model

101. **WW:** you need a conceptual model

102. **DG:** maybe so, we could have people develop conceptual models, maybe of the Chunnel or some accessible mechanism of that sort

103. **DL:** picking something where you could actually measure the real world may be a good choice

104. **DG:** one question is how does one find a measure of merit to represent the simulation; i want to see what measures of merit came back; we must get a body of observations that will lead to stronger hypotheses that we could then explore more rigorously; there are 89 industrial engineering departments that teach simulation and that doesn't include the computer science departments; that's a good resource from which to get a common body of observations

105. **PD:** another subject for study is looking at if it's essential to build simulations from the concept on to be useful; there are lots of reasons and they're not well understood; it's hard to build some things into the simulation; we've made only small progress (note: ask him about his reference to this to work done at rand ... how do you turn concepts into models of exploration); could you build automated software to add flexibility to simulations? today it's done by hand and that leads to lots of errors

106. **DG:** have people publish different ways, no; i want to see what they actually do; software processes often document what they are supposed to do and that's not what they actually do; there's all kinds of great literature about the right way to do simulation, very

little of which is backed up by actual data; i want what people actually do and not their conjectures about the best way to do it

107. **PD:** people have published lots of wonderful stuff in artificial intelligence but they're talking about toy problems and you have no idea about a real problem; they've often tried and it doesn't work but they don't publish that

108. **DG:** progress can be made if we get a whole bunch of observations; we're headed for a standard in conceptual models so it would be nice if we asked 1K people build one so we could standardize to what they actually did as opposed to drafting a standard and running it through SISO and then saying that's the right way to build one; in that situation, we may have only one or two cases where someone has actually built one that way

109. **WW:** we should be careful about what people say they do and what they actually do; we don't want to legislate what they actually do wrong

110. **DG:** that's true; there is a ying and yang to that

111. **WWh:** one of our objectives ought to be to simplify our understanding of the real world, models and simulations; that makes the argument that there is an underlying simplification; when you ask people to explain what they do, they often say that it's too complex; we ought to be able to simplify things to an explainable level

112. **WW:** a brigadier general may ask you to explain something in two slides; in simulation, in the doing and communicating it, the art is as simple as possible and not simpler; that's one of the tenets of representation; that's somehow professional and something that needs to be worked on; requisite complexity is really a key thing; it applies to representation and it applies at a meta-level to communication with regard to the perceived audience

113. **WS:** that ties to PD's point of how do we make these simulations understandable to people; that's partly tied up in how we build them; in the future if we really want them to be understandable then we're going to have to build them a little differently than we do now; if we do that, essentially having some of the design decisions to how to create this simulation actually represented as part of the simulation, that will tend to make them more understandable to the next people who come along to try to use the thing; it's a form of self documentation; also, it helps make a simulation adapt for new purposes

114. **PD:** some commercial tools (e.g., analytica and mathematica) exist as good models for that; if you model with these environments then you automatically create a lot of documentation and good structure and follow good practices; one of the things they don't do is ask you to generate what you're describing; in visual design environments, a lot of the conceptual model is looking you in the face; but, there are no hints as to what should be in that paragraph; we should define what generic questions to ask; this might be helpful

115. **WW:** that's the sense of regularizing the practice; making a conceptual model specification; i like broad-based experimentation through structured observations; that could provide a rolling wave of converging good practices

116. **DL:** we're doing MC02 in a couple of weeks; it is a large-scale simulation with 59 different federates in the core; its purpose is experimentation

117. **SH:** these are experiments for understanding force structures and not the nature of simulation

118. **DL:** it's part of the J9's looking at DoD transformation; it's a very large simulation and looks like it's going to work; if i were going to have ten people come in and say and tell us what their little piece was, what would be the ten papers that would tell us what they actually did?

119. **WW:** we want them to tell us how they build their conceptual model; you find out how they did it and what are the implications of it

120. **DL:** this is an opportunity to really formally document a bunch of stuff and they're going to do these things again

121. **SN:** let me make a concrete suggestion on that; i think that if you asked the people who build specific tools for that; you'd find out a great deal because the tools were built so they could figure out what was going on

122. **DL:** yeah, part of what i'm saying is let's go find the guy who did the multi-cast groups and don't make any value judgments on MC02, just what he had to do to make the multi-cast groups work

123. **PD:** this is an excellent idea; the people who had to do the analysis had to work hard to identify what they could do that is useful; if you had a situation where the Government was interested in doing a bunch of stuff and were doing an operational net assessment then could the C2 processes keep up? the hypothesis is that we can't currently do it; the hope is that the answer will be that we could do our job if it was organized a certain way; this is not rigorous; its hard to find these observations and conclusions; you think the experiments are about one thing when they're really about C2 processes; who would you go to to get the correct information?

124. **DL:** i could figure that out; there will be many briefings about MC02; but, they won't help you understand about the science of simulation; i need to get to the people who actually built the simulation

125. **WW:** ask them about the system integration; tell me how the system integration did and did not work and what would you do differently if you were given custody the next time around

126. **WS:** another paper is to have the people looking at the reorganization question, asking how that question influenced the conceptual modeling, the design of the system; how did that question change things?

127. **PD:** the true story would be a lot uglier but interesting

128. **DL:** the part that will get missed is what did you really do

129. **DP:** for MC02 you have a unique opportunity to collect that information if you ask

130. **DL:** Steve Moore is the right person; my fear is that it's so close that it might be hard to do that; we'll have more time next time to instrument things a little better

131. **SN:** Tony Cerri could point to all the nits in the geek world

132. **WW:** it's important that you structure the question, a set of ideas and the kinds of feedback that you want

133. **DL:** let's do a peer-reviewed conference on MC02; peer review brings a certain quality to the writing; a conference helps people write the paper; SCS may or may not be the right forum; we could get J7 to run the conference because they're the ones gaining from it

134. **WWh:** what would be the cost to do your experiment?

135. **DG:** we could give a $10K scholarship

136. **WW:** $10K is a small cost of running this; it would take 2-3 man-years to run a cycle of that

137. **SN:** what university could provide the labor to do it?

138. **DG:** you could go to SCS and ask them or to a graduate school

139. **DL:** i looked at this with ICT and there were some practical problems; i was looking at CGFs, a robo soccer; it was doable;

140. **WW:** the solicitation is one facet and constructing the event and you get the value; it's well within scope

141. **DL:** i really wanted to stimulate the university community to build simulations; one fear with getting 100-200 representations is that it might take 5 years to analyze; that's needed to insure quality; people want to believe that they could win and that there's value to that

142. **WS:** there are a couple of different versions of robo soccer; there's a version that involves robots and there's a version that is done in simulation; part of the cost in doing the simulated version is having the simulation constructed that everyone then uses to construct their players then also use to compete; that should be factored in but it gives a common base; finding that common base for this idea makes it much more manageable and insures a more consistent data set that we get back

143. **SH:** why couldn't we use the simulated robo soccer; that would provide the infrastructure

144. **DL:** if you're looking at the Chunnel thing then you have everyone buy SimCity and have everyone design something within SimCity

145. **DG:** you don't have to pick a winner; a $100 merit award from DMSO would be a big thing to a graduate student, resume fodder

146. **PD:** when was science advanced by a competition; this sounds wrong

147. **WW:** how about the clock; it had a terrific impact upon the advance of technology

**TAPE ENDED BEFORE SESSION CLOSED**

**NOTES TRANSCRIBED BY B. BAILEY & L. ALEXANDER (B PREFIXES)**

001. **WWh:** he introduced the session by outlining the following:

- That he has become convinced during the course of the workshop that M&S is not a "science".
- That M&S is certainly a worthy subject to be taught at the undergraduate level, however, his personal experience verifies that there is a barrier at the faculty-level.

002. **WWh:** There are two other areas of M&S that he is concerned about:

- Experimental design – there is very little actually done
- Simulating experimentation – the action of setting up an experiment with simulations without building in a bias.

003. **PD:** For the most part, the workshop discussions have blended the issues of "validation" of M&S products, as well as, the professional construction of M&S products. These are two separate issues that warrant two separate discussions.

004. **DL:** The workshop became a discussion of the "science of M&S" because there is not a set of practices that are built on some set of fundamentals. It is the "fundamentals" that we need to spend the next couple of hours addressing in the workshop. If we come up with the premise that "there is no science of M&S" then that would be "OK". However, he would appreciate the group addressing what makes up the basic fundamentals of the "science".

005. **SH:** The "apprentice" technique is not an efficient way to qualify an M&S professional.

006. **SN:** She would like to have a list of M&S foundational research topics for the purpose of obtaining the funding to pursue the initiatives.

007. **PD:** Complex adaptive simulations have a different set of concepts that would lead to a different outline of a "core body of knowledge" (Hollins' book was referenced). Also, there is a view of "computational experiments" which drive a difference set of knowledge sets because the purpose of computational experiments is to depict systems which are too complex to study otherwise.

008. **DP:** A worthy M&S experimentations is "visualization" – in terms of its simulation control and how you select the operational/implementation environment

009. **WW:** A couple of areas for experimentation are:

- Abstraction for intended purpose
- Conceptual model specification
- Architectural design

010. **EP:** As an important note to highlight, there has been some successes stories regarding M&S experiment initiatives, however, there is a ready list of experimental topic candidates (i.e., event list management schemes, random number generators, complexity theory, etc.).

011. **DP:** It is important to put this in perspective. In terms of general M&S impact, initiatives to date have been splintered/fragmented.

012. **DL:** One could build an argument that there is no science of M&S, however, there is certainly some important work being done concerning the sub-elements/foundations of M&S. One can possibly apply "science" to a discipline that has a large body of background information/references as opposed to an element that can withstand the rigors of "science discipline" (i.e., military science).

013. **DG:** There is a decided lack of M&S data from which to proceed on in a scientific manner within the M&S community. This is an extremely important circumstance because there is not a readily available body of materials that can be used for the community to come up with meaningful M&S hypothesis. He would like to see a graduate school competition for a conceptual model of which the body of materials would be available to further the study of M&S. Estimated cost would be: 1) a $10K scholarship; 2) approx. 2 man-years for the administration.

014. **PD:** Models need to be built so that conceptual analysis can be done on the model after it is built. To do this, the concept must be built into the model from the very earliest stages of the model development. This would have a significant effect on the scientific usefulness of the product.

015. **WWh:** Finds it interesting that there is an underlying thought within the M&S community that M&S products cannot be "simplified". In other words, there is a requisite complexion to M&S development and products.

016. **DL:** What are the 10 papers/questions which should be tasked to layout the lessons learned fundamentals for developing the MC02? There will be a significant body of knowledge on the "successes" of MC02, but he is not sure that the technical lessons learned issues will be documented for the M&S community.

017. **SN:** Suggested that the people who built the specific tools for the developmental fundamentals should be asked.

# Appendix 9: Session 6 Notes

The notes contained in this appendix refer to the participant making a statement by a two or, in one case, three letter code. Table 1 connects these codes to the participant speaker. These notes also sequentially number the statements, sometimes consisting of several sentences, from each of the speakers. The session records in the main body of this report refer to these numbers to correlate the record statements with the actual statements from the participants. This numbering begins with the first statement made in the session. Thus, a statement number higher than another signifies the utterance of that statement AFTER the lower numbered statement. A sequence of numbers is associated with the particular transcriber source. A new sequence begins with a change in transcriber source. In most cases, the two transcription sources worked simultaneously in workshop time. Letter prefixes were assigned to each source in the session records (e.g., a citation of [A046] refers to transcriber source A (in this case, Mr. Harmon) and the 46th statement). The assigned letter prefixes are shown with the transcriber source heading.

**Table 1.** Codes for the Participant Speakers.

| Code | Speaker |
|---|---|
| **BZ** | Bernard Zeigler |
| **DG** | David Gross |
| **DL** | Dell Lunceford |
| **DN** | David Nicol |
| **DP** | Dale Pace |
| **EP** | Ernest Page |
| **LA** | Larry Alexander |
| **MR** | Marc Raibert |
| **PD** | Paul Davis |
| **RS** | Randall Shumaker |
| **SH** | Scott Harmon |
| **SN** | Susan Numrich |
| **WS** | William Swartout |
| **WW** | William Waite |
| **WWh** | William Whelan |

In general, the transcribers attempted to capture the speakers' comments as accurately as possible where those comments clearly pertained to the workshop topic. Some discussion occurred between the participants that was not relevant (e.g., idle banter, jokes, references to the lack of coffee in the morning). That discussion was not recorded in these notes. The nature of spoken discourse made identifying individual sentences difficult so the transcriber made no attempt to do more than make a casual distinction.

### NOTES TRANSCRIBED BY S. HARMON (A PREFIXES)

001. **DP:** he proposes a 6-10 set of books that capture modeling and simulation knowledge; each book would address large topics that provide the material for undergraduate coursework

002. **WW:** he agrees with DP; we could use something like the Military Handbook on Infrared Technology as a model; each book should contain a threaded tutorial in each area; they are having trouble getting this idea started though

003. **DL:** we could pay people to divulge their linear thoughts on best practices then run peer reviewed efforts to document the lessons learned from MC02; we could start informally then move toward more formality; that might lead the right body of people to create these books then we could interest a publication house

004. **WW:** but then, publication houses will own the product; it must be constituency owned; the content is important to the evolution of the industry

005. **DL:** he can't justify asking for money to fund this project

006. **WW:** that's the same trouble that he has with his board of directors; we must establish a program and find funding for it; we could produce the program plan for this within a month

007. **EP:** we should look at the current literature and identify what's deficient then find someone to write about those topics and have them publish something in the journals that we currently control; we could worry about wrapping it as a CD later

008. **WW:** the product has story line and consistency; it must be done by a single coherent body; this approach holds the center on the enterprise

009. **EP:** you can't put a definitive work together that ignores everything else done; we should grow this through journal publications; the body of literature will necessarily be diverse

010. **WW:** a coherent body of description will not come together by itself; this product must be designed and built intentionally

011. **SN:** having some experience in the field gives her the willingness to take a survey up; but if inexperienced then she needs a tutorial approach

012. **DP:** he understood a desire to improve the simulation workforce (i.e., by making it more competent); his suggestion could be done within 3-6 months; this gives it the potential to be completed within a year; it captures what is present and fills in where needed; it gives people concerned with the current workforce something to work with and improve; it also gives the academic community something upon which to build courses; he can't see getting this done without help

013. **EP:** there is a book called the Handbook of Simulation

014. **WW:** that's not what we need; it's just a bunch of stuff slapped together

015. **SH:** from the scientific perspective, we need more visible data from which to understand the nature of simulation; this data is currently not visible; we're in a data poor situation

016. **DG:** yes, we need more data

017. **EP:** lots of stuff is out there, textbooks and journals; we need to be careful about saying what we don't have

018. **SH:** we don't understand the issue of fidelity very well

019. **DG:** he's convinced that there's not much data; there are lots of publications but they're all in the assertion realm

020. **PD:** we need something like a Reviews of Modern Physics in simulation; nothing equivalent exists for simulation; that vehicle is really good pulling together of work

021. **WS:** that's like high quality opinionated survey articles

022. **PD:** most of the stuff in simulation is barely journal article quality

023. **WW:** that's a great idea that meets a need but the problem is getting from the existing state to the desired state; SCS would be delighted to do this but no one knows how to get there

024. **PD:** it would be helpful to have data, some experimental, some experiential; we could plan a couple conferences to get the data out; he ran one and concluded that if they had money then they could write their experiences; that didn't happen; we don't have a sense for what exists but there may be enough to start with; we should get after action review reports from MC02 and others

025. **SH:** perhaps, a workshop is a better idea; but, we need another mechanism, a group of people going out and collecting the data; we don't have the equivalent of a telescope in astronomy, an instrument for collecting data about simulations

026. **PD:** the Internet is a sort of telescope; it allows running other peoples' programs

027. **SH:** that's glass but not a telescope; we need some instrumentation; with that we could get better data and understand error better

028. **DG:** agreed, the fidelity work offers that

029. **SH:** fidelity identifies what to measure; is there anything already out there

030. **EP:** yes, in some areas

031. **DG:** data is there for random number generators and event lists

032. **SN:** how does this work when implemented in simulation? do we have that data?

033. **DG:** no

034. **EP:** we must embed random number generators into simulation; some have done specific exercises to measure the effects they have; a large body of literature exists on that and event lists, multicast groups,.. but he doesn't know about fidelity

035. **DL:** must we pick a couple of these and run a couple of test cases? let's pick some and see what the literature has

036. **SH:** we should do that but not get paid for it?

037. **EP:** we could bring a list of texts and conferences that are relevant; let's be sure of that before running another conference

038. **SH:** we must identify those things that we come back knowing

039. WW: he doesn't know what the action items are from this workshop

040. **DG:** are we going to suggest a list of books that people should know if they're familiar with simulation?

041. **WW:** that's impossible

042. **SN:** can we look at this as the set of texts that we wish people had read?

043. **DL:** would he like to see a list of texts/papers that people had read if they were simulationists?

044. **WW:** that's a bad idea

045. **DL:** there is lots published on multicast groups but most of it is crap; how do I focus someone? he doesn't know what the answer is

046. **WW:** he's worried about giving endorsements to specific resources

047. **DL:** he doesn't understand the issue associated with suggesting a reading list

048. WW: it's best to tell them the contents of the desired knowledge; we should tell them what they need to know

049. **DL:** he's concerned about separating the wheat from the chaff in doing that

050. **WS:** in writing a survey article, you must decide what to include and exclude; he doesn't see the difference between that and providing a reading list

051. **WW:** a solution that gives only the references denudes the story; we must have the story

052. **WS:** we must also have a write-up of what this area is about that will supplement the reading list

053. **WW:** that is essential; we must advertise the domains of competency

054. **DL:** the real question is what can I assume away; what can I do to get started in the next 6-9 months? maybe we need to bundle all the stuff from a set of journals

055. **WS:** there might be an incremental approach, for example a website with a short view of the topical areas and that grows as knowledge is added

056. **DG:** that's a recommended list

057. **SN:** partial solutions are better than none; do I care where someone gets their knowledge? Yes, she does care where they get their knowledge; we must give examples of where to get knowledge; that tells how they'll use their knowledge

058. **DL:** that's why you have four-tiered schools

059. **WW:** theoretically not, these are secondary indicators

060. **SH:** there is a body of theory related to simulation; he's troubled that this theory may not have been validated by experiment; what theory has been confirmed by actual practice?

061. **DP:** he confirms that simulations have been built from that theory but no one has compared the effects of that

062. **SH:** what of that theory has been confirmed and how well?

063. **DP:** the issue is not does that work but how well do they work

064. **SH:** what is the scope of the theories and where do they agree and conflict?

065. **DG:** doesn't know if the existing theories could be validated

066. **DG:** regarding professional certification, we should do something with that; people may not have good knowledge of that

067. **DL:** he doesn't believe in it; we should do something in that area but he doesn't like what they've done so far

068. **DG:** then we should identify what we don't like of what they've done

069. **DL:** he wants to abstract some set of things that he doesn't need to deal with; he wants the certification levels to mean something; they are not the same as the PE certifications; he doesn't like it because they must first gain the knowledge; PE certification associates tests with experience level; how can he force simulationists to do something so that it means something?

070. **WW:** that's held as the objective; the problem is getting started

071. **DP:** Bill is going to send the certification test questions to us; send what exists; he will include the current criteria or test questions

072. **SH:** we should find out what is out there and what it consists of

073. **DL:** there's a huge body of knowledge about random numbers; there are other users of this technology; Ernie's list comes from computer science; as we move away from that knowledge, it gets thinner

074. **DG:** the question is within those boundaries what is the literature; there is lots of literature on software engineering and program management

075. **WW:** we must accept that knowledge related to simulation relates to other things as well

076. **SH:** we must go out and find out what's there; otherwise, we can't make that statement

077. **WW:** we tend to weight technical papers as significant; we must make a topical list and relationship diagram of those topics related to simulation

078. **SH:** yes, we must categorize but we can't now make such a list

079. **WW:** we must identify topical taxonomy of simulation, that would be hugely useful

080. **DG:** they presented their taxonomy as starting point; the science of simulation is a narrow branch and not much is written on it; we can't have a lot of success influencing those peripheral areas (e.g., large complex software projects)

081. **DL:**

082. **DG:** the difficulty with WARSIM is a simulation problem

083. **DL:** the problems include that we don't train computer scientists to be systems thinkers; we need the system guy for big complex systems; and, they typically don't understand how to build a simulation

084. **SN:** on any given day you want to represent the universe

085. **DL:** no, on any given day the developer wants me to represent the universe; I don't believe they know how to build a simulation engine

086. **WS:** there are multiple problems

087. **DL:** how do I translate user requirements; how do I build a simulation engine; he wants to add a topic; other sciences/professions have a consistent vocabulary; some may argue that we're not in the position to do that; simulation people use words differently; is there a need to start stabilizing the vocabulary?

088. **WS:** that's an artifact of how mature the terms are with respect to a field; it's analogous to our confusion in other fields; there are things in simulation upon which we can agree; there are emerging concepts upon which we won't; he agrees that we need a vocabulary

089. **DL:** everyone will have definition for a simulation engine

090. **DG:** we need to use the peer review process to get the vocabulary consistent

091. **DL:**

092. **DG:** we need the glossary

093. **DL:** is a consistent vocabulary useful? he thinks that the DMSO glossary is not useful

095. **WW:** the former BMDO is using that glossary; other organizations are as well; we must have a broad process for improving the syntactical and semantic uses but it's hard

096. **DL:** should we also take on stabilizing the lexicon?

097. **WW:** we should post the position and look for how to get started

098. **DP:** we come from the defense community; outside of that there's more diversity and much of the science is outside that community; maybe we can only tackle that in the defense community

099. **DL:** he disagrees about keeping it within DoD; we must not have a lot of separation; he wants a definition of simulation that the entire universe agrees with; multiple definitions are OK

100. **WS:** regarding another phenomena, if you build it then they will come; something of utility will be used

101. **WW:** we must invest in these

102. **SN:** in summary: (basic understanding) let's list relevant conferences, texts and papers that provide basic understanding; we need to develop a book set; (concrete understanding together) we need a review of modern physics for high quality survey information; we need a lexicon; (need to experiment and deal matter of simulation) perhaps we need a specialized conference, beginning with lessons learned (MC02); we should identify what data can literature provide and spur the university community to provide data; we must understand what an M&S professional is; we should look at certification at NTSA

END OF SESSION

**NOTES TRANSCRIBED BY B. BAILEY & L. ALEXANDER (B PREFIXES)**

001. **SN:** she introduced the session by outlining the following:

- Extremely important to continue the dialogue of studying and discussing the body of knowledge for M&S.
- Important to define how the information should be available to he community.

002. **PD:** Relayed that there was enough materials discussed during the workshop to merit the publication of a book with each chapter warranting the sponsored research for the titles of each title.

003. **DP:** There is a need for a set of books which layout the fundamentals impacting M&S. This set should document the core body of knowledge that a journeyman would need to have access to become proficient in M&S. Recommend that the materials be put on a CD for ready accessibility. Recommended literature layout: problem formulation, abstraction/representation process, simulation design, implementation alternatives, techniques, implementation of language choices, management, etc.

004. **WW:** If this effort is undertaken, then the initiative should be a community enterprise effort instead of paying a set of individuals to publish the documents. The process should produce a product that evolves in a "rollout fashion".

005. **DP:** To improve the quality of the simulation workforce, there would need to be a series of books (about a 6 month effort for each book) over the course of a year's effort that would be the foundation of a "best practices guide" to M&S. This approach would have a significant potential for success.

006. **SH:** From a scientific perspective, we need to have a more visible body of work from which the community could study the fundamentals for M&S. The work done so far is not visible.

007. **EP:** There are hundreds of publications that address M&S. Caution should be exercised before a wholesale statement is made to address the data deficiencies.

008. **PD:** It would possibly be worthwhile to hold a couple of specialized conferences to document "what is out there" which could used to define what deficiencies exist in the M&S community.

009. **EP:** As homework assignments, it would be useful if this body would share their literature searches.

010. **SH:** Relayed that he will document all of the action items derived from the workshop and will, in turn, send them to all of the workshop participants for action/response.

011. **DL:** Relayed that he would think it useful if a list of recommended M&S reading literature could be published/stated on a website for use to the M&S community. This is one of the actions that might be a "first step" on the task of accumulating a "common body of knowledge" for the M&S community.

012. **WWh:** Science is focused on simplifying knowledge of the real world. We should look to simplify knowledge of M&S.

013. **WW:** The art is to make it as simple as necessary but no more. Boiling down anything too far results in nothing.

014. **WS:** Endorsed the formation of a website outlining a recommended reading list.

015. **SN:** It is important that the community have access to a body of recommended literature.

016. **WW:** Will send the "M&S certification" questions to Harmon for distribution to the group.

017. **DL:** A "consistent vocabulary" for the M&S community is a problem. Is there a need to start stabilizing the vocabulary? (NOTE: After much discussion, there was not a consensus in answer to his question.)

# Appendix 10: Participant Survey on the Existence of a Science of Simulation

In the course of completing a briefing describing the workshop, the final report editor asked what the participants finally believed about the existence of a science of simulation. He asked for their vote on the question

Do you believe that there is or could be a science of simulation?

Choose one: No, Yes, Doesn't matter

Many participants responded with more than a choice of those three alternatives. In some cases, participants did not respond to this solicitation but had portrayed their positions in other communications or during the workshop sessions. The sections below capture those responses and positions.

**PAUL DAVIS:**

My answer is that there "could be," but I don't know that I care about whether there would be a new department and new PhD. Maybe it's just fine for a "simulationist" to get his MS or PhD in a computer science or applied math department, or even an electrical engineering/system sciences department. The specialty, then, IS feasible and important. Whether it's a capital-S science or a "specialty" is probably not something to decide now.

A really big issue, however, relates to whether the "it" (the simulation science) is about modeling, software engineering, the special problems associated with large-scale distributed simulations (as used by, e.g., US JFCOM), or what? Personally, I've always been concerned about the theory and content of the underlying models and not particularly interested in or intrigued by the terrific technology required to make the big simulations work. However, that implementation technology is profound stuff also.

**DAVID GROSS:**

YES (that is, there could be, but a very small domain)

**SCOTT HARMON:**

The term “science of simulation” has always bothered me because it implies that some scientific knowledge exists outside of science itself. My response to the question is yes but only on the condition that a science of simulation consists of knowledge that is an integral part of that greater body of knowledge we call “science.” I firmly believe that phenomena exist that govern many aspects of simulation development and use and that we can apply scientific discipline to extract knowledge about those phenomena. That knowledge I would define as the science of simulation.

**DELL LUNCEFORD:**

If it helps the casual reader with understanding, I would vote yes.

**DAVID NICOL:**

[Abstracted from a supplementary message] I think what we were looking for is more Engineering of Simulations than Science. Engineering can be about methodology, without the rigor of the scientific method. Engineering practices grow up as a result of experience, and working methodolgies are established without a scientific understanding of why they work.

**SUSAN NUMRICH:**

You forgot "maybe".

If you can't accept that answer, then I must answer that at this point in time "no"; however, I do not deny that it could emerge in the future.

**DALE PACE:**

My response is that it doesn't matter -- and to elaborate, there is not now a science of simulation, though it is possible that one could evolve in the future (but I do not think it likely to occur within the next decade or two).

**ERNEST PAGE:**

Like everybody else, I guess, I tend to resist binary choices... Most of my "on the one hand, and on the other hand" points are covered in my position paper. But for sake of argument and momentum, put me in the "yes" group for the moment.

**MARC RAIBERT:**

[Abstracted from a message prededing the workshop] In my world I don't discriminate between engineering and science (actually, engineering has a higher place than science for me, because it includes the human creativity component as well as all the science). So anything I say about simulation will probably be slanted toward what it needs to be to be an effective tool. Like my robotics, which has always emphasized experiment and application, my simulation focuses on validation and application. (Editor's Note: Marc's response was really to another question but I thought that it captured his position pretty succinctly. I interpret this position as a vote for "it doesn't matter.")

**RANDALL SHUMAKER:**

Yes, could be, and really should be to get out of the current mixed state of affairs in development.

**WILLIAM SWARTOUT:**

I would say "yes" taking "science" here to mean much what it does in the term "computer science", that is, we will have a science in the sense of having a well worked out way of attacking simulation problems --- a kind of scientific methodology for simulation --- much as computer science provides us with methodologies, tools and approaches for

attacking computer programming problems. It won't be a science in the sense of the natural sciences.

**WILLIAM WAITE:**

[Abstracted from the workshop sessions] [Regarding simulation,] my opinion is that it's technology there and not science the way we think about it wherein there's an objective reality that we come to understand. Although there may be stuff that we can tease out. Let's think about simulation as a technology because that's where there's the challenge

**WILLIAM WHELAN:**

I vote yes.

**BERNARD ZEIGLER:**

Yes