Computer Simulation: The Art and Science of Digital World Construction*

Paul A. Fishwick

Computer & Information Science and Engineering Department
University of Florida, CSE 301
Gainesville, FL 32611, USA
E-mail: *fishwick@cis.ufl.edu*

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WHAT IS SIMULATION?

Computer simulation is the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output. Simulation embodies the principle of "learning by doing" — to learn about the system we must first build a model of some sort and then operate the model. The use of simulation is an activity that is as natural as a child who *role plays*. Children understand the world around them by simulating (with toys and figurines) most of their interactions with other people, animals and objects. As adults, we lose some of this childlike behavior but recapture it later on through computer simulation. To understand reality and all of its complexity, we must build artificial objects and dynamically act out roles with them. Computer simulation is the electronic equivalent of this type of role playing and it serves to drive synthetic environments and virtual worlds. Within the overall task of simulation, there are three primary sub-fields: model design, model execution and model analysis (see Fig. 1). The chapter annotations in Fig. 1 relate to the author's recent simulation textbook (see the section READ MORE ABOUT IT) which focuses on the first two sub-fields. To simulate something physical, you will first need to create a *mathematical model* which represents that physical object. Models can take many forms including declarative, functional, constraint, spatial or multimodel. A multimodel is a model containing multiple integrated models each of which represents a level of granularity for the physical system. The next task, once a model has been developed, is to execute the model on a computer — that is, you need to create a computer program which steps through time while updating the state and event variables in your mathematical model. There are many ways to "step through time." You can, for instance, *leap* through time using *event scheduling* or you can employ small time increments using *time slicing*. You can also execute (i.e., simulate) the program on a massively parallel computer. This is called *parallel and distributed simulation*. For many large-scale models, this is the only feasible way of getting answers back in a reasonable amount of time.

*A Hypermedia version of this document can be found at `http://www.cis.ufl.edu/~fishwick/introsim/paper.html`.

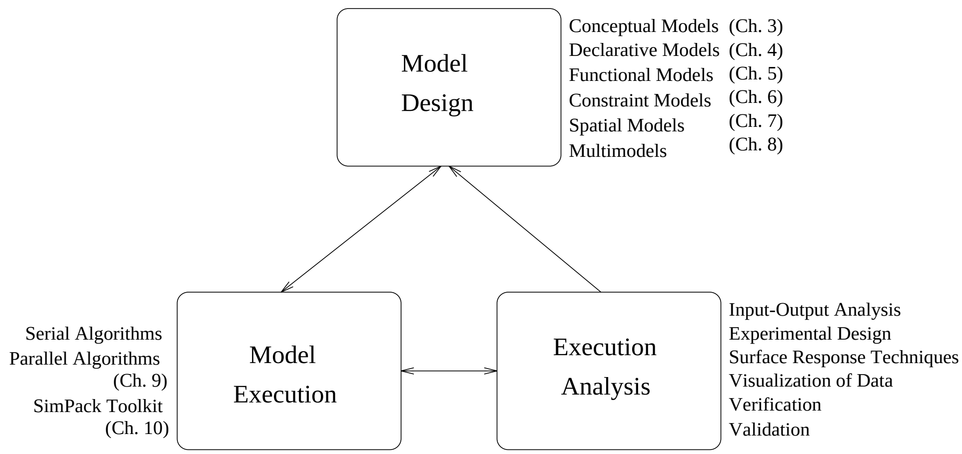

Figure 1: Three Sub-Fields of Computer Simulation.

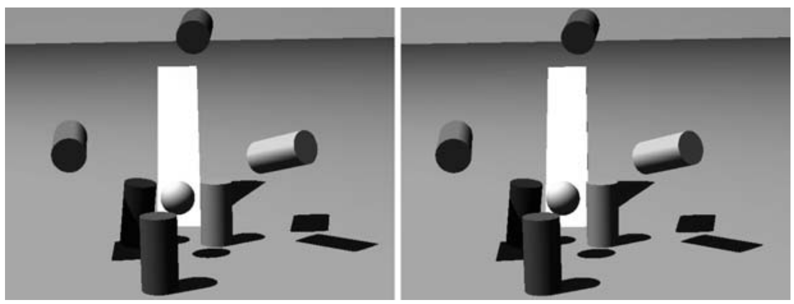

Figure 2: Falling cans stereo pair.

Simulation of a system can be done at many different levels of fidelity so that whereas one reader will think of physics-based models and output, another may think of more abstract models which yield higher-level, less detailed output as in a queuing network. Models are designed to provide answers at a given abstraction level — the more detailed the model, the more detailed the output. The kind of output you need will suggest the type of model you will employ. An example of graphical output from a physically-based model (generated using the program AERO[1] is shown as a stereo pair of "rigid bodies" in Fig. 2). You can view this stereo pair without the use of external viewing aids, by diverging the eyes[2].

WHY DO SIMULATION?

You may wonder whether simulation must be used to study dynamic systems. There are many methods of modeling systems which do not involve simulation but which involve the solution of a closed-form system (such as a system of linear equations). Simulation is often

[1] The stereo pair was provided courtesy of Thomas Bräunl, University of Stuttgart. AERO may be obtained from `ftp.informatik.uni-stuttgart.de/pub/AERO` and it provides a useful tool, using the X windows system, for exploring rigid body dynamics.

[2] Divergence can be achieved in a variety of ways. Try focussing on an object three or four feet from your eyes. Then place these figures between your eyes and the object. You will see three frames, with the middle frame being the combined left-right stereo frame.

essential in the following cases: 1) the model is very complex with many variables and interacting components; 2) the underlying variables relationships are nonlinear; 3) the model contains random variates; 4) the model output is to be visual as in a 3D computer animation. The power of simulation is that —even for easily solvable linear systems— a uniform model execution technique can be used to solve a large variety of systems without resorting to a "bag of tricks" where one must choose special-purpose and sometimes arcane solution methods to avoid simulation. Another important aspect of the simulation technique is that one builds a simulation model to replicate the actual system. When one uses the closed-form approach, the model is sometimes twisted to suit the closed-form nature of the solution method rather than to accurately represent the physical system. A harmonious compromise is to tackle system modeling with a hybrid approach using both closed-form methods and simulation. For example, we might begin to model a system with closed-form analysis and then proceed later with a simulation. This evolutionary procedure is often very effective.

SIMULATION EXAMPLE

Let's consider an industrial manufacturing example where we will build a model which has numerical, not graphical, output. Terms such as "computer-integrated manufacturing" (CIM) and "flexible manufacturing" guide the development of more productive plant configurations for building products from raw material. We introduce the following categories and definitions:

1. *Material*. Plants are built to process material—often called raw material stock—and shape the material into a product. As raw material goes through its changes, it turns into a *part* to be processed.

2. *Machines*. Plants are composed of machines of all kinds which process material and parts. Some examples are ovens, lubricators, flame cutters, lathes, and robots.

3. *Transportation*. Material flows through a network of machines. The method of transport is effected by devices such as conveyors and automated guide vehicles (AGVs). During this transit, it encounters storage areas and accumulators which buffer parts until the machines can operate upon them.

Figure 3 shows a sample manufacturing system containing nine parts. This type of drawing is essentially a schematic defining the overall structure of the system but lacking details on dynamics and geometry. The raw stock arrives from the left via a central conveyor. At this point, the material stock is a cylinder shape. The cylinder parts are loaded into a spiral accumulator (A) which holds parts for the pick-and-place robot (R) until both it and the lathe (L) are ready. Once both are ready to work with the part, the cylinder is turned into a barbell shape by the lathe and sent on toward a second spiral accumulator using a conveyor belt. A second robot also performs a pick-and-place operation and hands the barbell part to a drill machine (D) which punches a longitudinal hole through the part. That is the final product part, which proceeds to a small storage bin taken by the AGV which runs around a closed track while dropping the bin contents into longer-term storage. This type of application involves discrete parts flowing through a network of resources. The

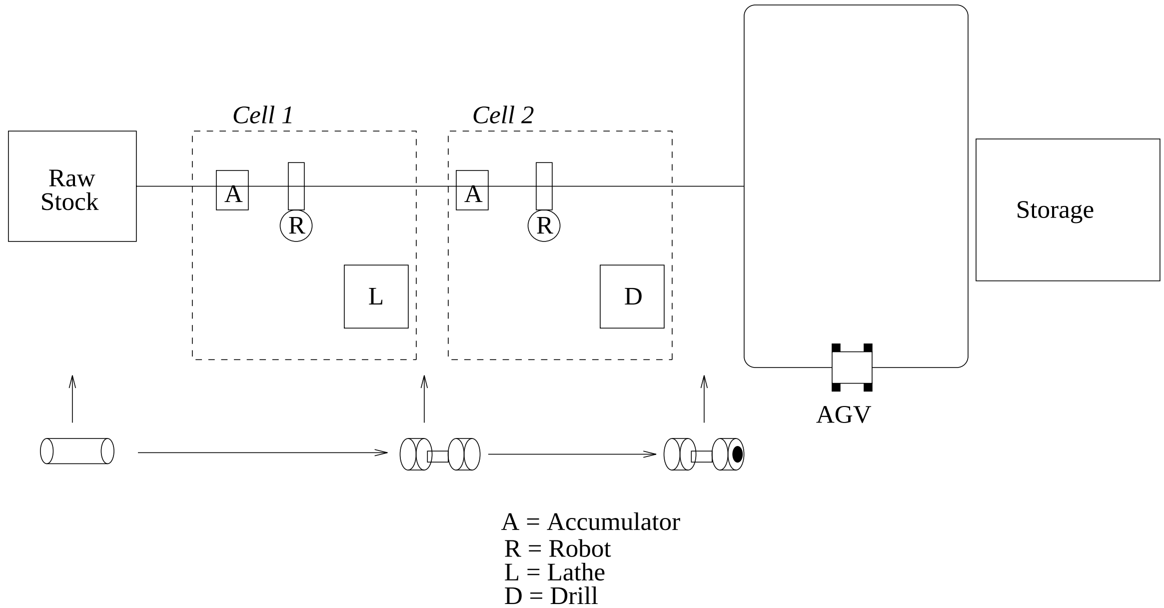

Figure 3: Manufacturing line with two robots and two machines..

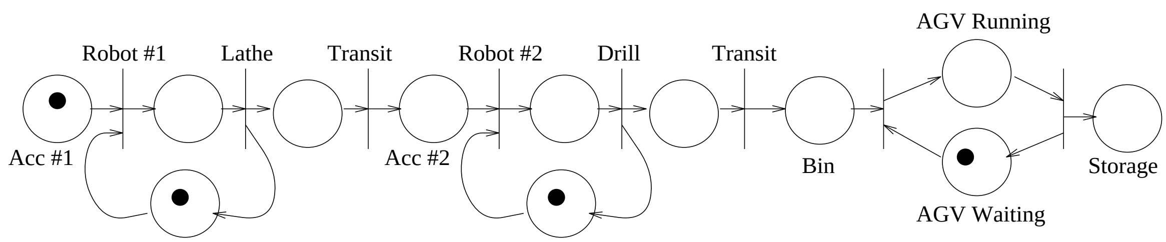

Figure 4: Petri net model for manufacturing line.

resource constraints and network flow suggests the use of a Petri net to model the system as in Fig. 4.

Figure 4 is the mathematical model for the system and is categorized as a *declarative* model (i.e., the Petri net sub-states and events are visible and emphasized in the model structure). In a nutshell, a Petri net operates by having tokens (the black circles) flow through the network while encountering resources (lathe,drill press, robot arm, AGV). Each resource operates or "processes" a token as it passes by. This is the specification that we need to encode in the form of a program and then execute on a computer. There are many Petri net simulators to be found. One such simulator is a tool within SimPack (See section SIMPACK SIMULATION TOOLKIT), which is a toolkit for exploring mathematical modeling and simulation. Once simulated, this Petri net can yield data which is subject to *analysis* (the third sub-field of computer simulation). The types of analysis methods for simulations are plentiful. For our manufacturing example, we may simply want to analyze the throughput of the system as a whole to determine how many parts can be processed in one hour. Actually, we *pre-determined* our use of a Petri net model because we knew ahead of time that we wanted throughput information. If we had wanted, say, information on the stability of the robot arm controller then a Petri net would not have served our purpose.

Moreover, if our Petri net model has a stochastic element (i.e., it uses random variates) then it is vital to make many simulation runs of the same model but with different samples; otherwise, we will not know the accuracy (measured by a confidence interval) associated with the simulation output.

THE SIMULATION DISCIPLINE

To characterize simulation, it is useful to compare it with other fields such as computer graphics/animation and virtual reality (VR), since these fields have much in common with simulation. Computer graphics is the computational study of light and its effect on geometric objects — the focus on graphics is to produce meaningful rendered images of real world or hypothetical objects. Animation is the use of computer graphics to generate a sequence of frames which, when passed before your eyes very quickly, produce the illusion of continuous motion. VR is primarily focused on *immersive* human-computer interaction as found in devices such as head-mounted displays (HMDs), position sensors and data gloves. Think of simulation as the "engine" which drives the graphics and VR technologies. That is, by doing simulation (creating a model, executing the model, and analyzing the output), you build the infrastructure necessary for other fields. The ultimate test of a computer anmation is that "it looks good" to the viewer. Most computer simulationists, however, regard this as only one component of validation (called *face validation*). As long as you are not doing engineering or science, creating a geometric model that looks good, as it undergoes motion, is satisfactory. However, if you are trying to validate a mathematical model with real world data (often of a non-visual nature), we must be concerned with more than mere "looks." Most VR researchers are concerned with the human-machine interaction and not with the mathematical models which actually create the artificial reality. For such models, we require computer graphics (for representing the geometry) and computer simulation (for representing the dynamics).

Working closely with people of other technical disciplines is one of the things that makes simulation fascinating. If you take a moment to talk with faculty and students in different departments spread throughout a typical university's colleges, you will find simulation being used everywhere. The person in a specific department is usually interested in simulation to satisfy a class of problem. For instance, someone doing work in Ecology and Wetlands Restoration will be doing simulation for hydrology and population growth and decay for wildlife species in a given geographic region. Someone in Astronomy will want to simulate the collision of galaxies and the formation of dark matter. Simulation provides these workers with a tool to let them explore their worlds without having to run extensive physical, on site, experiments which tend to be expensive both in time and money[3]. As a simulationist, your responsibility is to understand the common vocabulary of systems, modeling terminology and algorithmic procedures which form the simulation foundation. You will often find yourself seeing relationships between someone's problem, for instance, in astrophysics and someone else's problem in molecular dynamics. It is this *synergy* which creates a great deal of satisfaction for the simulation discipline.

[3]Simulation should be closely inter-woven with empirical studies where possible; it is not a substitute for physical experimentation.

WHAT TO STUDY

Let's suppose that you want to make a career in the computer simulation field. What subjects do you study? Is there an academic major in computer simulation, or do simulation departments exist? Simulation is not yet at the "department" stage of academic infrastructure evolution, but there are some important guidelines:

1. Take computer simulation classes, and make sure that you get a good douse of modeling, algorithms and analysis. Some simulation classes may offer only one or two of these three sub-fields. Computer Science, Industrial and Systems Engineering, Decision Science, and Statistics departments usually have simulation courses in their curricula.
2. Look at some closely related subjects which form the foundation for simulation such as Cybernetics, System Theory and System Science. Some of these topics may not be widely disseminated through lectures, but there are lots of good references in the library.
3. Take classes which serve as good auxiliary forums for computer simulation work. Computer Graphics and Human-Computer Interaction (HCI) are good courses.

READ MORE ABOUT IT

There are many resources for getting more information on simulation. Some are provided below. Make special note of the World Wide Web pages, since they will point you to yet other locations of relevance:

- Electronic News Groups on USENET:
  - `comp.simulation`
  - `sci.aeronautics.simulation`
  - `alt.materials.simulation`
- Electronic Simulation Journal:
  - Computer Simulation Modeling and Analysis (CSMA)
  - `http://piranha.eng.buffalo.edu/simulation/`
- Books:
  - Ashby, W. Ross, "An Introduction to Cybernetics," John Wiley and Sons, 1963.
  - Padulo, Louis and Arbib, Michael A., "Systems Theory: A Unified State Space Approach to Continuous and Discrete Systems," W.B. Saunders, Philadelphia, 1974.
  - Zeigler, Bernard P., "Theory of Modelling and Simulation," John Wiley and Sons, 1976.

- Law, Averill M. and Kelton, David W., "Simulation Modeling and Analysis," McGraw Hill, 1991, Second Edition.
- Çellier, Francois E., "Continuous System Modeling," Springer Verlag, 1991.
- Fishwick, Paul A. "Simulation Model Design and Execution: Building Digital Worlds," Prentice Hall, 1995.

- Societies:
  - Society for Computer Simulation International (SCSI), San Diego, California. Web: `http://www.scs.org/`
  - Association for Computing Machinery (ACM SIGSIM), New York, New York. Web: `http://www.acm.org/sig_hp/SIGSIM.html`
  - Institute for Electrical and Electronics Engineers (IEEE Computer Society TC-SIM), New York, New York, IEEE Computer Society. Web: `http://www.computer.org/tab/tab.html#tabsim`
  - The Institute for Operations Research and the Management Sciences: INFORMS College on Simulation. Web:`http://www.isye.gatech.edu/informs-sim/`
- Periodicals with a Simulation emphasis:
  - SCSI Simulation, SCSI Transactions on Simulation
  - ACM Transactions on Modeling and Computer Simulation
  - IEEE Transactions on Systems, Man and Cybernetics
  - International Journal in Computer Simulation, Ablex
  - International Journal of General Systems, Gordon and Breach
  - Simulation Practice and Theory, Elsevier
- Simulation-Specific Conferences (with greater than 300 attendees)
  - SCS Simulation Multiconference (held in April) Web: see the SCS home page under "Societies."
  - Winter Simulation Conference (WSC, held in December) `http://www.isye.gatech.edu/informs-sim/wsc95.html`
  - SCS European Multiconference (ESM)
  - European Simulation Conference (EUROSIM) `http://eurosim.tuwien.ac.at`
- Recent Simulation Conferences with Online Web Proceedings:
  - 1994 AIS (Distributed Interactive Simulation Environments Conference) `http://www.computer.org/conferen/ais94/ais94.html`
  - ELECSIM Conference `http://www.mystech.com:80/ ~smithr/elecsim95`

THE FUTURE

Technologies such as Simulation and Virtual Reality will dominate the entertainment and science forefronts well into the next Century. Since early childhood, we have always learned by role playing and building models of things. With today's computer prices, personal computers are highly affordable. Armed with your computer, you can proceed to build models of reality and "let them loose" to see what happens and to learn more about reality by modeling it. While what we may do today may be primitive by standards set in science fiction shows such as Star Trek (The Holodeck) and Lawnmower Man, the present computer simulation discipline will lead the way to these eventual goals. The key word is "digital" as pointed out by many such as Nicholas Negroponte at the MIT Media Lab in his recent text "Being Digital." We want to create digital replicas of everything you see as you look around you while reading this article. When you want to construct a digital world, you will pick digital objects, using a 3D, immersive construction tool to put them together. The digital objects may be located anywhere on the Internet and you will use help tools (or autonomous agents) to locate the building block objects for your digital world. Some of this type of work is being done in *Distributed Interactive Simulation* which is a thrust pioneered by the Department of Defense. The implications of these types of simulations are profound since the idea of distributed simulation has enormous potential, also, in industrial and entertainment fields.

SIMPACK SIMULATION TOOLKIT

To obtain SimPack, access the author's World Wide Web home page World Wide Web home page `http://www.cis.ufl.edu/~fishwick` by using Netscape, Mosaic or another Web browser, and click on "SimPack Simulation Toolkit." SimPack is a collection of C tools (routines and programs) for computer simulation. The purpose of SimPack is to provide people with a "starting point" for simulating a system. The intention is that people will view what exists as a template (or "seed") and then "grow a simulation program." SimPack tools have been used for six years of teaching computer simulation at the undergraduate (senior) and graduate levels at the University of Florida. You can subscribe to the SimPack mailing list by sending mail to `majordomo@cis.ufl.edu` with the message: `subscribe simpack`. A message containing the first word `help` will provide you with all the commands available through the list server.

ABOUT THE AUTHOR

Paul Fishwick is an Associate Professor in the Department of Computer and Information Sciences at the University of Florida. He received a BS in Mathematics from the Pennsylvania State University, MS in Applied Science from the College of William and Mary, and PhD in Computer and Information Science from the University of Pennsylvania in 1986. He also has six years of industrial/government production and research experience working at Newport News Shipbuilding and Dry Dock Co. (doing CAD/CAM parts definition research) and at NASA Langley Research Center (studying engineering data base models for structural engineering). His research interests are in computer simulation modeling and analysis methods for complex systems. He is a senior member of the IEEE and the Society for Computer Simulation. He is also a member of the IEEE Society for Systems, Man and Cybernetics, ACM and AAAI. Dr. Fishwick founded the comp.simulation Internet news group (Simulation Digest) in 1987, which now serves over 15,000 subscribers. He was chairman of the IEEE Computer Society technical committee on simulation (TCSIM) for two years (1988-1990) and he is on the editorial boards of several journals including the ACM Transactions on Modeling and Computer Simulation, IEEE Transactions on Systems, Man and Cybernetics, The Transactions of the Society for Computer Simulation, International Journal of Computer Simulation, and the Journal of Systems Engineering. Dr. Fishwick can be reached by email at *fishwick@cis.ufl.edu* or via his World Wide Web home page `http://www.cis.ufl.edu/~fishwick`