

Chapter 1

The Jade Mountain

Perhaps my favorite object in our local art museum is a Chinese jade sculpture of a mountain. Although a massive piece of stone, it is truly miniature compared to what it represents: tiny jade trees cling to its diminutive cliffs; a procession of poets and scholars ascends its paths; its rocks mimic the condensed shape of alpine crags. It is obviously a lofty mountain; perhaps it is the distillation of a sacred place. The artist surely intended it so. He created a microcosm that perfectly abstracts the macrocosm.

To capture the world in miniature has long been a human dream. Or, more accurately, to capture just that part of the world that is really meaningful, to distill its essence, has driven both science and art forward from the beginning. Such a blueprint or model of reality would grant both the knowledge of its vast structure and the primary means to manipulate it by, recalling Francis Bacon's remark that "knowledge is power." It would provide the aesthetic and even spiritual satisfaction of beholding reality in a single view. And this is, more or less, the aim of every model ever built: to reduce reality to a smaller, yet more concentrated form.

To jump in scale from the jade mountain to the world — to the whole of reality — seems an impossible leap. Yet the advent of computer modeling and simulation opens up this tantalizing possibility. Computer scientist David Gelernter calls such comprehensive models *mirror worlds*¹:

"A Mirror World is some huge institution's moving, true-to-life mirror image trapped inside a computer -- where you can see and grasp it whole. The thick, dense, busy sub-world that encompasses you is also,

now, an object in your hands ... Oceans of information pour endlessly into the model (through a vast maze of software pipes and hoses): so much information that *the model* can mimic *the reality's* every move moment-by-moment... Mirror Worlds are devices for showing you the big picture, *the whole.*”

The computer simulation, the “mirror world,” is nothing less than an attempt to construct a digital microcosm. It places a model of the universe — or that fraction of the universe you’re most interested in — on your desktop. The model provides a unified view of systems and organizations extending far beyond our own limited perspectives.

This is heady stuff. But is it really possible? Certainly computer modeling, simulation, and design are finding ever-wider applications, to an extent most people are unaware of. They are essential to many of the products we encounter every day. Chances are the car you drive was designed and tested through computer simulation. Modern aircraft are entirely prototyped in the virtual space of computer software, tested and “flown” on the computer long before the first “real” new plane rolls out onto the tarmac. Even advances in computers themselves have become dependent on computer simulation. Modern CPU chips contain millions of integrated transistors and circuits; a computer itself is needed to keep track of such complexity and numbers -- and to verify a new design works.

Such examples show us the main reason for the success of computer modeling. Building models can be dramatically less expensive than building a real system. Simulation -- the exercising of a model through its possible states and behaviors -- provides a means of exploring the system’s advantages and pitfalls in a rapid, easily repeatable fashion. Computer models have taken hold precisely in those areas where the actual system of interest, whether a microcircuit or a spacecraft, is difficult and expensive to build in reality. There is a premium on getting it right the first time. More subtle modeling advantages arise from the complexity of systems. Consider a modern commercial airplane. It contains millions of parts, and the parts are very different depending on what subsystem of the plane you look at: engine turbine blades made of advanced alloys, the cockpit avionics suite and control system, the shape and structure of the wings, the most comfortable and safe design for

passenger seating, and so on down a list of thousands of subsystems. Integrating these complex subsystems into a single harmonious design is beyond the grasp of a single unaided human mind or any group of human minds equipped only with pencil and paper – hence the long program of mockups, aerodynamic wind tunnel testing, and sometimes dangerous experimental flight testing that had traditionally gone into aircraft engineering. The computer model provides entirely new means for managing that complexity and integrating the design into whole. Aerodynamics can now be tested using computer models of fluids; important subsystems like the engines can be designed with the aid of combustion dynamics models. In other words, computer model grants a unified view of the aircraft that would otherwise be hidden; it lifts the designer up to see the entire “forest,” a perch above those blocked by the “trees.”

A simulated world takes form gradually, crystallizing one small piece after another into a moveable computer image. The piece might be a railway system, a business organization, or a hospital instead of a complex machine, but the principles are the same and the benefits similar. Economic gains from computer technology in recent years have largely resulted from managing companies along lines of greater, fine-tuned efficiency through software. Financial/accounting database software is now absolutely essential to the smooth running of large corporations. We see again the indispensability of computers in dealing with complexity and numbers, but there is more to it than that. The implementation of accounting software for a major company means replicating its business structure and practices within the software itself -- in other words, building a computer model of the company. Information flow within the software’s virtual business governs the flow of actual goods, services, and money within the real business. By refining the model, one refines the company. And the contents of the model are continually updated from any number of sources, which need not deal with the entirety of the model or even be aware of it. When an order is shipped out of a certain warehouse, this fact is immediately reflected in the inventory system and corresponding account changes. The database system provides the means by which to view and analyze

as an integrated whole the thousands or millions of such events that take place in the company.

The computer model's ability to handle complexity not only makes it an ideal design tool, but a powerful instrument for exploring nature. Models are essential for understanding complex systems where direct calculation is impossible. One example is weather and climate prediction, which Chapter Seven discusses at length. The question of global warming, for example, has catapulted climate modeling from the research lab into the headlines. Comprehensive understanding or prediction of global climate would be utterly impossible without computer models. The atmosphere is a fluid extended not just as a spherical shell, but also vertically. The forces and influences acting on it are so various that predicting the properties at a given point mean a consideration of the whole. Tomorrow's weather in my city depends not only on the solar influx at this place; it depends still more on the properties of large air masses and earth-circling jet streams. In other words, local weather is determined by a host of remote factors, all interconnected, the most important of which might be something on the other side of the world. Heating of the southern Pacific Ocean, the El Niño effect, leads to a stormy and rainy winter in North America. Global circulation of the atmosphere clearly is not something one can calculate by hand like a simple mechanics problem. Even if the calculations were finished, their predictions would be long obsolete. Instead, one builds a computer model by taking the known physical properties of air, setting up a grid of points representing the atmosphere, and then applying the energy inputs and losses to it. The model replicates atmospheric behavior and thus can make predictions: whether this summer is likely to be rainier than normal or whether industrial inputs of carbon dioxide into the atmosphere will cause it to warm significantly over the next century.

The connection of complexity and computer models applies to many other areas of scientific research, for systems as small as molecular chemical reactions or as large as coalescing galaxies. Without computer models, understanding such systems would be reduced largely to qualitative description or guesswork.

Computer modeling and simulation are increasingly important scientific tools. Indeed, as Chapter Five explains, they are where theory

and experiment come together. Since the interaction of theory and experiment is science's dynamic force, modeling and simulation are closely connected to the heart of the scientific method. Like theory and experiment, they are complementary. The model is like a theoretical construct in that it attempts to replicate reality; simulation is like experiment in that provides a means to test the model. Computer models are like microscopes or telescopes, except that peering into the very small or the very far, they grasp the incredibly complex.

Modern physics has striven mightily to develop a unified field theory that would be a "theory of everything," explaining all natural forces by a single set of equations. The direction of computer simulation is to develop of a *model of everything*, unifying the models of all parts of the world in a single system, replicating everything about everything. Models of individual phenomena would eventually interlock, like the formation of a crystal, and the world model will emerge. Not only would this model provide a virtual copy of the world — both human and physical — but would also provide a means of controlling and understanding complex systems up to the whole². The microcosm would perfectly copy the macrocosm. Being a digital copy of the world, continually updated with the latest information, the world model will be able to answer *any* question, predict *any* future. It would be a crystal ball that realizes the dream of the 18th Century Encyclopedists — the containment of all knowledge.

But doubts interrupt this reverie. And these doubts take us directly to this book's central questions. What do computer models really tell us? Is it possible to build a perfect model of the world — a true microcosm — or are there inherent limits that prevent such comprehensive models? And what is the true status of a computer model: is it an image of the world? A theory? An experiment? An equivalent in its realm to the jade mountain, capturing the essential and blocking out the meaningless? Or is it a glorified fiction, like a motion picture or video game? Can computer simulations of the world extend our knowledge of the world? These questions admit no simple answers. Since there is an increasing tendency to treat computer models as if they *are* reality, these questions must be answered without glib overoptimism.

Indeed, the very terms “model,” “simulation,” imply some separation from or fragmentation of the world. They mean a copy or partial outline rather than the original or the whole. Computer models are, after all, constructs. Programmers devise models on the basis of present data and known laws, type in the computer program, compile it, and run it. It is not the reality. And how does one *know* if the model has really captured the reality? Physical scientists often feel this doubt most acutely, even though fields like chemistry or physics, because of their obvious mathematical character, are a computer model’s most natural home. The scientist knows how difficult it is to get computer models to match data and to give unequivocal answers regarding the causes of what is observed. The astronomer Clifford Stoll expressed such misgivings in his book *Silicon Snake Oil*. His description of his model of Jupiter’s atmosphere illustrates well both the possibilities and limits of computer simulation³:

“So simulate Jupiter’s atmosphere in a computer program. Mix in some clouds and clear gas. Calculate how much polarization you ought to see. Compare it to the spacecraft data and see if your program got it right. If not, tweak the computer program and try again. It’s computer modeling, the same method used by population planners, geographers, and sociologists. Measure, model, and compare. ... Slowly, my computer models made sense. According to them, Jupiter doesn’t have a solid surface — just layer after layer of clouds. Near the top, there’s a thick cloud bank made of ice crystals. As gases rise from below, ammonia freezes, forming crystals. That’s what I’d been watching. From their scattering properties, they’re probably about two microns across. Above these clouds, clear gas. ... Yes, but do I believe it today? That question makes me squirm ... After years of modeling Jupiter’s atmosphere and exploring parameter space, I’m not certain. ... Probably the only way to clinch the issue is a visit to the planet with a microscope and tweezers.”

And the same physical assumptions and data can give rise to quite different models and predictions⁴:

“Plenty of computer models are just plain wrong or conflict with one another. Suppose the amount of carbon dioxide in the atmosphere doubles. What’ll happen to the climate? The global climate model

developed by the Geophysical Fluid Dynamics Lab predicts Chicago summers could be seven degrees warmer and 30 percent drier. In comparison, the Goddard Institute model expects only a three-degree warming, and 5 percent wetter. Much of the difference depends on programmers' assumptions about the complexity of the global-circulation patterns or the reflectance of the ground. But you won't know which programmer was right unless you wait a hundred years. Often, computer models can't be tested."

Can't be tested? This is a damning criticism. And, to the extent such criticism is valid, what distinguishes computer models from computer games?

So the computer model inspires not complete confidence, but an equivocation, a murkiness about what the model really means. It is a problem, in a way, roughly analogous to what Galileo faced when he made the first astronomical observations with a telescope and published his remarkable discoveries (lunar mountains, Jupiter's moons, Saturn's rings) in the *Starry Messenger*⁵. His critics claimed his observations were impossible; they violated the dictum of Aristotelian cosmology that the celestial realm of the planets was perfect and could not be flawed by mountains, craters, or orbiting moons. Galileo, with the guileless empiricism of the natural scientist, replied: if you don't believe me, then come have a look for yourself. Yet most of his opponents refused to look through his newfangled telescope, and those that did look claimed to see nothing real. They asserted the lunar craters or Jovian moons were an illusion created by the telescope itself, like the images in a kaleidoscope. The recourse was, of course, to independently verify the observations, which left Galileo's opponents looking pretty silly in the eyes of history. So where is the analogy with models? A computer model is like a telescope that peers not into the depths of the sky, but into the complexity of a system. Suppose the same criticisms were leveled at model predictions as were hurled at Galileo's telescope: its novel results were artifacts of the model itself. Unlike the telescope-builder, the model-builder could not simply say "run the model yourself" or "construct your own model, then." The controversy could be answered ultimately only by reference to hard data and scientific laws. In

comparison to the telescope, the computer model is crucially limited, for the model on its own brings us itself and not other worlds.

Is the computer model a telescope or a kaleidoscope? Actually, we will see it is a little of both:

- (1) Computer modeling and simulation, while hardly omniscient, can reliably reflect reality. We *can* make valid inferences from them. At the same time, however, there are limits to those inferences and that knowledge. The model's crystal ball will always be a little clouded. Indeed, in some scenarios we will have to admit defeat and see that our entire view is fogged in.
- (2) Modeling and simulation can even extend our knowledge of the world; they can be instruments of scientific research. They can do so in two ways. Computer models and simulations can implement scientific theories and yield predictions of new phenomena. In this, they are no different from any other predictive technique of theory. Computer models can also extend our knowledge through computer-aided design. The model provides the ability to exhaustively test all the aspects of a design virtually, and thus select the best possible design to actually construct. Once more, however, there are strict limits to where computer-aided predictions and designs can take us — they go only as far as the theories on which they are based.
- (3) The problem of the validity of computer models and simulation is closely connected to the problem of *induction* — how we draw scientific laws out of observations. In many ways, computer modeling and simulation attempt to achieve the ultimate goals of science, and thus represent the ultimate extension of natural science.

Computer models and simulations can also be understood in terms of the ultimate destination they attempt to reach. Actually, there are three distinct destinations they can aim at:

The first is to build *a unified model of physical phenomena*. And this goal is the most obvious. Computer models originated in engineering and the hard sciences, and it is there they have met with their greatest successes. Already, large swatches of phenomena can be adequately modeled. In future years, not only will models of particular phenomena

and regions of study grow more numerous, they will also become more closely knit together. For example, geological models can be integrated with models of the oceans and climate to form a single earth model, which in turn can be extended with other planets and integrated with still-larger models of the cosmos. In other words, the ultimate goal of this branch of computer modeling is nothing less than a complete model of the universe and everything in it. It would be based entirely on the laws of physics and chemistry. Given the initial conditions, one could sit back in one's chair and watch galaxies, stars, and planets condense out of fiery beginnings. Turning down the time rate, then presumably the earth transforms into a reasonably comfortable nest and life blossoms forth. And one would always be able to "rewind" the show and start it all over again. Such a world model would realize the dream of the 18th Century mathematician Laplace, a dream important enough to be the subject of Chapter Six.

A second ultimate aim of computer modeling would apply the approach used for the cosmos to the human realm: *a unified model of human society and its history*. It could not be exactly the same, for we would all agree that the "objects" being simulated are far more complex than natural phenomena. Nonetheless, computer models of various human phenomena, such as population growth or economic systems, are built and find increasing application. And as in the natural realm, the tendency is to form models that are both more comprehensive and more unified. The culmination of such a model would not be limited to present human society, but would delineate the whole of historical development and provide a theory of history. It would explain not only the significance of past events, but would also claim to predict future ones. It would explore different ways things might have happened — alternative presents — that could radiate from the same past event (assuming that chance and/or freedom break the mold of a single deterministic future). Now, such models are sure to stir more general interest than scientific models of nature. At the same time, it is easy to see the much more difficult problems that any model of human phenomena must face. Suppose, for example, I have developed a stock market model with the uncanny ability to predict tomorrow's closing prices. The moment such predictions are generally known and given

credence, the prices will be different from what the model predicted. Even this simple example points out the inherent difficulties — and indeterminacies — that await any simplistic computer model in human affairs.

The third destination toward which computer modeling heads is the construction and presentation of any number of different, seemingly realistic, alternate worlds. This is the problem of *virtual reality*. Virtual reality is a computer-aided extension of human imagination. The programmer fabricates a world and then presents it to the viewer; unlike a movie, however, the viewer can interact with the picture. Virtual reality raises interesting problems regarding reality itself: if we can both see something and act on it, is it not real in a way? Virtual realities themselves tend to divide into two distinct areas, depending on their aim. The first are *simulated realities*, where the aim is to reproduce, as accurately as possible, a given situation and display it to the participants. The best example of a simulated reality is a flight simulator, which present the would-be pilot with a real cockpit, but simulated images and motion, such as landing at a particular airport. The main purpose of the simulated reality, not surprisingly, is training. The second type of virtual reality is the *fictional reality*. The fictional reality attempts to fabricate a new world from the imagination of the programmer and makes it seem as realistic as possible. The natural realm of the fictional reality is that of entertainment; it already exists in the increasingly sophisticated form of video games. The question of model versus reality in fact leads us to the question, what is reality? Virtual reality's simulated worlds shed interesting light on this. The virtual reality is meant to substitute for reality and replace it. Can a virtual reality be “real enough” to be real?

Computer modeling and simulation are only a small fraction of the way down the road to their ultimate destinations. Can they reach them at all? And, if so, in what form? To answer those questions, we must first explore exactly what models are and how they work. Next, we will look at their limitations, capabilities, and applications, both to the physical and human worlds. Last of all, we will see how simulated worlds and virtual realities might act substitutes for reality itself.