WHAT DOES SIMULATION WANT?

It was September 1977, my first week on the faculty at MIT. Trained as a psychologist and sociologist, I was finding my bearings in a sea of scientists, engineers, and designers. A colleague in civil engineering took me to lunch to give me the lay of the land. He jokingly told me that I had come at a good time but had missed a golden age: "This place is going to hell."[1] At the heart of the decline as he saw it: students used calculators instead of slide rules. With slide rules, he explained, the user had to know the number of decimal places that made for a meaningful answer. With calculators, this was no longer required. Students, he reported, had lost all sense of scale. In his classes, answers were coming back wrong by orders of magnitude. Moreover, students couldn't manipulate numbers in their heads the way they used to. "And the calculator thing is small potatoes," he said. We spoke of the new personal computers, only recently on the scene; he saw them as giant calculators. Projecting forward, he unhappily imagined computers in pedagogy. Scientists and engineers had to have "numbers in their fingers . . . the back of the envelope calculation is where science is born." He told me to keep my eyes open for the kinds of change that come once in a lifetime.

Six years later, I was studying faculty and student reactions to the widespread introduction of personal computers to the undergraduate MIT experience (an initiative known as "Project Athena"); computers were now officially central to pedagogy. Twenty years after that, I was investigating how simulation and visualization had changed the face of research and teaching in science, engineering, and design. At a Fall 2003 MIT workshop on this theme, an MIT molecular biologist offered an arresting gloss on the fears expressed at lunch a quarter century before. He admitted that his students "couldn't tell the difference between x to the 12th power or x to the 24th." He went on to say that naturally this couldn't be a good thing, but "what they do know how to do, is hit the calculator button twice to make sure they get the right answer."

This biologist builds mathematical representations of molecules for virtual experiments. His goal is to build a scientific life in simulation. He is a major contributor; his laboratory is changing our understanding of proteins. Neither MIT nor protein science has gone to hell. But the civil engineer who took me to lunch in Fall 1977 had a point: I had been witness to a sea change.

"Simulation and Its Discontents" is my view of that sea change. My studies of the 1980s and 2000s explored simulation as a dominant force in changing scientific and design identities.[2] Here I trace the threads of doubt raised by those I met along the way. Why focus on discontents? These days we see the world through the prism of simulation. Discontents with this hegemony draw our attention to settings where simulation demands unhappy compliance; discontents draw our attention to things that simulation leaves out. As is the case when we study scientific controversy, looking at discontents is a way to discover deep commitments.[3]

Among my subjects of the 1980s were custodians of doubt. They were professors at MIT who, for the most part, saw simulation as central to the future of their disciplines. Yet, as they introduced it to their students, they were sensitive to the ways it could overreach. In prospect, they saw creativity, certainly, but also the opportunity for seduction and betrayal, times when simulation might beguile. They feared that even skeptical scientists would be vulnerable to the allure of a beautiful picture, that students would be drawn from the grittiness of the real to the smoothness of the virtual. These days, professionals who voice discontent about simulation in science, engineering, and design run the risk of being seen as nostalgic or committed to futile protest. The early skeptics may have felt they were engaged in what one called a "rear-guard action," but they did not feel their objections to be futile. They worked in the attractive belief that they could take action to protect what was important. They wanted to preserve what they termed "sacred spaces," places where technology might disrupt sacrosanct traditions linked to core values. So, for example, architects wanted to preserve hand drawing; they stressed its history, its intimacy, and how it tied architecture to the arts. Physicists wanted to maintain the pedagogy of the lecture hall because they saw it as a place to model a scientific identity. A physicist in a lecture hall was there to answer such questions as: What do physicists care about? What do they put aside? How do they handle doubt?

Twenty years later, in the study of simulation and visualization in the 2000s, I hear echoes of these early discontents, now voiced by some of simulation's most sophisticated practitioners. Across disciplines, there is anxiety about the retirement of senior colleagues: they are seen as special because they were in touch with a way of doing science and design that was less mediated, more direct. The senior colleagues used pencils; they knew how to revise drawings by hand; in the laboratory, they knew how to build and repair their own instruments. They understood computer code, and when things weren't working right, they could dive into a program and fix it from the ground up. As they retire, they take something with them that simulation cannot teach, cannot replace.

Sensibilities shift. In the 1980s, an MIT engineering student was amazed to learn that there was a time when skyscrapers were designed without computers. He could not imagine how engineers could tackle such projects "by hand." To this student, a 1950s high-rise was a veritable pyramid, even prehistoric, life before simulation. Twenty years ago, professionals in science and design flirted with simulation even as they were suspicious of it. Today, they are wary but wed to it.

In a design seminar, the master architect Louis I. Kahn once famously asked: "What does a brick want?"[4] It was the right question to open a discussion on the built environment. Here, I borrow the spirit of this question to ask, "What does simulation want?" On one level, the answer to this second question is simple: simulations want, even demand, immersion. Immersion has proved its benefits. Architects create buildings that would not have been imagined before they were designed on screens; scientists determine the structure of molecules by manipulating them in virtual space; nuclear explosions are simulated in 3D immersive realities; physicians practice anatomy on digitized humans.[5]

Immersed in simulation, we feel exhilarated by possibility. We speak of Bilbao, of emerging cancer therapies, of the simulations that may help us address global climate change. But immersed in simulation, we are also vulnerable. Sometimes it can be hard to remember all that lies beyond it, or even acknowledge that everything is not captured in it. An older generation fears that young scientists, engineers, and designers are “drunk with code.” A younger generation scrambles to capture their mentors’ tacit knowledge of buildings, bodies, and bombs. From both sides of a generational divide, there is anxiety that in simulation, something important slips away.

In 1984 an MIT professor of architecture said that to use simulation responsibly, practitioners must learn “to do” and “to doubt.” He thought that students were not in a position to sufficiently doubt simulation, because the demands of acquiring technical mastery made it too hard to achieve critical distance. But he believed that, in the end, professional maturity would bring with it both immersion and skepticism.

Things have not been so simple. Simulation makes itself easy to love and difficult to doubt. It translates the concrete materials of science, engineering, and design into compelling virtual objects that engage the body as well as the mind. The molecular model built with balls and sticks gives way to an animated world that can be manipulated at a touch, rotated, and flipped; the architect’s cardboard model becomes a photorealistic virtual reality that you can “fly through.” Over time, it has become clear that this “remediation,” the move from physical to virtual manipulation, opens new possibilities for research, learning, and design creativity.[6] It has also become clear that it can tempt its users into a lack of fealty to the real.[7] With these developments in mind, I returned to the experiences of simulation's early adopters with new regard for their anxieties as well as their aspirations. At the heart of my story is the enduring tension between doing and doubting. Simulation demands immersion and immersion makes it hard to doubt simulation. The more powerful our tools become, the harder it is to imagine the world without them.

DESIGN AND SCIENCE AT THE MILLENNIUM

In the 1980s at MIT, many early users of simulation genuinely could not imagine such things as designing without drawing or thinking without a "back of the envelope" calculation. Those who had grown up accustomed to physically taking apart their laboratory instruments were upset by programs whose inner workings they did not understand. In response to simulation's provocations, faculty and students identified areas that they hoped to keep as simulation-free zones. Architects wanted to protect drawing, which they saw as central to the artistry and ownership of design. Civil engineers wanted to keep software away from the analysis of structure; they worried it might blind engineers to crucial sources of error and uncertainty. Physicists were passionate about the distinction between experiment and demonstration. They believed that computers did have their place in the laboratory, but only if scientists were fluent with the details of their programming. Chemists and physicists wanted to protect the teaching of theory—the elegant, analytical, and inspiring lectures of great MIT scientists were the stuff of legend.

The 1980s were marked by substantive disagreements about the role of simulation and visualization in science, engineering, and design. These days, the space for this kind of disagreement has largely closed down; in the past twenty years, researchers have gone from using simulations for discrete, tactical purposes to working almost full time in simulation.[1] Over time, factions for and against the computer have been replaced by individuals expressing ambivalence about what has been gained and lost. Protecting sacred spaces has given way to enduring anxieties about life on the screen.

Generational differences influence the distribution of this anxiety. An older generation feels compromised by simulations that are essentially "black boxes"; using them seems an abdication of professional responsibility. A younger generation is more likely to accept that computational transparency, in the sense that their elders speak of it, is a thing of the past. Indeed, today's professionals have watched the meaning of the word *transparency* change in their lifetime. In the early days of personal computing, command lines on a screen reminded users of the programs that lay beneath. With the Macintosh in 1984, users activated screen icons with a "double click." Transparency once meant being able to "open the hood" to see how things worked. Now, with the Macintosh meaning of transparency dominant in the computer culture, it means quite the opposite: being able to use a program *without* knowing how it works. An older generation, one might say, is trying to get a younger to value experiences they never had and understand a language they never spoke.

Recall the MIT faculty member who feared that students could not use simulation and maintain critical distance from it at the same time. He thought that the problem of "doing and doubting" concerned novices. Time has proved otherwise: simulation seduces even experienced users. For one thing, these days the body is routinely brought into simulation—think of chemists who manipulate screen images of molecules with gestures they once used to twist physical models. When the body is part of the experience of simulation, doubting is difficult even for experts, because doubting simulation starts to feel like doubting one's own senses.

Today, those who grew up in the days of Athena hold positions of professional authority. Like their teachers, many see the limits of simulation, but they face different challenges than the generation that came before. With research and design now indissociable from simulation, one cannot simply put a pencil back in the hands of a designer or ask a molecular biologist to model proteins with balls and sticks.

But even if the notion of sacred space now seems quaint, what remains timely is finding ways to work with simulation yet be accountable to nature. This is a complex undertaking: as we put ever-greater value on what we do and make in simulation, we are left with the task of revaluing the real.

NEW IDENTITIES

Although many architects and planners in the 1980s looked toward a future when designers would be computer-fluent, most continued to define their professional identity by contrasting themselves with so-called "computer types." Two decades later, a basic tension remains. Even as computer-aided design has become commonplace, it is just as commonplace for design professionals to describe who they are by making clear what they do *not* do with computers.

In a Spring 2005 MIT workshop on simulation and visualization, an MIT architecture professor trained during the Athena years contrasts designers and technologists: “I’m absolutely skeptical. Can those two mentalities exist in the same brain? I haven’t met the person yet who is a designer and a programmer.” An MIT student at the workshop concurs by distinguishing between design logic and computer logic, complaining that the codification intrinsic to computer logic inhibits his creative thinking.

The resistance of individuals to simulation shows up in the social world of design firms. Instead of the heated debate of the 1980s, these days one sees more passive strategies: not showing up for meetings, learning computer skills and choosing not to use them, demanding to use old techniques next to the new, launching complex negotiations about when designs should be digitized.

In one practice, an architect in his thirties turns to the colleague who will teach him how to use a design tool known as CATIA (Computer-Aided Three-Dimensional Interactive Application) and says: “Why do we have to change? We’ve been building buildings for years without CATIA.”[2] His instructor, an engineer who has introduced CATIA to several architectural practices, is familiar with this kind of comment; he ruefully characterizes three difficult phases of resistance to his teaching. The first is “the brick wall”: architects say they are too busy to learn. They argue that learning how to use digital technology is time consuming, so much so that it will exclude other kinds of practice. Then comes a “tutelage with resistance” phase, when the firm’s principal designer insists that his architects learn the program. In a final, "implementation with continuing resistance" phase, firm architects finally use the program but find cause for constant complaint. Some argue that CATIA helps consultants and contractors but not designers. Some complain that it produces drawings that are "cluttered, both visually and conceptually."

The CATIA instructor sees computer-aided design as a new way of looking at the world while his colleagues tend to describe it as "just a tool." As in the 1980s, the phrase "just a tool" is charged with the work of keeping the computer in its place, away from the core of architectural identity. But these days it is less common for designers to reject simulation technology than to accommodate it and complain about the problems it fosters.

Marshall Tomlin, a young designer at the firm where CATIA is being introduced, laments that much of his work, rendering architectural drawings, consists of choosing among options on a computer menu. He admits that he is always tempted to go with the "default," the choice that the system offers unless you specifically choose another. He wishes that his work felt more "his," but a sense of authorship eludes him. And he worries that his drawings mislead. He explains that when rendering was done by hand, detailed drawings signaled a commitment to a design program. Now, he adds details to what look like final drawings while his firm's engineers are still working to create the underlying geometry of the plans. Design firms have always used beautiful drawings to sell not-yet-completed projects. For Tomlin what has changed is that computer drawings make all buildings look as though they have been fully considered, designed down to the last detail.

Beyond issues of authorship and his anxiety that his work creates an illusion of commitment, Tomlin thinks that the use of computers in his firm leads to a greater rigidity of roles, an increased tendency to identify people by their function. His job as a renderer has come to feel reduced to a particular relationship with the computer. He is not happy that his colleagues seem content to leave him alone with his machine.

Tomlin's firm uses both computer-aided design systems (CAD) and technologies (CAD/CAM) that support design, project management, and manufacturing. One group of architects uses the computer to sketch out the basics; another group enters the design on a computerized system that sees it through production. Most of the firm's architects don't know much about the workings of this second system. In the past, Tomlin and his colleagues sent off preliminary designs to be specified in more detailed drawings and cardboard models. They say that those physical drawings and models remained accessible to them, open to being fine-tuned by the organization as a whole. These days, when they hand over their designs, they feel loss. One of Tomlin's colleagues says that when he sends a design to the technical group he immediately feels left out: "It's going into the land of the hackers, people who don't necessarily know design the way I do."

Often, when designers seem to be objecting to a particular computer system, they are really objecting to how the machine forces them to abdicate control over their design. In most firms, there is social pressure to do everything and put everything on the computer.[3] It is the gold standard for current "best practices." In response, designers make efforts to balance their experience. They sit in front of giant screens, but on their desks are plastic building blocks, clay, wooden dowels, cardboard, and glue. One young architect explains how hand sketches and cardboard models "preserve my physical intuitions.” Another, who describes herself as an “AutoCAD baby,” says that while the computer enables her to go “inside the materials,” she still needs physical models to recall what she terms their “atmospherics.” Designers check their computer models against cardboard ones that they describe as more “real.” They wait until their designs have fully stabilized before bringing in digital tools, even if the intended purpose of these tools was to afford the opportunity to play with design ideas-in-process. One says he lies down on computer printouts, bringing his body into the world of the simulation.

In Tomlin’s firm, the principal designer works with computer design tools by sitting next to a technologically adept apprentice.[4] When the tools were first introduced, the master architect made sketches that his apprentice translated into a geometric model on the computer. The master made revisions by working with tracing paper over the model’s printout. Over time, the master stopped requesting printouts. He began to make changes directly at the computer, always in the company of his apprentice. The master does not work alone but has found a way to stay close to the evolving design.

Some senior architects welcome a new alliance, indeed a new symbiosis, with what several call a “digital person.” Others feel uncomfortable with this kind of dependency, either rejecting any technical involvement or insisting that they have to master the technology themselves. They try and succeed or they try and fail and make plans to try again. It is hard to have both the responsibilities of being a senior designer and enough time to learn complex computer systems.

At the Spring 2005 MIT workshop on simulation and visualization, the architect Donna Gordon calls herself a “digital person” and speaks to the complexity of such partnerships. She herself has worked with several master architects whom she describes as people "looking over her shoulder." While it is the master who directs the action, Gordon feels that it is she and those in her position who are in the more intimate relationship with the design. She suspects that from the perspective of the master, the technical apprentices are merely "cranking it out." But from her point of view, the technical apprentices are better able to see when "something is wrong or something could be better. . . . They are the ones who are so intimately focused in on it. They are three-dimensionally seeing the space from inside-out." It is the technical apprentices who are "sculpting space."

As she works, Gordon feels herself "falling into the model," developing something she experiences as a body knowledge of its contours. Her job in working with master architects is to get them thinking virtually—to get the mentor inside the model. Her strategy is to take the master architect on a walk-through of the building, renamed a "fly-through" when one speaks of digital space. During the fly-through, Gordon rotates the model to reveal hidden structures; she zooms in and out to give the master architect a kind of guided tour.

The digital model is not simply shown, it is performed.[5] In the process, observers are brought into a new relationship with what is on the screen. Gordon describes this as "bringing that person into the intimate connection . . . you are taking them in by the hand." She has only good things to say about her own experience of that intimate connection. But sometimes, architects can "fall into a model" and have a hard time getting up, in the sense of maintaining a sight line outside the simulation. In the Athena experience, when a missing set of contour lines on the screen led a student away from the topography of an actual site, it was reasonable to blame the mistake on the limitations of a primitive computer system: it could not fit enough contour lines on the screen to present the site in all its detail. Today's sophisticated systems do not have that problem. In fact, now it is their fluid and detailed virtual realities that can sometimes edge out the real.[6]

EDGING OUT THE REAL

In the Spring 2005 MIT workshop, one young architect says that he has lost "references" outside his digital models. "It is always an interesting kind of breaking point," he says, "where the simulation is so novel that you can't judge it anymore. Because you don't have a reference to say that this is wrong or right. Because there is no frame of reference . . . no precedents." His digital tools are designed to capture the feeling of working with traditional materials, but he had no part in designing them and does not understand how they are made. Most distressing to him is that when he gets confused and loses his "frame of reference," his model can feel more compelling than any real building. Simulation mesmerizes.

His colleagues discuss an example on this point: a high visibility project that envisaged replacing a block of century-old brownstones with a luxury hotel in a traditional European style. To cut costs, developers asked for revisions to a planned design. The designers at the workshop imagined what had happened next: architects used a CAD/CAM program that allowed them to open a stylebook, click on a surface, and "paint" it on sections of the building. At the computer, the designers clicked on a limestone look. This translated into an order for simulated limestone, limestone surfacing etched on fiberglass. Additionally, a choice was made for cutout dormers, less expensive to build than real ones. On the screen the simulated limestone and the cutout dormers might have looked acceptable. But when built, the hotel provoked an outcry. Critics described it as worthy only of Disneyland. The physical building looked like a simulation,[7] out of place surrounded by "real" buildings. The hotel's developers were required to redo its façade, one that had been born of and, one might say, *for* simulation.

In the terms of Louis I. Kahn's question about bricks, we might ask "What does fiberglass want?" and find the answer is not French Second Empire architecture. Although news reporting of this architectural cause célèbre made it clear that the motivations for design changes were financial, at the MIT workshop, the story is discussed as a cautionary tale about the risks of making design decisions on the computer. The architects at the workshop speak about how easy it is to make mistakes when materials are chosen with a double click. One comments that for him, layers of simulation are like "levels of myth making." He says that when designing on the computer, "We believe that the space is going to become what we see." He calls this "the visualization/reality blur."[8]

When using a CAD/CAM system, it is the system that manages contracting and purchasing. The architect who specifies materials is at a remove from the craftspeople who will actually construct the building. The architect who worries about the "visualization/reality blur" recalls that craftspeople once understood "what the building was going to become"; they once "took part in the design process." CAD/CAM has disrupted these relationships. For him, craftspeople are no longer colleagues in the old way; workers with their "real" materials are less likely to be "building the thing that we [the designers] visualize."[9]

Designers have commented that there may be a connection between computer-aided designs that go awry and the sensibility encouraged by the digital fly-through where architects sweep through their simulated buildings, always in movement. The hotel with the faux-limestone facade was the kind of building that looks best either on the screen or in the blur from a highway where the observer is put in a situation of speed and movement that calls to mind the sweep of a fly-through.

Even architects who feel confident that *they* would never design such a problematic building are respectful of the seductions of simulation. They understand that there can be a day at work when fiberglass limestone and cutout dormers look good on a computer. Working in simulation, one often has a feeling of exhilaration, of being liberated from traditional materials. It is not unusual for this experience to be brought up short by the resistance of the real.

One young architect at the Spring 2005 MIT workshop says that graduate education taught her that architects must be "careful with visualizations." The gap between the building on the screen and on the ground can be huge: "Architects," she says, are "losing their connection to materiality." With irony she adds that when designers use CAD/CAM, it is too often the case that "the architect has left the building."

RECONSIDERING SACRED SPACE

In the 1980s architects tried to protect drawing from the inroads of computation. Indeed, they wondered if those who could not draw should be architects. In drawing, they argued, the architect felt as well as thought the building. Drawing was the place for inspiration. Over time, simulation has come to occupy (some would say, has encroached upon) this sacred space.[10] While some architects are comfortable with this development, pleased that a larger group of people are now able to participate in design, others remain skeptical.

One such skeptic, Howard Ramsen, now in his mid-fifties, went to design school in the 1970s. He was drawn to architecture by his love of art. The most pleasurable aspect of design, he says, was the time he spent sketching. But by the early 1990s, he forced himself to learn computer-aided methods to maintain his competitive edge in the profession. "But I never liked it," he said. "I didn't become an architect to sit in front of a computer." After a few years, he felt a conflict: "I love to draw, I think as I draw, that is how my ideas come to me. When I draw a building, I have confidence in the building. I know the building in a different way than when the computer draws it for me."

For Ramsen, the palettes, menus, and default programs of computer-aided design make him feel less like the author of his buildings. Looking back on his career, Ramsen says he felt most alienated when he worked in a large firm where designs were developed by offering architects a set of "starter elements." At the computer, Ramsen missed the flexibility of smudging a pencil line with his fingers. For him, the designs seemed to have moved "inside the computer," where he couldn't touch them; designing itself had become more like puzzle solving. At first, he comments on this experience by saying that "design had lost its artistic fluidity." But a few moments later, he phrases it otherwise: "I lost my artistic fluidity." When he worked with a machine that he experienced as "drawing for me," it had the effect of undermining his sense of authority:

> When I draw a building myself I check all the dimensions. With the computer, well, I don't. It seems presumptuous to check, I mean, how could I do a better job than the computer? It can do things down to hundredths of an inch. But one time, on a big project, the computer drawings came back and I didn't check dimensions and the foundation was poured. We didn't know until the contractor started framing that there had been a mistake. All because I grew up to be intimidated by the authority of the printout.

When Ramsen draws a building, he feels a responsibility for it. He commits himself to what, in the 1980s, MIT professor Ted Randall called the designer's "marks." But when presented with computer output, Ramsen feels deferent, outmatched. How could he be more precise than something that makes discriminations "down to hundredths of an inch"? In the case of the project with miscalculated dimensions, the computer's precision caused Ramsen to confuse precision and accuracy; he assumed that his computer's output would not only be precise but correct. Reflecting on that project, Ramsen knows that at some point he made an input error, an error that was not the computer's doing. But despite himself, he had come to experience the computer as a kind of correction machine. As a result he no longer checked the drawings the machine produced. His contractor (who also did not check the computer drawings) confessed that when designs had been hand-drawn, he checked them all the time. But when given computer-generated drawings, he just went ahead and poured the foundation they specified. "Intellectually," says one of my students, "you spend your lifetime with computers learning that it is 'garbage in/garbage out.' But the fancier the computer system, the more you start to assume that it is correcting your errors, the more you start to believe that what comes out of the machine is just how it should be. It is just a visceral thing."

Ramsen ended up leaving the big firm and going into private practice. This is where he works at present; he likes paying close attention to small projects. He designs by hand and sends his drawings out to be "put into the computer" by somebody else. Hand drawing makes him feel closer to his roots in design. And he feels that his new distance from technology makes him a better architect. He says:

> The computer makes all sorts of things possible, buildings that you could never, ever have built before. But just because you can build a building, doesn't mean you should build a building. So many buildings today are "extreme," they test the limits of what material can do. But they are really not solid. The computer said that everything was okay, but people can't understand the physics of buildings at that level of complexity, so a lot of mistakes happen.

In our conversation that had begun with his relationship to drawing, Ramsen moved from considerations about aesthetics to the fantasies he had developed about computational precision. He then turned to questions of process. Does the computer enhance flexibility in design or close it down?

> Everyone says and you would think that the computer is supposed to put you in a state of mind where you try this and that and keep making changes because it is so easy. But in the firm where I worked, because it [the computer] presented everything at such a level of detail, the building seemed finished after we had put in pretty much our first idea. So, I found that things stopped being in process way too soon because everything looked so finished.

A pattern emerges: in simulation, architects feel an initial exhilaration because of the ease of multiple iterations. But at a certain point, the graphics are so spectacular, the sketches so precise, that possibilities can feel like inevitabilities. Detailed hand drawings once signaled that major design problems had been resolved; when computers produce such drawings, they cue a similar response. Today's designers may experience that sense of completion, even when they know it is not warranted. As the renderer Marshall Tomlin found to his distress, in digital format, even preliminary ideas look finished.

As we have seen, simulation produces paradoxical effects. Despite offering the possibility of multiple iterations, in simulation, it often turns out that the first idea wants to be the last idea. When confronted with a detailed computer-generated drawing, one could simply undo what has been done. But in practice, the fine resolution of screen drawing is more likely to persuade people to accept it as a fait accompli. Currently, this makes drawing not a sacred space but a contested one that preoccupies architects. As one designer puts it, "Everything we do when confronted with a new project is to figure out when we stop drawing, what we draw, what we need to draw, what we don't need to draw and don't want to draw, what we expect others to draw."[11]

So while some take the loss of hand drawing as the cost of doing business in contemporary practice, others feel that, without the sense of ownership that comes from the sweep of hand on paper, design is diminished. Today's architects face a beautiful screen. But it may be that the master architect we see leaning over the shoulder of the apprentice will still choose to walk through the fly-through in his mind's eye, asking: what does the real want?

LIFE SCIENCES: THE TENSION BETWEEN DOING AND DOUBTING

What does the real want in the life sciences? There, simulation began with a kind of deception, an aesthetic compact with nature. Early simulations were qualitative and evocative. For example, one biophysicist, Stéphane Leduc (1853–1922), working at the Nantes Medical School, drew on the persuasive powers of mimicry to simulate the mechanical processes governing life forms. He used salt crystals and dyes to produce artificial cells and organisms. These chemical creatures, formed by virtue of osmotic gradients, seemed strangely alive, their growth mimicking those of dividing cells, sporulating mushrooms, blooming plants, and free-swimming algae. Leduc's simulations mimicked life without reference to its underlying processes.[12]

As biology matured and computation became its dominant tool, this kind of simulation was discredited. These days, a life scientist at MIT, who models protein-protein interactions and trains a new generation of biological engineers, describes a model that has no mathematical precision or predictive capability as just a "cartoon."[13] For him, anything less than the quantification of physics at a molecular level is "mere philosophy." These days, visualization and simulation underpin biology as it manipulates and reengineers life at the molecular and cellular level.[14] Mathematical simulations animate models that represent proteins and cells over time. Algorithms predict molecular interactions within cells and the pathways of protein folding. Scientists have built a second nature within the computer through simulations that are ever more manipulable, ever more easily experimented on. Some describe the result of such virtual practices as "new forms of life."[15]

In today's biology, the simulation of life is central, but getting it right has remained elusive. Living systems work on many levels, from atoms to organisms; integrating levels is difficult. And the intricate workings of cells and molecules are hard to see, quantify, and analyze. These challenges encourage some life scientists to approach simulation with what the MIT architects of the 1980s termed a *critical stance*. In the life sciences, a critical stance toward simulation enforces modesty. In the field of protein crystallography, which uses X-rays to investigate molecular structure, some researchers take pains to insist that the models of complex molecules they produce are "just models." Microscopists are quick to describe the extent to which their images are only mediated representations of the cells they study. These life scientists take as a given that simulations can deceive and that to assess simulation one must find a vantage point outside of it. Simulation and visualization have become the everyday workplace of life sciences. But the programs that scientists use are typically "black boxed." In this way, scientists' feelings of mastery become tied to anxiety and uncertainty.

Computers first came into protein crystallography in the late 1940s. Their job was to lighten the labor that stood behind crystallographic calculations, labor that had typically been allocated to women, who ironically were known as "computors."[16] By 1957, computers had been used in the construction of the first visualization of a protein, a model built by hand out of Plasticene and wooden pegs. Computer graphics for molecular visualization came later, in the mid-1960s.[17] From this point on, scientists would build molecular models by interacting with computer graphics; physical models were too cumbersome.

These days, the X-ray diffraction analyses that protein crystallographers depend on are collected, measured, and calculated by computers. For the most part, protein crystallographers have welcomed this innovation. In 1959, it had taken Max Perutz and his team of technicians twenty-two years to complete his Nobel Prize–winning model of hemoglobin. These days, models of even larger proteins can be built by a single graduate student or postdoctoral researcher in a year.

Perutz and his colleagues, with limited computing power, built their molecules one amino acid residue at a time. They relied on tacit knowledge, their "feel" for molecular structure. Perutz described seeing the molecule emerge as "reaching the top of a mountain after a very hard climb and falling in love at the same time."[18] His comment recalls the sensibility of physicist William Malven who spoke of science as a place where "the mundane and profound go together—like washing dishes and love." In this view of scientific practice, science will always be a human practice, a labor of love that cannot be fully automated. Malven was willing to automate only the most laborious calculations, and then only with the most transparent instruments, as transparent as his Swiss Army knife.

This "human practice" view of science still informs the professional identities of some protein crystallographers. For example, Professor Diane Griffin, head of an East Coast protein crystallography laboratory, uses the phrase *manual thinking* to refer to aspects of protein crystallographic practice that resist full automation, including data gathering, imaging, image analysis, and the calculation of crystallographic maps and models.[19] Griffin belongs to a generation of protein crystallographers who grew up writing their own programs to calculate electron density maps from X-ray data. Her science depends on the accuracy of these programs and she knows how hard it is to get errors out of them. Like Malven, twenty years before her, who spoke of a black box as the most dangerous instrument in a laboratory, Griffin loses confidence when she cannot see inside the programs she uses. At the Spring 2005 MIT workshop, she says:

> When I was a graduate student, if you were going to convert some data or something like that, you would write the FORTRAN code to convert the data yourself. That's how you would do it. Now there are these programs. There are these windows and you click. I find with my students all the time, they don't know why something isn't working. I'm like, well, did the data convert properly? Open the file and look at it. It is so black box and it is going from the time when you knew how the data was converted, because you wrote the code to do it yourself, to you don't even open the file to see if it is full of zeros or not. So there is a very big disconnect.

Like Malven, Griffin is particularly skeptical about the use of proprietary software in science; manufacturers have a stake in closing the black box, of keeping code a secret.

Griffin was mentored by a generation of researchers who taught her that scientists should never abdicate authority to instruments they did not fully understand. For them, the advent of opaque software put the scientist in an unacceptable state of ignorance. In a spirit of vigilant skepticism, Griffin educates graduate students, both in her laboratory and across her campus, to exercise critical judgment about computer-generated data.[20]

The field of structural biology includes two distinct groups. Scientists such as Griffin crystallize proteins, conduct X-ray diffraction experiments, and build onscreen molecular models "by hand." A second group of predictive modelers work on complex algorithms to predict protein structure. Those who work with Griffin's methods insist that they need transparent software to achieve their ends. They need to continually adjust and readjust code. The intensity of their involvement keeps the limitations of their representations constantly before them. They are not likely to confuse the model with the molecule. Today, it is these crystallographers who produce the trusted structures against which predictive modelers test their algorithms. The future, however, is uncertain: predictive modelers put their faith in increasingly powerful computers, increasingly powerful algorithms.

Griffin does not trust the claim of predictive modelers, that their software can automatically fit molecular structures to X-ray crystallographic data. She has banned their software from her lab. When she discovered that one of her students had used predictive software to help build part of a model, she made the student repeat the modeling work by hand. And indeed, the computer program had gotten the structure wrong. Griffin's fears had been well founded.[21]

These days, there is intense competition between predictive modelers and crystallographers to be the first to publish protein structures. In competitive science, speed is always of the essence, and this pushes the field toward greater use of automatic techniques. But for Griffin, the automation of model building is a kind of futile cheating: it provides a shortcut that might get you to the wrong place. And even if it brings you to your destination, automation may shortchange you. It certainly shortchanges students because it does not teach them how to use simulation with vigilance. It deprives them of some fundamental experiences they need to develop a tacit knowledge of molecular configurations. Griffin thinks that crystallographers learn to "think intelligently about structure" by slowly building onscreen models. To do this, protein modelers must learn to work intimately with the computer, building a new hybrid instrument, a "human-computer lens."[22]

MATERIALITY IN IMMATERIALITY

In today's biology, computer simulations are ever more manipulable, ever more easily experimented on. They offer an interactivity that makes screen objects seem "material" to the point that contact with them feels like engagement with something quite real. Traditionally, scientists rely on "witnessing" and "participation" to make claims for the legitimacy of scientific knowledge.[23] Familiarity with the behavior of virtual objects can grow into something akin to trusting them, a new kind of witnessing. It is a different sort of trust than Diane Griffin requires, but it can come to feel sufficient.

Griffin began her graduate training in the late 1980s when trust in one's computational tools was associated with familiarity with their underlying code. Younger scientists are increasingly comfortable with black-boxed simulations. They grew up with personal computers that did not come with programming languages. They grew up on computer games that offered interactivity without transparency. Unlike a previous generation, they did not program their own games. When these younger scientists work with screen molecules, they are more likely than their elders to give themselves over to feeling in the grip of a new materiality.

In this they share an aesthetic with the architects who "fly through" virtual buildings. In architecture, models of buildings are rotated on the screen. In biology, molecular models are rotated on their axes. Through these actions, molecules are kept in motion so that the hidden parts of the structure can be brought into view. In both cases, the experience of depth is suggested by performances that engage the body.[24]

Although generational markers are important, in design today, attitudes toward simulation do not neatly sort by generation. The same is true for science. Youth does not automatically confer uncritical comfort with what simulation offers. And age does not automatically lead to resistance to simulation. Some older scientists, for example, justify their use of opaque software by pointing to the infinite regress of computer representations. After all, they argue, it doesn't really mean much to know how your simulation is programmed if all you are looking at is a high-level computer language. The "real guts" of the program is in assembly language and in all that lies beneath that, and no one wants to go to that level with today's complex machines. In the 1980s, Professor Barry Niloff insisted that his students learn the physics of display technology; today, such scruples seem of a different era, practical impossibilities that lead scientists, young and old, to accept opacity. These days, the problem for the working scientist boils down to a question: What level and language will provide enough understanding for me to compare the simulation before me with what I know of nature?

Some younger scientists who are not altogether content with their opaque simulations feel they have no way to act on their unease. One, a physicist at a national research laboratory, admits that when he works with new, elaborate 3D simulation, he misses the algorithmic understanding he enjoyed with earlier models. An older colleague encourages him to play with immersive virtual realities in the spirit of a tinkerer. Time and interaction will do their work: "Give yourself a few years to try it out and fiddle with it awhile," he says. "You will probably find something you can do that you couldn't do the other way." He is convinced that at some point his younger colleague will feel at one with the technology; he will come to "see in simulation," despite its opacity.[25]

Gordon Research Conferences provide an international forum for the presentation and discussion of frontier research in the biological, chemical, and physical sciences. At a Gordon conference in 1965, the structural biologist Robert Langridge presented an interactive computer graphics workstation for visualizing and manipulating molecular models to an unenthusiastic audience of his peers. Langridge recalled that the objections had to do with people not having their "hands on something, something physical so that [they] could understand it." He was not discouraged. In contemporary terms, molecular biology did not yet have the right "interaction metaphor." He said: "Standing up at a conference and showing 16mm movies, in the early days, was really not a good substitute for sitting in front of the computer and actually using it." Even though the early simulations were slow, they made it clear that screen molecules could be compelling: "When you first got your hands on that crystal ball at Project MAC and moved the thing around in three dimensions it was thrilling. There was no question."[26]

As the virtual became increasingly manipulable, as screen movements seemed to happen in real time, protein crystallographers became willing to make the transition from physical to virtual models. With the new technology, one had the sense of dealing directly with the molecule, a feeling that did not depend on the model's appearance, but on the smoothness of the user's interaction with the screen representation.[27] In 1977, a molecular graphics system called GRIP (Graphics Interaction with Proteins) reached a turning point in fluidity of use. GRIP gave its users more than an illusion of smooth connection between modeler and molecule; users experienced the system as a prosthetic extension of themselves into what felt like a tangible world of screen molecules.[28] It is an effect that is familiar to all who play computer games.

In a lecture on the role that simulation plays in protein crystallography, Griffin describes the physicality of today's modeling systems. The best-designed modeling systems try to give protein researchers the tactility and immediacy they came to expect in molecular modeling work.[29] A user sits in front of a screen, often wearing stereoglasses to enhance three-dimensional effects: "You are physically dragging pieces of protein structure, amino acids, and sticking it in [the screen molecule]. You drag it in and you stick it there. And then with your dials or your mouse, you are adjusting it, moving the pieces to get it to fit. So you are physically building with the stereoglasses and the mouse."[30] Protein crystallographers report that they feel the model in their bodies and that their bodies mirror the models they manipulate onscreen.[31]

It is not surprising that, in this relationship with the computer, individual scientists express individuality and differences in style. Some scientists want to use the most up-to-date tools, but many enjoy the comforts of the most familiar well-worn virtual tools.[32] Griffin says that, in her laboratory, researchers tend to use the programs they built or the programs they learned on. Griffin herself uses a program she wrote herself: "Because I'm so familiar with it, I can just do things automatically, which with another program I would have to sit there and think. . . . I've connected with the software in a way that I don't have to think about the direction. . . . I just kind of know how to move the mouse to do what I want to do without thinking."

Across the professions, software has become increasingly uniform and black boxed, even as there is demand for nonstandardized tools that can accommodate users with different intellectual styles. Since today's users cannot change fundamental things about their programs, many return to what in the 1980s was called "customization," small changes that make people feel more at home.

These days, life scientists do not talk much about moving from physical models to computer screens—that ship has sailed. Now they talk about the stress of moving among different virtual environments. Griffin knows that "forcing people to use a uniform program" doesn't work. Researchers are searching for a subtle connection, to make of the software what the psychoanalyst D. W. Winnicott would call a "transitional object," an object that is experienced as separate but also as part of the self.[33] Griffin describes the delicate dance of scientist and choice of simulation in terms that evoke Winnicott. She says that biologists need to work with individualized software, "because some people find certain kinds of manipulations easier. Or just the way a program is organized just works with their brain better." The well-worn or best-loved virtual starts to take on some of the qualities of the real. It feels familiar, comfortable; it is able to assuage anxieties about being cut off from nature.

ENGINEERING THE LIFE SCIENCES

In the life sciences, classically trained engineers, experts in simulation, have created a place for themselves alongside biologists. The engineers, with their expertise in structures and mechanics, bring a distinct way of looking at nature, one that hopes to quantify. Their aspiration is to someday design and build their own molecules and synthetic cells. Life scientists have long used metaphors drawn from engineering and design, as for example, when they referred to proteins as "molecular machines."[34] But current simulations bring them closer to algorithmic descriptions of life.

Today's engineer/life scientists are frustrated that biology is information-rich but data-poor. Its experiments are highly specific and this makes it hard to share data, to build a quantified "metamodel." The engineers push for more shared conventions; one engineer in the MIT biology department speaks wistfully of a "service manual for representing information." His goal is a kit of parts that would let him design new biological systems in simulation. Thus formalized, one could "mine" biological models for data, all of this a dream that requires engineers to "organize the parts, the rates, the components." These aspirations recall those of architects who dream of putting the building inside a machine, of becoming its "geometer."[35]

If biology wants to take on these kinds of goals, it will need engineering-style standards for how it codes and communicates information. Traditional biologists fear that such standards will change what they look for when they look at life—they worry that the biologist's vision will be shaped by the standards that simulations demand. At the Spring 2005 workshop Griffin describes feeling a disconnect between herself and one of her research partners, a biologist with an engineering and computer science background. In a common project, the engineer and his students were to create a simulation of a protein molecule at its lowest possible energy level. Their program produced a result, and Griffin describes them as "proud of themselves," for "they had gotten this fabulous lowenergy structure." But when Griffin checked their result against her understanding of proteins, she realized that her colleagues were suggesting a molecule that could not exist.

> I tried to explain to them that proteins don't look like that. What they had created did not exist except in sort of a proteosome that was degrading it but this was not a structure. I got them books and [showed them] what an alpha helix was and all this stuff and I finally gave up. There was no ability for us to communicate because they were bound. Their program told them that this was the lowest energy and they were not going to listen to me.

Her engineer colleagues see a result; Griffin tries to interpret its relevance. In her view, the engineer/modelers did not have a sufficiently rich appreciation for biological systems; they did not understand the system's constraints. Their result was beautiful, but its referent was the simulation on its own terms. For the engineer/modelers, the logic of the simulation had overtaken the logic of nature. What Griffin is calling for here is an acknowledgment by her engineer colleagues that simulation's results need to be discussed in light of her understanding of how molecules can look. Her contention was that molecules could not look as they had been represented in the simulation. But there was a barrier to communication, "they were bound." In telling this story, Griffin describes an "enormous divide" between herself and her colleagues from engineering and computer science. They could not put themselves in a position to "check the computer." At the limit, from her point of view, they lost interest in the molecule when it challenged their simulation.

In the early days of Athena, when engineers spoke about a "sacred space" that should be protected from simulation, they identified the analysis of structure. It is telling that in Griffin's efforts to communicate with her engineer colleagues, structure was the first thing to which she turned. ("I got them books and [showed them] what an alpha helix was.") But the engineers she was dealing with were well past trying to reserve the understanding of structure for the tacit knowledge of the experienced scientist.

Some would celebrate the exhilarations of "remediation," translating the gestures of the physical into the virtual, as though what is remediated is illuminated. In the 1980s, simulations let you manipulate what was on the screen; more recently, simulations encourage you to inhabit worlds, or as the architect Donna Gordon put it, "fall into them." These systems are powerful but require a new discipline. We have seen architects and contractors who do not check computer printouts against the reality of their sites and scientists who have a hard time looking up from their screens.

From the earliest days, simulation seduced. In the 1980s, Ted Randall worried that his MIT design students were composing for the screen—its constraints now dictated vision: "I couldn't work with that many contours," said the student who couldn't make screen reality match what was on the ground. If this meant that, in the simulation, twenty-five feet of a site were unaccounted for, so be it. Twenty years later, Griffin's engineer colleagues would not even entertain the notion that their program could be wrong. With the computer on hand to deliver the real, simulation can seem world enough.

NEW WAYS OF KNOWING/NEW WAYS OF FORGETTING

Twenty years ago, designers and scientists talked about simulations as though they faced a choice about using them. These days there is no pretense of choice. Theories are tested in simulation; the design of research laboratories takes shape around simulation and visualization technologies. This is true of all fields, but the case of nuclear weapons design is dramatic because here scientists are actually prohibited from testing weapons in the physical real.

In 1992, the United States instituted a ban on nuclear testing.[1] In the years before the ban, frequent physical tests, first above ground and then underground at the Nevada Nuclear Test Site, provided weapons designers with a place to do basic research. Through tests they developed their scientific intuitions even as they reassured themselves that their weapons worked.[2] More than this, the tests compelled a respect for the awesome power of nuclear detonations. Many testified to the transformative power of such witnessing.[3]

In the years after the 1992 ban, newcomers to the field of nuclear weapons design would see explosions only on computer screens and in virtual reality chambers.[4] At Lawrence Livermore and Los Alamos National Laboratories, some of the most powerful computer systems in the world are used to simulate nuclear explosions. Until recently, these simulations took place in two dimensions; now, simulations are moving into three dimensions.[5] In a virtual reality chamber known as a CAVE, one stands "inside" a nuclear explosion wearing 3D goggles, in order to observe it, one is tempted to say, "peacefully."[6] My story of simulation began with the Athena project centered in a garden, a glass atrium with a ficus tree; it ends in a CAVE, a self contained virtual reality. The CAVE simulation is there to "demo" an explosion; those who work there become accustomed to experiencing in the virtual what could never be survived in the real.

When nuclear testing moved underground, it became easier for weapons designers to distance themselves from the potential consequences of their art. Hidden, the bomb became more abstract. But even underground testing left craters and seismic convulsions. It scarred the landscape. Now, with explosions taking place on hard drives and in virtual reality chambers, how much harder will it be for weapons scientists to confront the destructive power of their work and its ethical implications?[7] One weapons designer at Livermore laments that he has only once experienced "physical verification" after a nuclear test. He had "paced off the crater" produced by the blast. It changed him forever. His younger colleagues will not have that.[8]

This senior scientist is concerned about the moral effects of moving nuclear weapons research to virtual space, but he and his colleagues are also troubled about the effects of virtuality on their science itself. They argue that "physical intuition is a skill you want to keep" and worry that the enthusiastic reactions of young designers to new, flashy virtual reality demonstrations are naïve. One says: "The young designers look at anything new and they say, 'This is so much better than what we had before. We can throw out everything we did before!'" Senior scientists at the national laboratories describe young designers immersed in simulation as "drunk drivers." Within simulation, the happily inebriated show less judgment but think they are doing fine. Dr. Adam Luft, a senior weapons designer at Los Alamos, shows sympathy for the young designers: the new rules compel them to fly blindly. They cannot test their weapons because they must work in the virtual and they are given computer systems whose underlying programs are hard to access. Luft himself feels confident only if he is able to access underlying code. He is frustrated by the increasingly opaque simulations of his work environment. When something goes wrong in a simulation, he wants to "dig in" and test aspects of the system against others. Only a transparent system "lets [me] wander around the guts of [a] simulation." He is wary of making any change to a weapon without personally writing its code. Luft worries that when scientists no longer understand the inner workings of their tools, they have lost the basis for trust in their scientific findings, a concern that mirrors those of MIT designers and scientists of twenty years before.[9]

Across professions, successful simulation gives the sense that digital objects are ready-to-hand. Some users find these interfaces satisfying. Others, like Luft, focused on transparency, are not so happy. They look askance at younger designers who are not concerned about whether they wrote or have even seen underlying code. One of Luft's colleagues at Los Alamos describes his "fear" of young designers: "[They are] good at using these codes, but they know the guts a lot less than they should. The older generation . . . all did write a code from scratch. The younger generation didn't write their code. They grabbed it from somebody else and they made some modifications, but they didn't understand every piece of the code." He speaks with respect of "legacy codes," the old programs on which the new programs are built. "You can't throw away things too early," he says. "There is something you can get from [the legacy codes] that will help you understand the new codes."

At Livermore, a legendary senior weapons designer is about to retire. At the Spring 2005 MIT workshop, his colleagues discuss this retirement and refer to it as "a blow." They are anxious about more than the loss of one man's ability to make individual scientific contributions. He has irreplaceable knowledge about the programming that supports current practice.[10] His colleagues fret: "He has such a great memory that he hasn't written down lots of important stuff. How will people know it?"

The response to this scientist's imminent retirement is a movement to videotape him and all the other scientists who are about to leave service. This will be no ordinary oral history. It is infused with anxiety. Those who know only the top layer of programs feel powerful because they can do amazing things. But they are dependent on those who can go deeper. So those who feel most powerful also feel most vulnerable.

Nuclear weapons design is divided by dramatic generational markers: some designers grew up with routine underground testing, some glimpsed it, some have only experienced virtual explosions. Some designers were trained to program their own simulations, some simply "grab code" from other people and are unfazed by the opaque. Yet when Luft sums up attitudes toward simulation in his field, he makes it clear that the wide range of opinion does not reduce to simple generational criteria. The cultures of weapons laboratories are also in play. For example, at Livermore, older weapons scientists who were very hostile to simulation became far more positive when the laboratory adopted a new metaphor for weapons design. Livermore began to liken weapons design to bridge building. According to this way of thinking, engineers do not need to "test" a bridge before building it: one is confident in its design algorithms and how they can be represented in the virtual.[11]

At Livermore, the change of metaphor made simulation seem a reasonable venue for weapons testing. And at Los Alamos, there are younger scientists who find themselves eloquent critics of immersive virtual reality displays. One says: "I was so attuned to making plots on my computer screen. I was surprised at how little new I learned from [the RAVE]." (The RAVE is the nickname for Los Alamos's virtual CAVE technology.) This designer complains about not being able to work analytically in the RAVE; others say that it gives them a feeling of disorientation that they cannot shake. In the RAVE, scientists work in a closed world with rigorous internal consistency, where it is not always easy to determine what is most relevant to the real.[12] For some younger scientists, even those who grew up in the world of immersive video games, the RAVE seems too much its own reality.

Across fields, scientists, engineers, and designers describe the gains that simulation has offered—from buildings that would never have been dared to drugs that would never have been developed. And they also describe the anxiety of reality blur, that "breaking point" where the observer loses a sense of moorings, bereft of real world referents and precedents.[13] And the very complexity of simulations can make it nearly impossible to test their veracity: "You just can't check every differential equation," says Luft. He pauses, and says again, "You just can't, there are just too many." In nuclear weapons design you can make sure that you have solved equations correctly and that your system has internal consistency. In other words, you can "verify." But he adds, "validation is the hard part. That is, are you solving the *right* equations?" In the end, says Luft, "Proof is not an option."

PRETTY PICTURES

At the Spring 2005 MIT workshop, astrophysicist Peter Charles tells a story of a beautiful image he produced in simulation. It was beautiful, but it did not correspond to anything in the physical real. Charles was working on a scientific problem, but then he "made a mistake," and a compelling image emerged when he plotted his mistake. The image, says Charles, "was very pretty." He plotted an error and created an image that "looked cool but was wrong." There was no question of using the image in a scientific publication—it did not refer to anything real—but it was so visually elegant that Charles could not resist putting it on his personal Web site. There, it attracted the attention of a television network and a scientific funding agency—one used it as a logo, the other for publicity posters. The beautiful but meaningless child of simulation was now traveling in the world as an icon of science. Charles had published it as something beautiful; it was read as something real, something scientific. Charles says, "I see these posters and I cringe."

Charles is a distinguished scientist. What encouraged him to post an image that only had meaning within the world of the computer? At the MIT workshop, Charles does not excuse what he did, but tries to explain how it happened. He explains how long it took him to create the image ("I only put it on my Web site because we had spent all this time running it"). And he talks about the image's beauty ("I made a great picture and somehow that sells"). As a scientist, he knew he had to "let it go." But as a curator of images, he did not want to let it go; he may cringe when he sees it displayed as science, but there is the awkward pride of having made something so fine.

Twenty years before, MIT's Ted Randall argued that one feels at a distance from computer printouts. A designer or scientist will not feel the same kind of connection to something that is not inscribed with his or her own "marks." In a certain sense, Charles did not fully identify with the beautiful image as *his* "mark," for it was the computer that had made it so seductive.

When Charles tells his story at the workshop, his colleagues understand how displaying something beautiful on a personal Web site could feel like a statement of artistic rather than scientific appreciation. The image had not crossed any boundaries. Born in cyberspace, it had stayed in cyberspace. But they all knew how quickly simulations travel. They take on a life of their own. Simulation's pretty pictures are routinely used to persuade nonexpert audiences.[14]

At the workshop, Charles admits that his experience with his beautiful image had left him discouraged. "You can sell anything if you dress it up correctly. . . . You can give a result which is complete 'garbage' but taken out of context, reviewers can't tell the difference." He asks the group if his story about "pretty pictures" had relevance to other fields.[15] Around the table, his question is answered with a resounding yes. Tom Kinney, a professor of aeronautics, points out that sometimes pretty pictures can be deployed to disastrous effect. Airplane pilots get "fixated on their displays and shooting down the wrong things because the displays are so compelling." The architects respond to Charles's question—"Could a good rendering sell a bad design?"—with the story of the hotel with the faux limestone facade, a case where something designed in simulation became a problem when it became an emergency.

In the early days of Athena, architects used colored pencils to prettify computer printouts. After twenty years of technological refinement, things have tipped in the other direction. Now technology persuades with elegant computer-generated images. Across disciplines, researchers resent that they are encouraged to spend energy producing such images. Echoing the concerns of architects who create beautiful computer drawings of buildings not yet designed, Diane Griffin complains that in protein crystallography beautiful images mislead because they imply a finished result even when research is at an early stage. Ribbon drawings of the backbone of protein structures used to take a long time to produce; while they were being developed, their rough look reflected that the scientist was not "quite sure of everything yet." Only a fully determined structure would get a "fancy picture." No one would invest the time to make a beautiful drawing of unproved work. "Now," says Griffin,

> you can make that fancy picture in two seconds. The program spits out pretty pictures and when you show that picture, people go, "Oh it's all done!" And you can stand up there and say, "These are sort of the distances but don't believe them. There are big error bars! It's not finished yet! This

> is a rough idea!" And they'll just hold on to it and go: "This is done because look how pretty it is." So we now on purpose make ugly figures to show it's not really done yet because they don't listen to you when they see it with their eyes [laughter in the background]. You have to show them something ugly if you don't want them to set on it and have it be the truth forever.[16]

On hearing how Griffin intentionally degrades her images to convey lack of certainty, Luft points out that some scientists in his world do the opposite. They use simulation to dress up the not-yet proven so that it looks true.

> They don't put the caveats in so you can't call them out, but they make it so pretty that everybody believes it. . . . Let's be honest, sexy images sell. A good portion of my work I based on being able to present a sexy picture. I was talking to a research sponsor who was at a research organization that shall remain unnamed. They told me that the next visualization that I gave them had to sparkle.

Luft would not try to fool peers with "sexy images." But his funders want and, in fact, specifically ask him to produce something sparkly.

Scientists and designers at the Spring 2005 MIT workshop are conflicted in their relationships to the products of simulation. Charles feels disconnected enough from his beautiful image to publish something he knows to be meaningless. Griffin wants to disconnect from her pretty pictures because she finds them too convincing. She adds ugliness to the products of her simulations to signal that they are not-yet-proven. Luft disconnects when he adds sparkle to sell. But even when scientists feel alienated from the demands of their audiences, pleasing them is gratifying. Successful simulations flatter even those who are most critical of them.

FROM THE GARDEN TO THE CAVE

We began with a question inspired by Louis I. Kahn: "What does simulation want?" We have seen what simulation seems to want—through our immersion, to propose itself as proxy for the real.

The architecture faculty who designed Project Athena's Garden dreamed of transparent understanding of design process; today scientists are reconciled to opacity and seeing only a CAVE's shadows. Over the past twenty years, simulation has introduced its dazzling environments and we have been witness to our own seduction. A mechanical engineer instructs his students: "Don't be fooled by the graphics."[17] Luft says that beautiful codes promote the "illusion of doing really great science." Kinney teaches "human supervisory control" to inoculate students against the flashy colors and confusing styles of air traffic control displays. When simulation pretends to the real, buildings look finished before they have been fully designed and scientists find no fault in "impossible" molecules that could only exist on a screen. Computer precision is wrongly taken for perfection. The fantasy, visceral in nature, is that computers serve as a guarantor, a "correction machine." Kinney puts it this way: "As technology becomes more and more sexy, the problem is that we get lured into it, the seduction, and we actually come up with what we think are good displays but actually they're bad."[18]

But scientists such as Luft show us another side to what simulation wants. Perhaps we could say, with no irony, it is what simulation really wants—not to replace the real but to reveal it. Luft describes the paradox of simulation used in this way: "I know the simulation isn't right, but because I have the simulation of something tested and the results, I can make adjustments and prophesies about how it was wrong."

I ask Luft how he tells his laboratory director that "simulations are wrong." How does Luft confront him with this subversive reality? Luft responds: "The polite way to articulate that is that a *single* simulation that is not validated by applicable data cannot be trusted." What speaks most loudly in his answer is what Luft does not say. He knows that the problem is not with a single simulation, and he believes that his laboratory director understands this as well. Together they work with simulation and devise fictions around its use. As Luft says, "Simulations are never right. They're all wrong. Forget it. That's it. They're wrong. Guaranteed. There is more entropy in the real world then there is in your computer. That's just the way it is." Nevertheless, every year, he says, "you can use all that data" from simulation and put it in an "annual assessment document" and "every year the lab directors tell the president that everything is cool. . . . That's what we're doing . . . and the punch line is that all simulations are wrong, thus far."

When Luft says that simulations are wrong, he means that they are incomplete. When he places simulation alongside the real, it is to throw the real into sharper relief; simulation's errors sharpen his view of where the real resides. But, like the inhabitants of Plato's cave, Luft, in his own CAVE, knows reality through the shadows it casts. He describes how he makes those shadows work for him. Luft does not see simulation as a way to see what is "true," but to engage in a dialogue with code. "One of the major skills [in simulation] is being able to identify additional simulations you can run which will determine whether the code [you are working with] is behaving reasonably . . . or whether there is some sign of a bug or a mistake." Similarly, MIT biologist Dean Whitman insists that you need a simulation to produce error so that you can test it against reality, to figure out how it is wrong. If you get the simulation right, you will never understand how it is right. You need it to be wrong and you need to figure out how it is wrong.[19]

Whitman, like Luft, articulates a discipline of extracting information from inaccurate models. Both approach simulation as a trusted error-making machine. An inaccurate model generates an interesting hypothesis, which can then be tested. In the Fall 2003 MIT workshop Whitman sums it up by saying that his research simulations are not represented by pretty pictures but by "uglier and more complicated ones. They have more spaghetti hanging off but they are really useful for research." When Whitman and his colleagues confront these ugly pictures, they expect to take simulation error and do something constructive with it. From Garden to CAVE, the notion of a "critical stance" toward simulation has been transformed. These days, for simulation's most sophisticated users, a critical stance is no longer about vigilance to protect simulation from error. It is about living with shadows that bring us closer to the forms beyond them.

Whitman sums up this point when he talks about the necessity of being very clear about what simulation cannot do. It cannot keep you open minded. The scientist must always ask, "To what extent does a model limit us to iterations rather than opening our minds to new questions?"[20] As a scientist, one must attend to what lies beyond any model:

> When you have a hammer, everything looks like a nail. . . . So when you have either a model or a certain capability, and you come to work every day,

or you start to write a proposal . . . you say to yourself, "Gee, what kind of crazy blue sky idea can I come up with today?" or "Gee, I think there are some more nails out there and maybe we should start hammering." That's the way I see it. It's a trade-off in the lab how much of one or the other we do.

For Whitman, the hard work begins with resistance to pretty pictures. In the Fall 2003 MIT workshop, he is asked to describe the emotional power of molecular visualizations. Whitman insists that what is most important is to be inoculated against their buzz: "When I started . . . people would show pictures of biological models and say, 'Now we understand.' And I would say, 'No, we don't understand. We have pictures and have the beginnings of something you can use to understand.'" Whitman works in an informed partnership with simulation. It generates alternate realities and enables him to do experiments that would otherwise be impossible. But the limitations of these experiments humble him. Whitman makes progress by chastening simulation, by increasing his understanding of what it cannot tell, and in the end, deferring to human judgment: "I really need a human being to understand why the model says what it is saying and to evaluate that."

In response to Whitman, Professor Roberta Drew, an organic chemist, presents her view of chastened simulation. Drew uses complex probes to determine the forces and energetic fields within molecules. She appreciates the place to which simulation has taken her discipline: "This has given to the microscopist and chemist—I don't want to say a 'godly sense'—but a sense that you can now go in and one-by-one, engineer your molecules or touch the molecules." But she acknowledges that her deepest understanding does not come from her models: "How many times," she asks, "have you heard the story of someone musing about a truly inspirational vision [coming] to them while they were staring at clouds?" She describes the moment of understanding where "totally out of context" one has a thought, "not consistent with going over the model again and again," and indeed, "a bit adversarial to the iterative model, something that comes out of seemingly nowhere." At that moment, we are left godlike, childlike. Understanding comes out of simulation, out of discontents, and out of nowhere.