# Building Models

**Designers design things, engineers** engineer them, and builders build them. There's been a clear progression in their workflow, from high-level description to low-level detail to physical construction. The work at each stage is embodied in models, first of how something will look, then of how it will work, then of how to make it. Those models were originally tangible artifacts, then more recently became computer renderings. Now, thanks to the convergence of computation and fabrication, it's possible to convert back and forth between bits and atoms, between physical and digital representations of an object, by using three-dimensional input and output devices that can scan and print objects instead of just their images. These tools are blurring the boundary between a model of a thing and the thing itself, and are merging the functions of design, engineering, and construction into a new notion of architecture.

Many different domains have had "architects," people responsible for the overall shape of a project. All these architects are starting to use the same kinds of rapid-prototyping tools, both hardware and software. Better ways to build a model and model what's built offer this new kind of architect—whether of a house, a car, or a computer—an opportunity to work not just faster and cheaper but also better, tackling tasks with a level of complexity that would be beyond the barriers imposed by the traditional division of labor between developing and producing a design. The introduction of automation into the making of models has implications across the economic spectrum.

## Frank

Frank Gehry is the architectural equivalent of a rock star. The building he designed for the Guggenheim Museum in Bilbao, Spain, was a rare crossover hit, simultaneously transforming the popular perceptions of the nature of a building, a museum, a region, and even of the whole practice of architecture. An enormous number of people who wouldn't have thought much about buildings have been transfixed by the expressive form of this commanding structure (which also happens to house some great art). Few of Frank's fans realize, however, that the way his buildings are designed and constructed is even more revolutionary than how they look. They can appear to be as random as a crumpled-up piece of paper, and that's in fact exactly how they start out.

Gehry began his architectural practice in Los Angeles in 1962. Starting with single-family homes, he became interested in incorporating more expressive materials and forms in architecture. The way he worked was fundamentally physical, based on manipulating models made out of easily modified materials—cardboard, plastic, foam, clay, and the like. The models weren't just representations of a design; making the models became the process by which the design itself was developed. How the models looked was inextricably linked to how they were made: Rather than rigid rectilinear forms, the flexible materials most naturally created the fluid curves that conveyed the sense of movement he sought to construct.

Frank Gehry's flowing forms led to a landmark commission in 1989 to work on a giant scale: a sculpture for Barcelona's Olympic Village. He designed a stylized representation of a fish, 180 feet long and 115 feet tall, that manages to be simultaneously organic and enormous. It also doesn't have any straight lines. Every piece in the apparently simple fish was different, turning it into a dauntingly complex construction project. For help with how to turn his tabletop model into this huge reality, Frank Gehry's office urgently contacted his UCLA colleague Bill Mitchell, a CAD (computer-aided design) guru who later became MIT's dean of architecture.

***Modeling MIT's Stata Center***

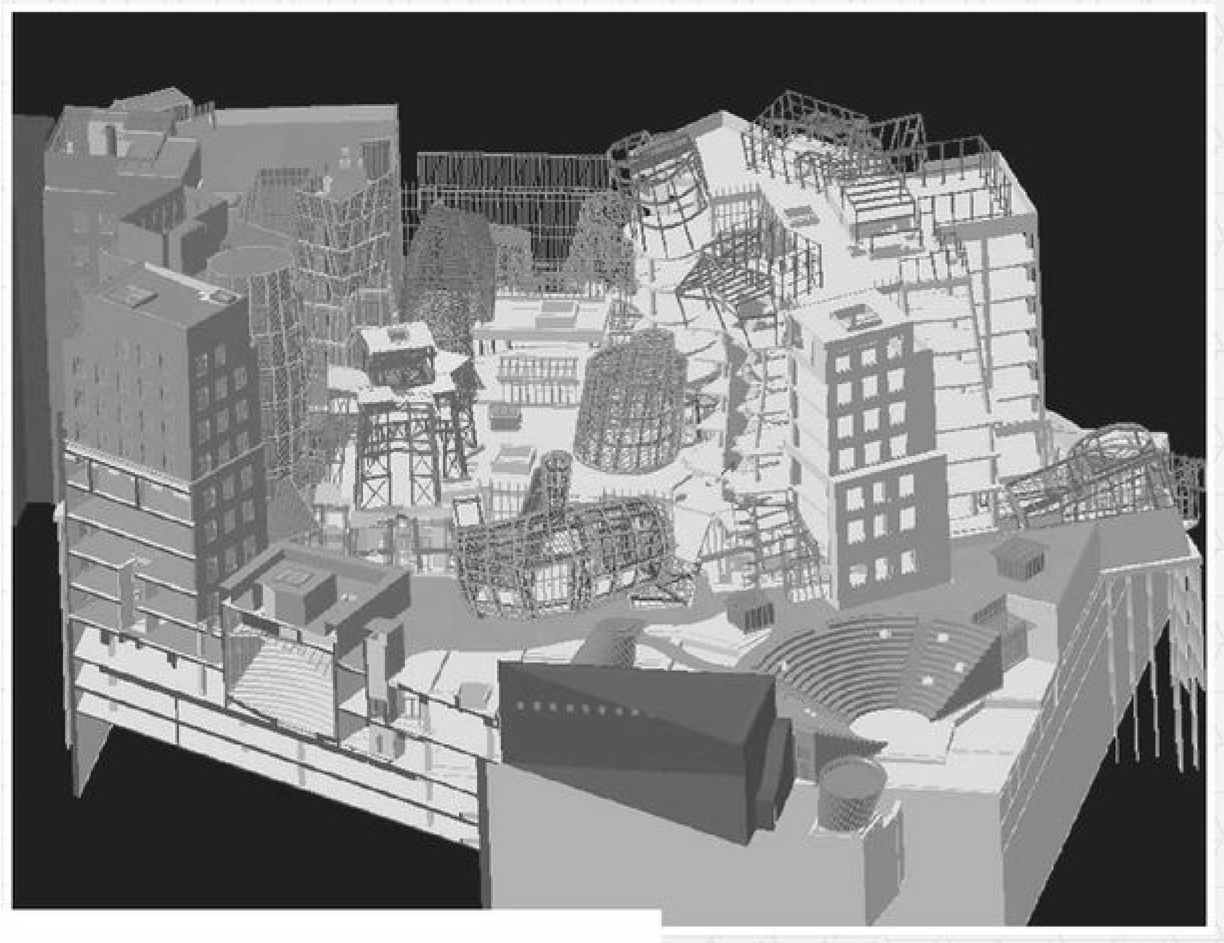
As Frank's architectural practice grew, he resolutely avoided the use of computers. He saw no need for what was not-so-politely referred to as "Nintendo crap." With all due respect to Nintendo, at the time, computers were seen by architects as more like a video game than a serious expressive medium. But a flowing three-dimensional form like the fish could not be adequately captured by the two-dimensional drawings that architects transmit to engineers, and engineers to contractors.

Bill Mitchell responded to the query from Frank's staff by introducing them to the computer modeling tools used in the aerospace and automotive industries rather than existing architectural software. Because the development and tooling expense for producing a new plane or car can reach billions of dollars, it's of some interest to get it right before committing to a design. This has led to the development of sophisticated engineering software environments that can carry a design from conception, through simulated testing, and all the way to production, without ever appearing on paper. Unlike early architectural programs that mimicked a drafting table, engineering software was increasingly able to model all aspects of the physical world—a world that buildings as well as airplanes inhabit.

In 1990 Jim Glymph, with a background in guiding large architectural projects, joined Frank Gehry to bring CAD into the then computerless office. Jim's job was to carry the flexibility of Frank's physical models into equally expressive computer models that could then control production machinery. The absence of computers in Gehry's operation allowed Jim to skip the two-dimensional drawing stage of architectural software and go directly to three-dimensional design tools. But the software needed to be descriptive, not prescriptive, so that it would not eliminate the essential role of model-making in the design process. Instead, the design defined by a physical model was converted to digital data. Three-dimensional scanners recorded the coordinates of the tabletop models such as the one made for MIT's Stata Center. Engineering software then filled in the supporting mechanical structure and infrastructural services, and the resulting files were electronically transmitted to the companies that fabricated the components. Steel frames and skins were cut and bent to shape under computer control, and assembled on the job site like a giant jigsaw puzzle.

This way of working proved to have a number of advantages. Most important, it made it possible to build buildings unlike any that had come before, because they were limited only by the properties of the materials rather than by the difficulty of describing the designs. But it also turned out to be faster and cheaper to build this way. The Barcelona fish went from preliminary design to construction in just six months, beating the planned construction schedule and budget. There was no uncertainty for the contractors because they didn't have to interpret anything; they received a specification with the precision required by a machine rather than the ambiguity accepted by a person. All of the padding that architects, engineers, and contractors built into their schedules and budgets to cover the unpredictability of their communications was removed, because they were all sharing the same computer files rather than regenerating drawings at each stage.

***Digitizing MIT's Stata Center***



***Engineering MIT's Stata Center***


***bricating MIT's Stata Center***


***Assembling MIT's Stata Center***

***Constructing MIT's Stata Center***

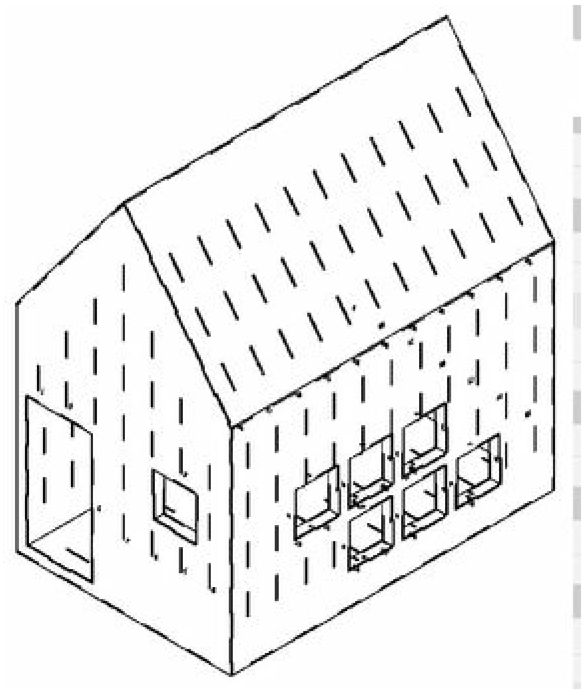
Ultimately, the introduction of engineering design and production tools into architecture challenges the whole division of labor between designing and constructing a building. Once Frank has made a model, he effectively pushes a one-hundred-million-dollar print button to transmit the design all the way through to construction. The real creative work is done by his hands; the rest is relatively automated. If there was a 3D printer as big as a building, it could truly be automated to produce a desired structure, and there are now serious efforts aimed at doing just that.

## Larry

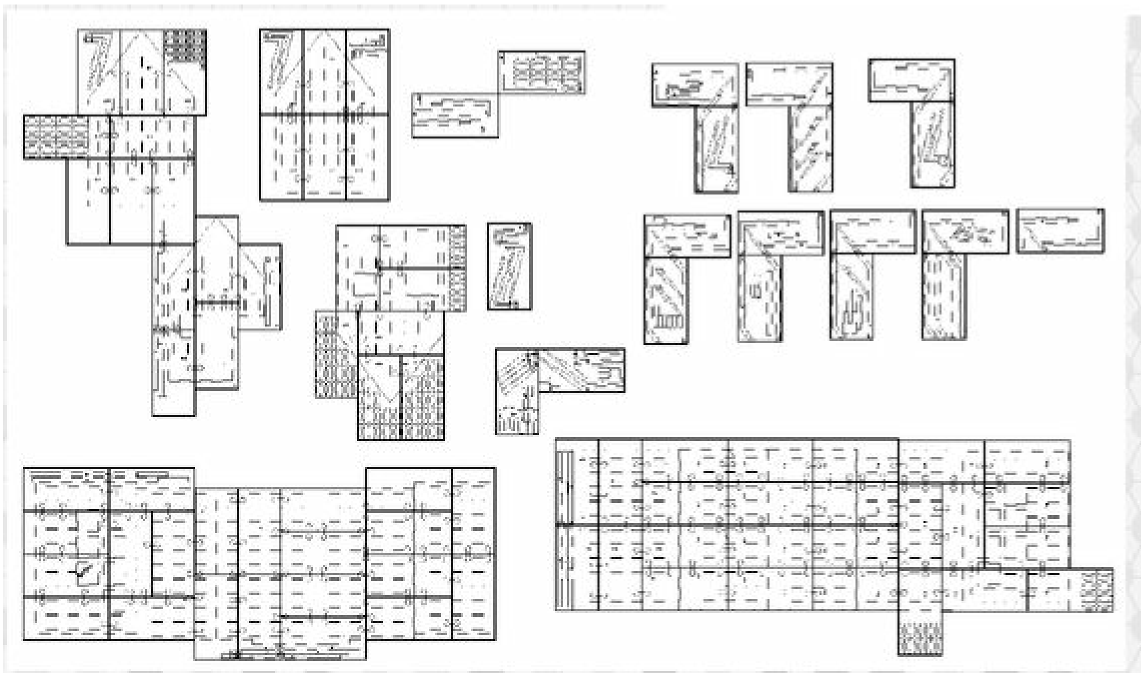
Bill Mitchell's collaboration with Frank Gehry's operation was carried on by one of Bill's former students, Larry Sass, who went on to join MIT's architecture faculty. Larry comes from a new generation of architects who grew up comfortable with computers. He mastered programming as a professional skill, and sees computers as an expressive medium rather than just a tool in a workflow.

Larry was interested in the inverse of the way Frank worked. Rather than turning physical models into digital data and then back into components to be pieced together, Larry wondered whether rapid-prototyping processes could convert a computer model of a building into a table-top prototype in a way that reflected its eventual pconstruction. Instead of elaborately emulating the appearance of everyday materials on an enormous scale, he sought to develop designs aimed at automated assembly. In so doing, Larry saw an opportunity for architecture to be responsive to the needs of the poorest rather than the wealthiest members of society.

Larry looked at the design of simple houses. Much like the way my children, Grace and Eli, made their play structures on a lasercutter (described in "Birds and Bikes"), Larry designed models of houses using 2D press-fit panels that could be laser cut out of cardboard and snapped together to produce a 3D prototype. Unlike a toy, though, these models include the load-bearing elements needed to support a full-size structure.

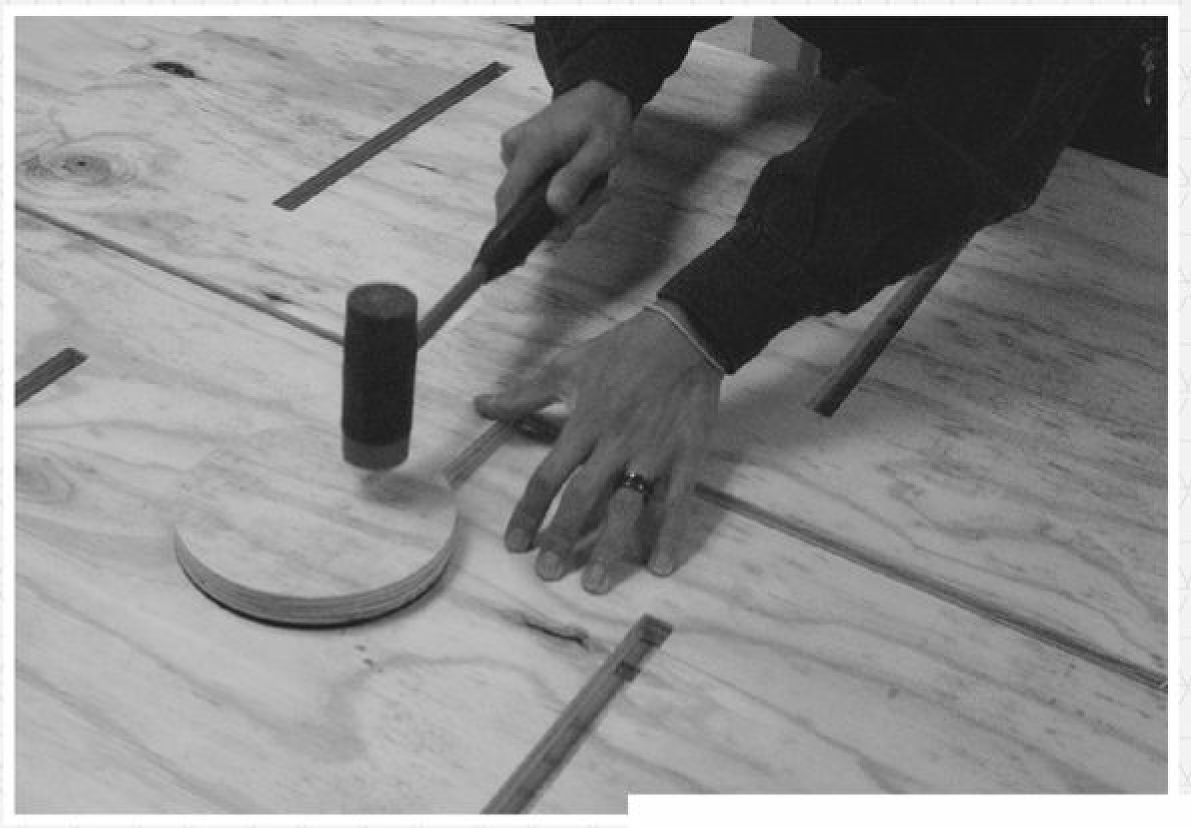


***Designing a house***
***Engineering a house***



***Modeling a house***

***Fabricating a house***



***Constructing a house***

Once the tabletop model looked and fit right, the very same design could be scaled up and produced at full size using a computer-controlled routing machine and readily available 4 × 8 foot plywood panels. A router is somewhere between a milling machine and a laser cutter, moving a rotating cutting tool over an enormous bed to plot out the life-size parts. These fit together in exactly the same way they did in the tabletop model, though now the model makes a real house, ready for final sealing and painting.

At my local home products store, a 4 x 8-foot plywood sheet costs about twenty dollars. One of Larry's designs might use one hundred such panels, corresponding to just two thousand dollars in materials for a house. All of that could fit compactly into one shipping container, ready for assembly where it's needed. And because of the computer-controlled cutting, each house kit could vary to respond to the needs of its occupants and the site.

Around the world there are currently a number of other processes under development for house-scale "printing," pumping concrete like a 3D printer, and snapping together supports like a kid's construction kit. Beyond constructing houses faster and cheaper, these projects promise to produce structures that are more responsive to the needs of their occupants, because the most inflexible construction material of all is a stack of static construction documents. By carrying the same digital description of a model from a computer screen to a tabletop prototype to a full-size structure, machines at each step can talk to one another about the dimensions so that people can talk to one another about what really matters: the design.

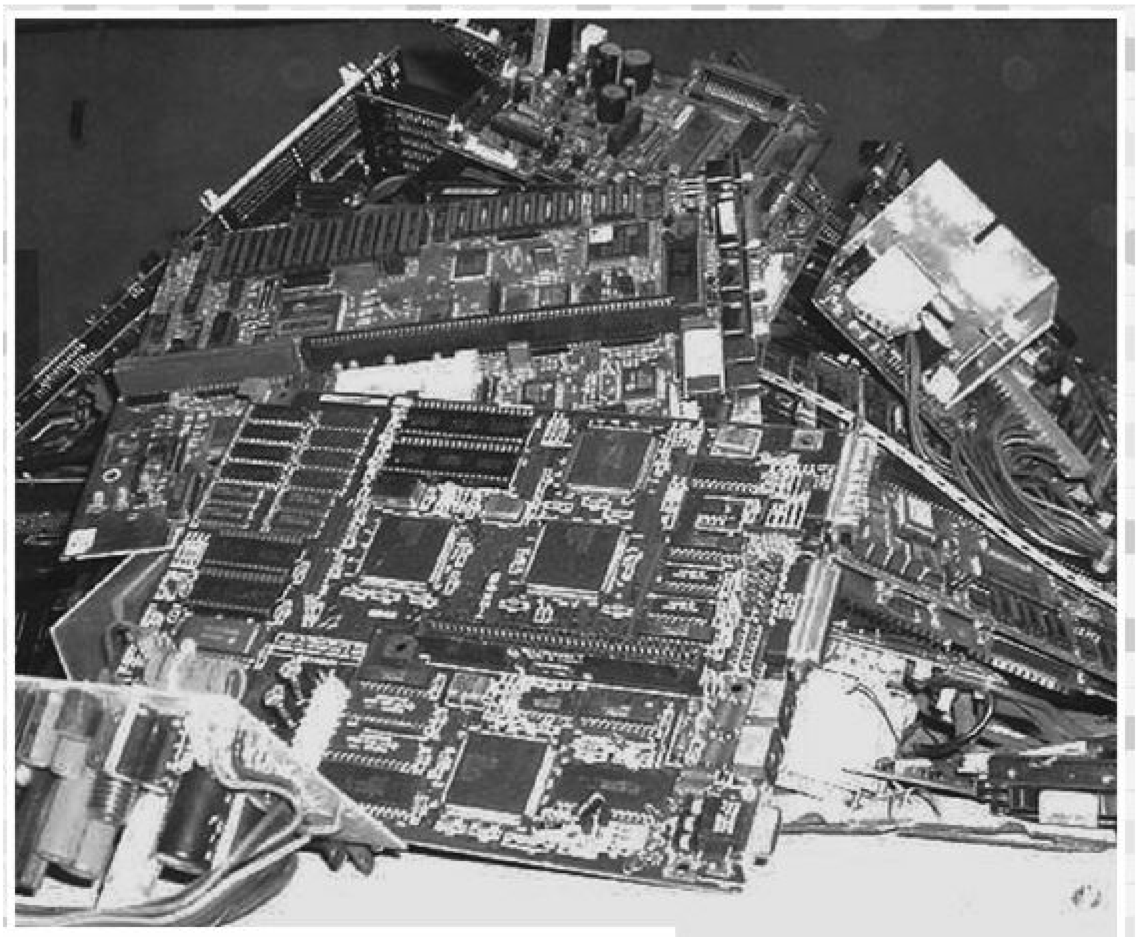
## Etienne

Frank Gehry pioneered the use of CAD tools to turn tabletop prototypes made out of everyday materials into buildings. Larry Sass is using CAD tools to make buildings out of everyday materials. Etienne Delacroix is using CAD tools to make computers out of everyday materials.

Etienne was trained as a physicist, then came to the conclusion that his experience doing science could form a foundation for doing art. He spent fifteen years as a painter, working out of a studio in Paris. Then, in 1998 he came as a visiting scholar to MIT, where he began experimenting with bringing the approach of an artist to the use of technological tools. He made software sketches of painting programs with user interfaces aimed at artists rather than computer scientists. And he started thinking about how to extend the expressiveness of an artist's studio into the domain of computer hardware.

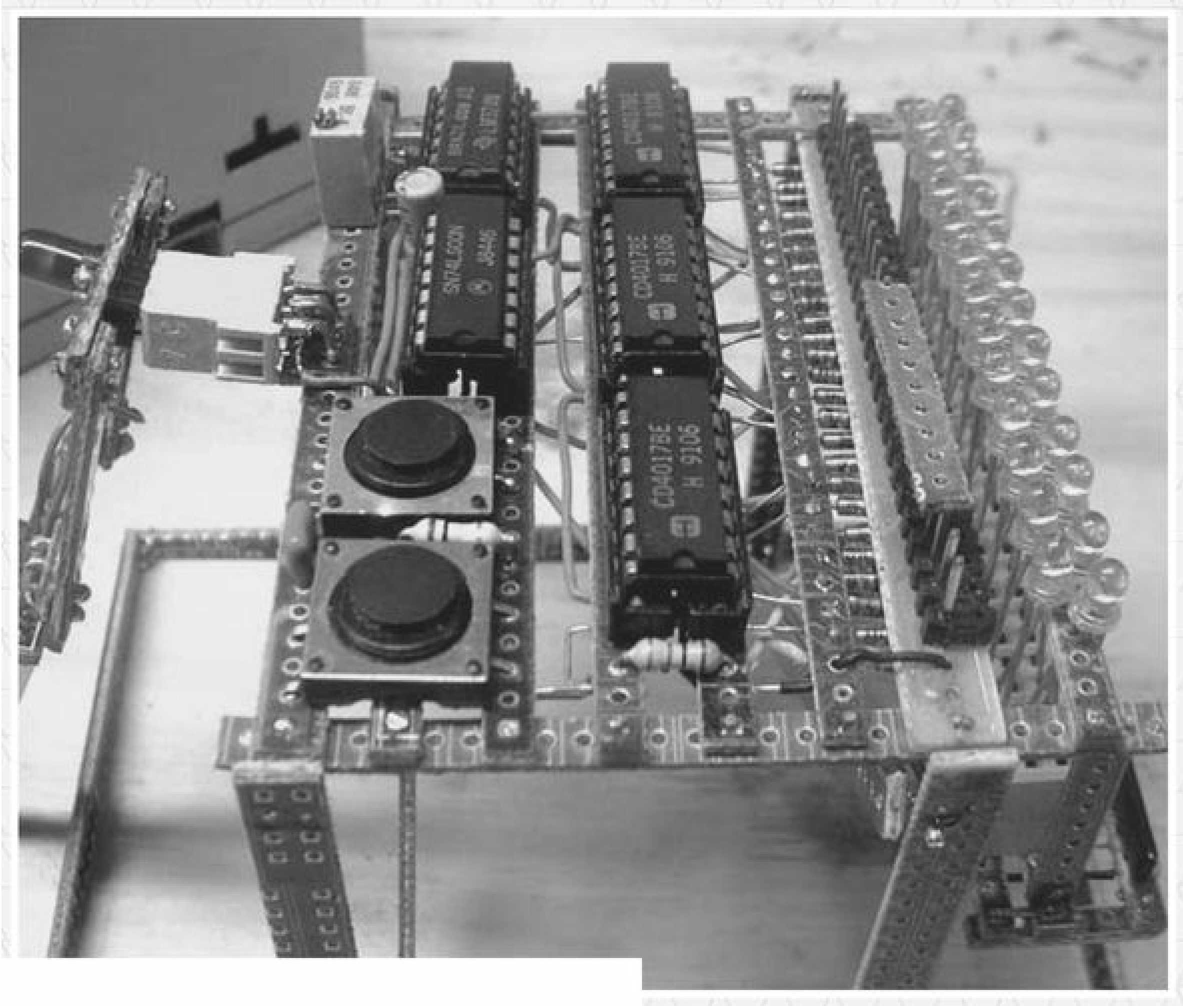
That thought led him on a nomadic journey, ending up in 2000 in Uruguay and Brazil, where he found a fertile intersection of technological, cultural opportunity, and need. In a series of workshops, he started teaching engineers how to work like artists, rather than the more common goal of teaching artists to use the tools of engineers. Like Frank Gehry, Etienne sought to retain the hands-on approach of an artist in a studio, directly manipulating materials. But unlike Gehry, Etienne's materials were electronic.

Etienne started with the mountains of technological junk that are piling up around the world, in poor as well as rich countries. He chopped discarded computers and consumer electronics to bits. Chips and components were desoldered from circuit boards and sorted. Like a good scavenger, he let nothing go to waste—the circuit boards themselves were cut up for use as a construction material, and even the solder was collected for use in making new circuits.

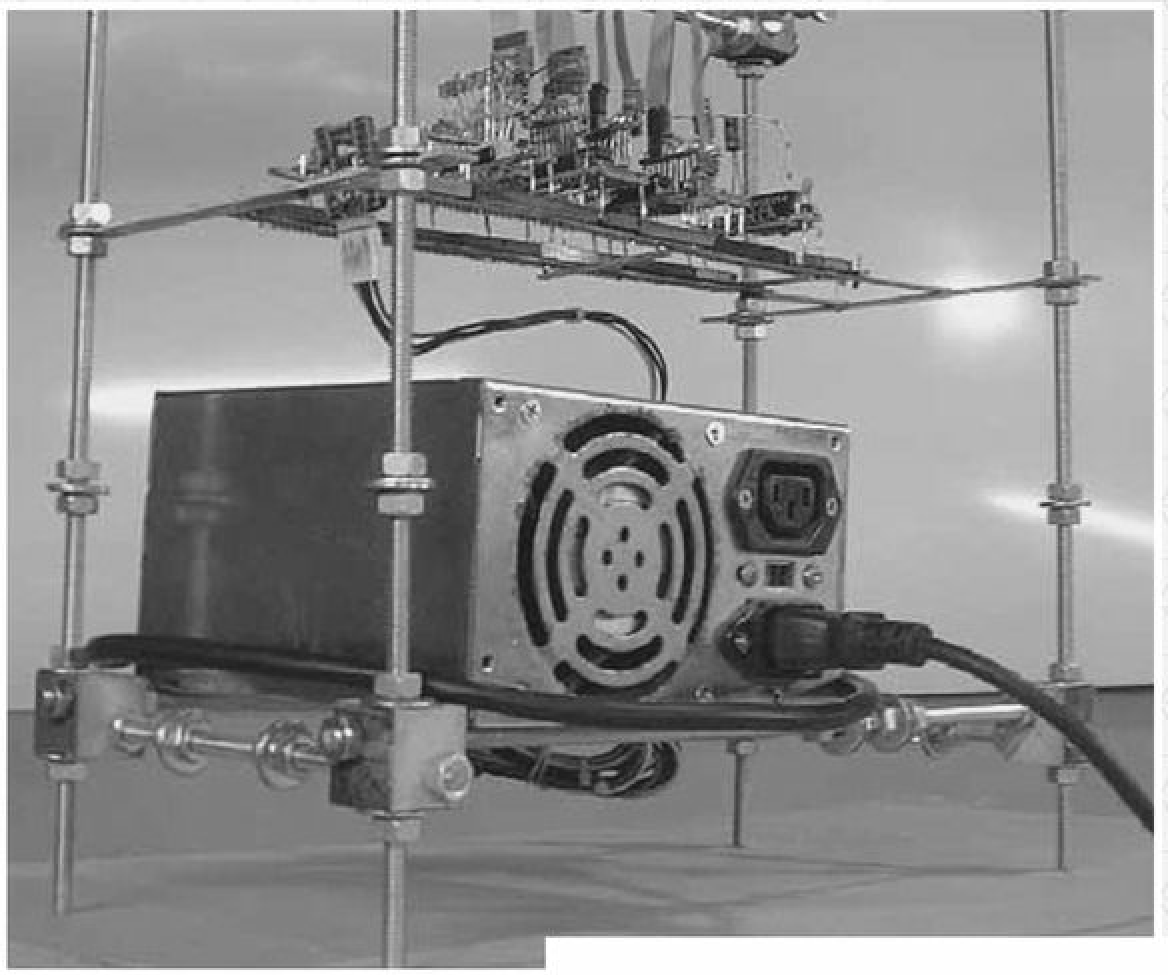


***Raw materials for a computer***

***Sorted materials for a computer***




***Fabricating a computer***



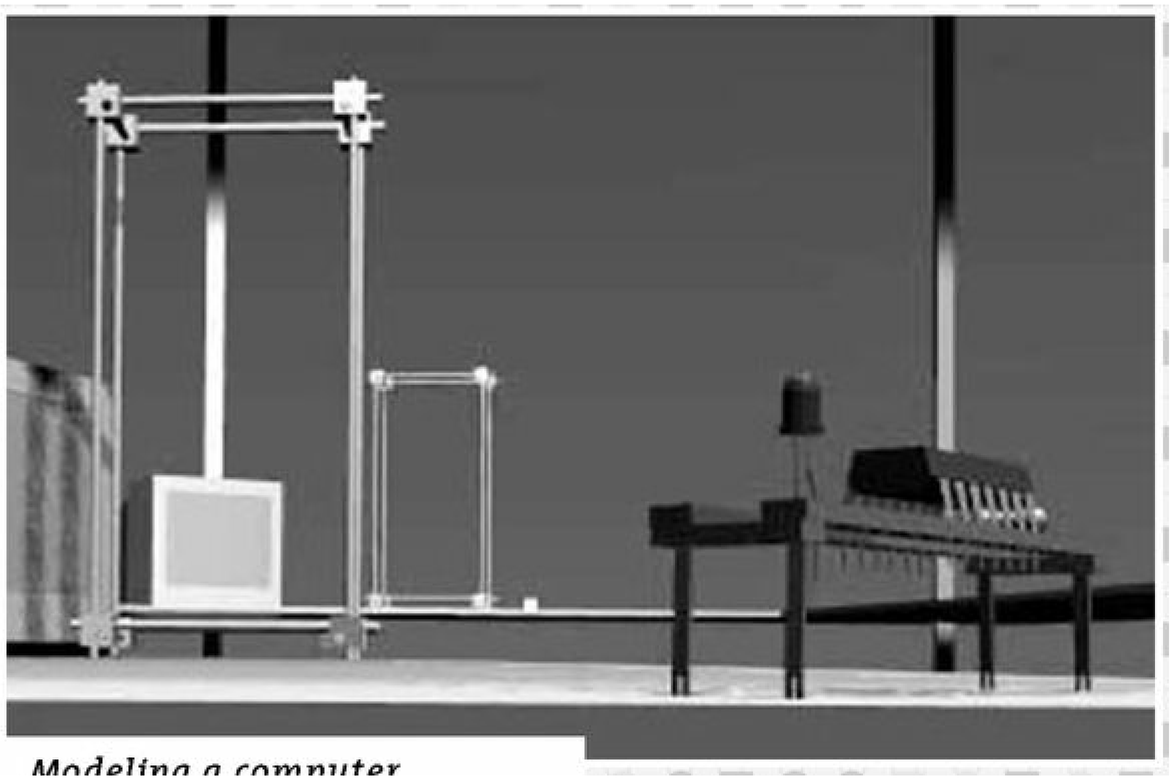
***Assembling a computer***

The result was a kind of high-tech raw material. Etienne and his students approached it almost like archaeologists, extracting the condensed engineering knowledge that it contained. Having taught his students how to deconstruct modern technology, Etienne showed them how to reconstruct it into new forms. They started with the basics, like power supplies, switches, and lights. As they mastered working with this medium, they progressed through digital logic and microprocessor programming, eventually building complete working computers out of discarded materials.

Hundreds of students showed up for his workshops, somewhere between eager and desperate to gain control over the technological trash around them. In the middle of communities torn by economic, social, and political unrest, Etienne encountered a response exactly like the one I saw at MIT on “How To Make (almost) Anything.”

Etienne found that the most difficult technical lesson to teach was imagination. He could see the possibilities lurking within technological junk, but he had a hard time conveying to students how to put the pieces back together short of actually doing it himself. This problem inspired Etienne to turn to the same kind of three-dimensional CAD software that Frank Gehry and Larry Sass were using. He taught his students how to make a virtual version of their studio, freeing them to assemble simulated parts. When they found a good way to put those together, they could then build with the real components, making best use of their available resources to turn trash into treasures.

Etienne’s use of CAD tools to model the construction of a computer is literally pushing the boundaries of engineering software. In the aerospace and auto industries, where three-dimensional design tools were developed, the software models the construction of a car or plane. These CAD models contain subsystems, such as the dimensions and connections of a car radio or navigation computer, but don’t descend down to the details of individual circuit components. The contents of the subsystems reside with the vendors that produce them. But to simulate remanufacturing discarded digital hardware, Etienne needed to open the boundaries between subsystems in order to simultaneously model the electrical and mechanical components, their circuit and structural connections, and the physical and software architecture that holds it all together. In current engineering practice those design functions might be decomposed over ten programs: one for 2D design, another for 3D design, a program to draw circuits, another to lay out printed circuit boards, one to program microcontrollers, a different one to program microprocessors, a program for generating manufacturing toolpaths, one for modeling the mechanical forces, another for modeling electromagnetic radiation, and one more for airflow and heat transfer. A current frontier in the development of engineering software is the integration of all those levels of description into a single environment that can span all the different elements of a design such as Etienne’s.



***Modeling a computer***

Frank, Larry, and Etienne are all pioneers in exploring the opportunities afforded by turning physical objects into digital data, and vice versa. A mathematical specification, a graphical rendering, a tabletop prototype, and a full-size structure can now contain exactly the same information, just represented in different forms. The intersection of 3D scanning, modeling, and printing blurs the boundaries between artist and engineer, architect and builder, designer and developer, bringing together not just what they do but how they think. When these functions are accessible to individuals, they can reflect the interests of individuals, whether architecting an art museum made to look like a tabletop model, low-income housing made like a tabletop model, or a computer made by modeling recycled refuse.