When Machines Touch Back:
Simulating—and stimulating—the most intimate of senses

by

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ABSTRACT

Thomas Massie invented the Phantom, a computer peripheral for simulating the sense of touch, that became the de facto device for haptics research. The thesis recounts the story of Massie, his invention, and present and potential applications as varied as telesurgery and teledildonics. Along the way the thesis explores the science of touch and considers the implications of the fact that perhaps the most reassuring and intimate of senses can be simulated.

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I am probing a rather ghoulish head. I feel the hollow eye sockets and the skull. Then I puncture it with a sharp instrument, carving a tunnel between the hollows through the bridge of the nose. After I pull the tool out, the hole is so small I can barely see the opening, but as I feel around the probe slips back in. I can feel the ragged shape left by my shaky passage through the clay.

I am sitting at a desk in a conference room. The instrument I wield is a stylus attached to a mechanical arm. The head hangs suspended on a computer screen. Earlier, when I first saw the head, it seemed like all images on a computer—insubstantial. I grasped the stylus, and a stylus-shaped cursor slid effortlessly across the screen. When the cursor bumped into the image and I felt the head, however, my experience of the computer world changed. The glass of the screen seemed to dissolve. It was as if I had reached into the computer and touched the strange skull.

The device I used, called the Phantom, creates the illusion that I can feel the head on the computer by resisting the movements of my hand in precise ways. It simulates touch almost eerily well. It can convincingly simulate textures as smooth as wet ice and as springy and gripping as rubber. The virtual material can seem to resist the scrapings of the stylus like granite. Or the carving tool can pierce the virtual clay as easily as a skewer slipping into tender steak. The Phantom creates an illusion so real, it has convinced some sculptors, previously dedicated to working with real clay, to switch to virtual clay.

But at times the illusion seems to go too far, bleeding into the real world. When I lay down the Phantom's stylus and take up my pen to take notes, I cannot shake the feeling that I am still holding the stylus. The machine heightens my awareness of the subtle texture of the paper, the smoothness of the pen's movement. But it also makes my paper feel slightly less real, less a permanent resident of the world outside the computer.

Phantom is a name derived from a longer description of the device—Personal Haptic Interface Mechanism. This remarkable machine has become central to a relatively new field called haptics, a name derived from the Greek word meaning to grasp. Haptics combines the scientific study of touch with engineering. The Phantom has become the de facto haptic device for designers and for researchers seeking simulated-touch applications as varied as telesurgery and oil exploration. Since the Phantom was invented in 1993, engineers have created a variety of touch simulators. While the Phantom allows a person to feel the virtual world as if prodding it with a stick, another device, worn like a glove, simulates grasping objects with all five fingers, but without the fidelity of the Phantom. Researchers point to the goal of using tiny motors, piezoelectric actuators, controlled puffs of air, and even vibrations from tiny loudspeakers to transmit fine sensations to a whole hand or even the whole body. Some hope to incorporate haptics into the displays of handheld computers, giving a new meaning to the term "touch screen."

As new devices are being developed, new uses have been found for the Phantom. It is being used by researchers around the world to feel and manipulate individual atoms, sift through geological data about oil fields, and simulate surgery. Connected to the Internet, the Phantom promises to change the way people interact online. For example, in 2002 scientists used a pair of the devices to exchange touch across the ocean, a press release declaring it the first "transatlantic handshake." Jay Leno in his Tonight Show monologue suggested it might be used for online sex. Indeed, an industry selling Internet-linked sex toys has already sprung up. The industry has taken the descriptive, if startling, name "teledildonics." The devices are rudimentary now, but the Phantom shows the potential of convincingly simulating physical relationships online.

Simulating touch requires understanding how touch works, including how the brain commands muscles to move the hand about. As scientists learn more about these mechanisms, they are developing techniques that might soon restore mobility to the paralyzed. Eventually, researchers hope to allow armless amputees to touch the world again. And by creating a powerful new way for computer users to receive information from a computer and send information back in, haptics might also open the bottleneck that prevents people from using computers to their full potential as thinking tools.

The promise of haptics, however, comes paired with questions. Haptic devices can deceive the most intimate and most trusted of our senses. A blind person, upon being given a demonstration of the Phantom, seemed unimpressed as he stroked an object's virtual surface. When the person giving the demonstration, MIT haptics expert Kenneth Salisbury, reminded him that "there was no 'real' object present, he jumped with surprise, suddenly grasping wildly with his other hand at the void in front of him in search of the nonexistent object he had been exploring."

People who can see may not realize just how much they depend on touch throughout a day. But nothing is as shocking as a slap or as reassuring as a hug. Touch is so fundamental to our experience of the world that we rely on it as a metaphor for understanding and clarity. When friends part, they promise to stay in touch. We grasp difficult concepts. Now, in a world in which simulation and reality are becoming more and more difficult to tell apart, haptics may leave us little to hold onto.

The modern era of haptics research began, arguably, in a sixth-grade classroom at the Lewis County Central Elementary School in Vanceburg, Kentucky. The year was 1982. In that classroom, Thomas

Massie, who would go on to invent the Phantom, decided he wanted to build a robot. Soon after he thought of a purpose for the robot. He needed help cleaning up the clutter in his room, a problem that, not surprisingly, became more serious once he got started on his project. Massie's ambition made him a menace to household electronics. His toys never survived long intact, and once apart, they were done for, at least for their intended purpose. "They were usually terminal autopsies," he told me many years later.

Every year at Christmas Massie's mother would put out a lawn decoration that his father had acquired as a beer salesman. Stroh's beer marketers had devised a clever advertisement in the form of a rotating "Stroh-man," a beer-loving snowman. The winter after Massie decided to build a robot, his mother was furious to find the Stroh-man inoperable. Massie had scavenged its electric motor.

Because of his interest in hands, and because he had no idea how he'd give the robot a brain or eyes, Massie started his robot project with the arm. In addition to "cannibalizing," as he put it, the Stroh-man, he used gears from a broken clock to make the wrist, motors from toy "tumble-buggies" to power the shoulder and elbow, a thread spool for the palm, lead tire weights to counterbalance the arm and make it easier to control with the motors, and various pieces of salvaged metal. He used the motor from the Stroh-man to open and close a pincer-like hand.

At first, the arm didn't work. He had designed the arrangement of joints based on what he could observe about his own arm and hand. The tendons he saw moving beneath his skin reminded him of rubber bands, so he used these to connect the motors to the arm segments. But the bands stretched as the motors wound them up, especially when the arm was trying to lift something. They tightened without moving the object until they suddenly sprung, flinging the object dangerously and destroying the arm. An interesting catapult, but not the best system for organizing the room. He replaced the rubber bands with string, entered the machine in a science fair, and won.

Massie entered robot arms in science fairs every year from then until his junior year in high school. His eighth-grade robots used light sensors from a toy shooting game. Since his mother managed to keep him from taking apart the family's new PC Junior, he had to find an indirect way to use the computer to control the arm. He taped the light sensors to a computer monitor and wrote a program that displayed white boxes arrayed across the screen. These boxes activated the sensors and relayed signals to the arm. This ingenuity helped send him to an international science fair in Texas.

When he got there, his rag-tag invention and magic-marker posters seemed totally out-classed. Seeing the competition, even the teacher who came with him, and who had taken extra time to encourage Massie's projects, was so sure the young man had no chance of winning that he stayed behind in the hotel during the awards ceremony. Massie only went to the ceremony to find out who won and to get a look at the winning entries.

But the judges called his name. NASA had picked six entries for special prizes in addition to the regular places. The agency's judges had been impressed by Massie's ability to use creatively what he had on hand. He felt a little awkward to be the only one on stage without a teacher, but he also felt good to be up there alone. After all, it was his accomplishment. He began to realize that his tinkering ability could pay off in ways he'd never imagined. The NASA prize came with a trip to Silicon Valley, where he saw technology geeks like himself driving Ferraris.

Of Massie's science fair projects, the final one came the closest to being a haptic device. He'd taken apart two radio controllers for model airplanes. He wired these to joystick potentiometers that he in turn attached to the fingers of his own hands. The potentiometers could sense the position of his fingers and relay this information via the radio controllers to the fingers of a mechanical hand. Using this control system, he could make the hand crawl across the floor like the disembodied hand in the Addams Family. While it did not provide force feedback like the Phantom, Massie was able to sense the position of the robot hand by the position of his own hand.

As Massie was learning his craft in high school, the man who would become his mentor in college was attempting to build the first full-fledged haptic devices. These machines had their roots in the Manhattan Project, the mission to develop the atomic bomb. For the project, scientists had to manipulate radioactive materials with precision from a safe distance. The answer was the teleoperator. This was made of two devices connected by mechanical linkages. One device, called the slave, sat with the hazardous materials behind a meter-thick quartz window. Scientists manipulated the master device, and the linkages caused the slave to mimic their actions. Eventually engineers replaced the mechanical links with electronic ones.

In the late 1960s, researchers including Fred Brooks of the University of Northern Carolina at Chapel Hill, began experimenting with master devices hooked only to computers and controlled by computer programs. Brooks hoped to use these devices to allow people to feel simulated objects, such as molecules. This work continued over decades, involving several researchers, including Kenneth Salisbury who would become Massie's mentor and thesis advisor at MIT. According to Salisbury, the devices could not produce convincing illusions of touch because the computers and mechanisms were too slow. Unbeknownst to the pros, a kid living in Kentucky was developing the skills needed to create the next generation of these devices.

In time, Massie would link his interest in hands to MIT. As an eighth grader he had watched an annual engineering contest at MIT broadcast on PBS. In these annual contests, the organizers give students a bag of parts and a specific challenge. He laughed when students tried to use rubber bands as mechanical tendons. "That's so seventh grade," he recalled thinking.

That contest made him want to go to MIT. So he applied and won admission, beginning school in the fall of 1989. On a tour of the engineering departments, he recognized a robot arm that had been featured in a magazine and immediately persuaded its designer, Kenneth Salisbury, to take him on as a lab assistant. Massie worked in Salisbury's shop, part of the Artificial Intelligence Lab at MIT, for four years. Along the way, he entered and placed first in the contest that drew him to MIT. After he won, he was interviewed on PBS. "I've been dreaming of this since like the eighth grade," he said, sporting oversized safety glasses. His friends put this quote on a t-shirt and made him wear it around campus.

The idea to build the Phantom came during one of Massie's conversations with Salisbury about a potential senior thesis. While typing an e-mail, Salisbury suggested that it would be cool if he could reach into his computer and feel the shapes he could see on his screen. After 6 weeks of work, Massie made this possible with the first Phantom.

Massie had known he needed a device that would create the same sensations we feel when our hands encounter objects, just as stereos and movie projectors create sound and light. We feel objects by moving our hands over them and detecting the ways the objects affect our hands. For example, a sphere will redirect a hand around its curved surface. If an object stops an exploring hand suddenly, as a concrete wall would, the object will seem hard. If it slows the hand gradually, as a pillow would, it feels soft. A high fidelity device for simulating the feel of various virtual objects would need to track the movement of a hand and resist and redirect it in precise ways.

Massie decided to give a computer the ability to sense and react to hand movements by giving it an arm of its own, a project he was prepared for by his childhood experiences building mechanical arms. Just as his science fair projects mimicked his own arm, so the Phantom mimics a human arm in many ways. When I used Massie's machine, I grasped the stylus and saw my wrist mirrored by the joint that connects the stylus to the rest of the Phantom. As I flexed and extended my elbow, the elbow joint of the machine extended and flexed. Its shoulder pivoted in time to mine. Sensors called spindle cells that are embedded in my muscles sent signals first to my spinal cord and then to my brain, detecting the position of my arm. Likewise, sensors in the Phantom tracked the exact angles of its joints and relayed this information to the computer. My brain sorted through signals from my arm and sent signals directing my muscles to contract and relax, moving both my arm and the stylus I grasped. The Phantom sensed this movement and signaled the computer, which then sorted this information and activated motors to make me feel as if I were touching a solid object.

The Phantom creates the illusion of touch by resisting the hand precisely, updating the position of the stylus 1,000 times a second, which is over 40 times the rate of still images passing through a film projector. As Massie noted in his thesis, the hand is quicker than the eye. To create the sensation of a sphere, the Phantom senses the position of the stylus and prevents the hand from pushing the stylus tip into the space the sphere would occupy. The device is so precise that as the user moves the tip of the stylus across the surface of the sphere, it can vibrate and resist this movement in ways that make the sphere feel like, to give two examples, a hard, dimpled golf ball or a rubbery racquetball.

Massie had to solve many engineering problems. For example, the mechanical arm, like anything with mass, has its own inertia. A user feeling the resistance to both starting and stopping a movement would notice the arm, ruining the illusion. Massie overcame this problem with a system of counterweights, cables, and springs.

Not all of the ideas for the device were Massie's. Salisbury's knowledge of earlier attempts at haptic devices led him to suggest a radical step. The other designs used motors to control what engineers call six degrees of freedom. They could control movement up and down, side to side, and back and forth, the first three degrees of freedom. They could also control how the end effector, the stylus in the case of the Phantom, tilted left and right and up and down, and twisted—three more degrees of freedom called yaw, pitch, and roll. Salisbury suggested that a convincing illusion might be created with just the first three degrees of freedom, which could be controlled using just the shoulder and arm joints. His idea was to make the wrist freely moving, with no motors attached. This seemingly simple suggestion made controlling the device dramatically simpler. Massie followed Salisbury's design suggestion, and the smaller demands on the computer allowed the Phantom to update the position of the stylus twenty times faster than previous devices.

Salisbury's simplification of the problem was an engineering "hack," in MIT-speak. Such hacks have proven essential to research in haptics. Much of the field focuses on learning precisely how sensitive the sense of touch is, so engineers can build machines to mimic this sensitivity without overdoing it. Movies use a similar kind of simplification. A projector can create a convincing illusion of movement moving film at a rate of 24 frames per second. Knowing this fact allows filmmakers to minimize the cost of making movies, since a faster rate would take up more film. Simplifying the Phantom meant it could be run with a desktop computer instead of a more powerful, and more expensive, refrigerator-sized research computer.

To make convincing haptic simulations, researchers want to know factors such as what vibrational frequencies a human fingerpad can detect and how far apart two pins need to be before someone can detect them separately. Two pins closer together than 2 millimeters feel like one pin because the receptor cells in the skin cannot tell the difference. This is partly because of the way the receptors are spaced, and partly because when one receptor detects pressure, surrounding receptors are shut down to help the brain pin-point the pin.

This is not the same as saying we can only feel objects in the environment larger than 2 millimeters. We can detect textures with variations in height as small a few microns. A Braille dot, according to MIT neuroscientist Mark Bear, is 167 times taller than the minimum humans can notice. To detect these small differences, however, we have to move our fingerpads over a surface. As the finger moves, touch receptors signal each time they encounter a variation, such as a grain of sand on sandpaper. The brain can interpret the texture based on the frequency with which the receptor fires. The frequency will be much higher, for example, as a finger moves over the densely packed particles of fine grit sandpaper than it would moving over rough sandpaper or gravel. Knowing both the 2 millimeter rule along with the fact that skin detects fine textures based on frequency lets engineers know that a haptic display made of a grid of pins does not need to have pins spaced closer than 2 millimeters and that various textures can be simulated by changing the frequency of the vibrations of these pins.

Massie was surprised when the Phantom worked. His science fair experiments had taught him to expect failure after failure followed by only temporary success, but this latest robot arm performed well early, after just a few weeks of work in the spring of 1993. Shortly after he'd proved the prototype, Massie first met Patrick Winston, the head of the AI lab in those days. "I'd worked there for four years and I didn't know who Patrick Winston was," Massie remembered. "I did not rate his attention." But the Phantom made him an instant hit. The director's first words to him were, "So, you're the undergraduate whose bachelor's thesis is going to save this lab." When Massie looked surprised, he added, "Don't worry, kid. It won't be the first time."

Massie soon found out that saving the lab meant giving tours of the lab and demonstrations of the Phantom. "Every person who could possibly influence funding for the AI lab was brought up there, and I had to demo to them. I had to skip classes to give demos. I was basically chained to that thing giving demos."

Massie met many distinguished visitors. As he led directors of the Sandia National Labs and Army and Navy labs, he had to point to example after example of robots that had functioned just long enough to get someone's thesis approved. One famous example was a machine that could navigate the complicated environment of the AI lab to pick up empty aluminum cans. "As far as I know," Massie said, "That robot maybe picked up one can once, and then broke." But he told the tourists, "That's Herbert. He picks up cans. He's not working now, but if you come back next week, maybe he'll be working." Massie didn't want his thesis to add to the clutter of the office. This inspired him to make the Phantom robust, and his experience building mechanical arms helped him do this. "I made the Phantom for myself," he said. "I have a theory that the best inventions are the selfish ones."

Massie graduated in 1993 and signed on for a Master's degree at MIT. Late that summer he got married and started graduate school. In the same month, Massie had his third cousin, a lawyer, incorporate a business called SensAble Devices, which later became SensAble Technologies. The company, which at first consisted of only Massie and his wife, would manufacture and sell the Phantom. And so Massie fulfilled the dream of many a student at an institution where it is not surprising for students to found their own companies, even while still in school.

The demos Massie had given helped him launch his company. "I was being used. But it was a blessing," he said. After seeing a succession of broken thesis projects, the distinguished visitors were suitably impressed to find the Phantom working. They were even more impressed once they had a chance to use it themselves. "The Air Force asked if I could build one for them," he said, and with that he had his first order. Journalists also gave him a hand. He gave tours to writers from Wall Street Journal, Popular Science, Science News, and Omni. An Australian television program called Quantum featured Massie and his device. When researchers called and said, "I saw your device, but I've got to talk my boss into letting me spend the $20,000 on it," Massie made color photocopies of the magazine spreads. These and the Wall Street Journal article became his marketing literature.

During its first months, according to Massie, SensAble was a makeshift operation. He and his wife, Rhonda, who was finishing an MIT undergraduate engineering degree, built the parts using diagrams Massie had scribbled on napkins and the backs of problem sets for his classes. The AI Lab director let him use the machine shop to manufacture the parts as long as he continued doing demos. After a while Massie and Rhonda "got a little more discreet," he said, and moved the assembly stage to their one bedroom apartment on campus. They shipped the Phantom using the same UPS van that delivered care packages to students in the nearby dorms.

In addition to skipping classes to give demos, Massie was now pulling all-nighters to meet production deadlines. As long as the plans for the device were on napkins, Massie and Rhonda had to do all the work themselves. The work was exhausting and the company could not expand. Rhonda decided something needed to change. So she taught herself a design program that could make specifications a machine shop could follow. Because of her foresight, the business could expand, and they could sit back and let someone else build the machines.

The first Phantom shipped in December of 1993, only half a year after he'd invented the device. A year later they had sold $220,000 worth of Phantoms. They didn't quite keep all the money. "That's when I learned about taxes," he said.

SensAble was successful, but Massie worried about how long it would last. His first customers had to write their own software applications, and he didn't imagine there were many willing to do that—maybe a hundred, he estimated. As it turned out, there were many more. Still, he felt the company needed to find a killer application if it were to keep going. Eventually the company developed FreeForm, software that let designers carve virtual clay. To conceive of and realize this software, Massie sought venture capital and engineers and assembled a leadership team to answer to the investors, including a new CEO. Eventually the company won some $32 million. With this money, the company moved from a two-person operation to an enterprise employing numerous engineers as well as financing and marketing staff. At one point, SensAble employed 60 people and regularly called on a dozen consultants. In 1999 the company was featured in Inc. magazine because its revenues had grown by about 25 times in five years.

During the first several years of the company, Massie did very little creating with his own hands. He told me that most of his feeling of accomplishment was vicarious, through the work of his software engineers, and that being a businessman had started to wear on him. That's when he had an idea that would change his vision for the company and get him back to designing. Massie wanted his device not just on the lab benches and design studios of big manufacturers. He wanted one sitting beside the mouse on computer desks in homes across the country. He wanted to democratize the promise of haptics. He wanted to turn people from being passive consumers to being creative producers. Perhaps most of all, he said he wanted to "wake people up to their hands."

So Massie set to work redesigning the Phantom to make it cheaper to manufacture. And he began to dream about how ordinary people might use it.

Meanwhile, the original Phantom was quickly catching on with scientists and product designers. The two major toy companies, Hasbro and Mattel/Fisher-Price had been trying to switch to computers, which speed up the transition from design to production. But they met resistance from designers, who were used to working in clay. The Phantom and its virtual clay, however, provided an intuitive way to work with the computer and won over many designers. Recently, using the same version of the Phantom that I tested, a sculptor who works for Mattel/Fisher Price designed detailed busts of Kirk and Spock for a line of Star Trek toys. He also made a line of figures for the Lord of the Rings movie series and a jolly, wobbly Homer Simpson. A Hasbro designer used the device to create a Jurassic Park Junior Thundering Triceratops with head-ramming action.

Others found more serious applications. A system developed at the University of North Carolina at Chapel Hill pairs the Phantom with a scanning probe microscope, allowing researchers to feel molecules in real time as they are measured by the microscope. Researchers have also put a dimple in a single virus particle and tested the strength of virus-sized carbon nano-tubes using a Phantom to control the tip of an atomic force microscope. In these cases, the Phantom is not linked to a virtual world, but to a world too small for unaided humans to feel and manipulate. This has become an important tool for nanotechnologists who are making materials and simple devices the size of viruses. Because the Phantom precisely measures small variations in force, versions of it have been used to test the strength of new nano-scale materials. Other researchers, whom Massie calls the "rat shakers," use the precision of the Phantom to measure how much force laboratory animals can exert. These researchers take advantage of the fact that the Phantom can both exert and measure forces precisely.

Military researchers plan to use haptics devices inspired by the Phantom to extend the reach of surgeons. The Army's Telemedicine & Advanced Technology Research Center (TATRC) in Frederick, Maryland, funds projects such as mobile robotic rescue vehicles that will eventually have these systems onboard. The vehicles will be able to find wounded soldiers using directions from other soldiers, a more powerful version of the Global Positioning System navigation devices used in many automobiles today, and a gadget reminiscent of Star Trek. Dubbed a transcorder, prototypes of this device can now measure heart and breathing rates through walls and detect the movement of a body through 20 feet of rubble.

Early versions of these vehicles are already being tested. They are armored, to let them go into a battlefield, retrieve wounded soldiers even as the shooting continues, and load them aboard with mechanical arms and a conveyor belt. Once inside, soldiers can be evacuated to a safer area where, in the next generation of the system, on-board mechanical arms with haptic feedback will be remotely controlled by medics to do simple procedures. They should be able to "clear the airway, apply pressure bandage, [and] inject narcotics or hemorrhage-retarding drugs," wrote Gary R. Gilbert, an engineer for TATRC.

The Army wants eventually to develop a system that enables surgeons far from the front lines to operate on soldiers still in the field. Surgeons will evaluate wounds using stereo video that gives a sense of depth and haptic arms that can sense force, pressure, and temperature. A doctor safely away from the battle could then calmly stanch bleeding, remove bullets, and sew up wounds using an array of instruments attached to the arms. She could do even better than in person, the mechanical arms steadying her movements and automating repetitive tasks.

In peacetime such technology may allow specialists in one city to operate on patients in another. In addition, because a surgeon's every movement can be recorded by a computer and played back through the haptic mechanisms, these systems can be used to train new surgeons, guiding their hands based on the movements of experts.

Haptics-based training programs would address what Dr. Janey Pratt, a surgeon at Massachusetts General Hospital and an instructor at Harvard Medical School, considers a significant deficit in the way surgeons are now trained. Currently, trainees learn surgical procedures using books and computer programs with no haptic feedback. Their first exposure to the true feel of human tissues comes with live human subjects. Cadavers can help with anatomy but the tissues of the dead feel substantially different from those of the living. The same holds true for tissues in animals, which have the added disadvantage of being different in shape. Polyurethane and plastic surgical models can give a general feel for the tissues, but they have to be replaced with every use, which gets expensive. Furthermore, these models do not give a sense of how the feel of tissues varies from person to person. Imagine shaking hands with a line of people, Dr. Pratt suggests. Some hands will feel dry and calloused, others soft and clammy. She says differences between people are "multiplied by something like ten on the inside."

The limitations of current teaching methods mean that a surgeon in training has to learn during an actual surgery. An expert leads the student through the procedure, pausing to point out the characteristics of different organs. Under the expert's guiding hand the trainee feels how hard she can push on the liver without puncturing it. But to get a real sense for the organs, Pratt admits, "You almost have to rip tissue a few times." Indeed, she says trainees commonly do, by accident, puncture delicate organs such as the liver.

Although liver damage is usually not serious, other more dangerous mistakes do occur. A good haptics-based simulation would let students make these mistakes before they get into an operating room with a live patient. It would also let them experience the full range of tissue variations, something that might not happen even in the multi-year training surgeons undergo.

As useful as haptic training may prove, Pratt believes another application is even more important. While surgeons now must pass written and oral exams, they currently take no practical exam before being licensed to operate on their own. No independent evaluators determine whether surgeons have skills to go along with their knowledge.

At present, no such comprehensive test is feasible. But future haptic simulators could vary the feel of tissues while candidates demonstrate their skill in a variety of procedures.

So far haptic surgical simulations are still in the early stages. One obstacle has been the difficulty of making accurate representations of how tissues feel. Engineers cannot simply run tests on live subjects, straining stomach tissue, for example, until it breaks. Animal testing will not be accurate; a pig stomach does not feel the same as a human one. Instead, engineers must rely on the subjective descriptions of surgeons such as Dr. Pratt. They say some tissues feel like cheese, others more like apples. The engineers take the descriptions literally, measuring the properties of apples and programming the results into the simulation. Surgeons then test them to make sure they are accurate. Using these time-consuming methods, haptics researchers have made some progress, producing very accurate simulations of specialized procedures such as inserting a breathing tube or a needle for an epidural injection. Surgery is much more difficult to simulate, however, since it involves more tissues and the added variable of movement. Organs not only have their own physical characteristics, they can move within the body cavity. Surgeons need to know how far they can push them without doing damage.

These applications show how haptics can extend the reach of the hand over vast distances or into virtual worlds. Simulated worlds also hold the potential of extending the reach of the mind by improving the ability of humans and computers to work together.

"The current input devices to the computer that we have, namely the keyboard and the mouse, are very simplistic compared to the exquisite capabilities that our hands possess," says Mandayam Srinivasan of MIT's Touch Lab, who is one of the pioneers of haptics. "Haptic interfaces are more compatible with the capabilities of our hands and in the future, as they evolve, we will be able to interact with more complex information in a computer in a more natural manner." As these interfaces improve, according to Srinivasan, haptics will extend the reach of computers as thinking tools. This will happen as engineers find ways to use the powerful methods our sense of touch uses to process the environment to instead process data generated by a computer.

Touch is adept at sorting the world into specific categories of texture, shape, hardness, weight, and temperature. This is possible because an array of specialized receptors, such as spindle cells embedded in muscles and Meissner's corpuscles that sit just under the outermost layer of skin. Each receptor's structure reacts to specific frequencies, pressures, temperatures, degrees of stretch and other tactile inputs.

Some of the signals sent by these receptors are processed by the spinal cord, causing the familiar reflex actions. Touch a hot stove and the signal enters the spinal cord, where circuits direct one set of muscles to jerk the hand away and another set of muscles to keep the body from being thrown off balance by this quick movement. Other touch signals ascend through the spinal cord to areas in the brain. One such area, the cerebellum, compares sense information to predictions it has made about what it expects the information to be. Differences between the actual signal and the predicted signal trigger a cascade of changes in other parts of the brain, the result of which is learning. Many areas of the brain exclusively process touch-related information. Others combine functions such as touch and vision.

This complex system is a very sophisticated way of sorting through information and making connections. Before haptics, the only way to get information out of a computer was to see it or hear it. Now you can feel it. Haptics makes use of active touch—the process our hands use to explore the environment. Active touch can both sense the world and change it. Haptics enables this sort of two-way exchange with computers, which many haptics researchers believe will add to the amount of usable information that can be exchanged between a human and a computer.

This expectation is borne out by the use of haptics to sift through geological data about oil fields. Oil companies use a range of techniques to figure out what lies miles beneath the surface of the earth, including core samples that provide direct information about the composition of the ground and small explosions (or more recently, mechanical thumpers) that provide more indirect seismic information. The resulting data can seem a bewildering mess. Hoping to discover economically accessible oil fields, Shell Oil and Chevron Texaco use the Phantom in combination with special software to help geologists make sense of this information. The software allows them to navigate "complex 3D surfaces, follow their shapes, and perceive their minute local anomalies," geoscientist Chris Harding of Iowa State University writes.

Bewildering data sets are common to more disciplines than geology. Particle accelerators and satellites plunging into the atmosphere of distant moons keep physicists busy. Data about the genome and the many thousands of proteins keep biologists neck-deep in information. If these mountains of data are a challenge for experts, they probably seem insurmountable to students. Currently scientists and policymakers are concerned that too few students in the United States are choosing careers in the sciences. One reason may be that while science is about the real world, it often includes realms not directly accessible to our senses, making science education seem abstract and dry.

The need for direct sensory experiences in education became clear many years ago to Seymour Papert, the pioneering educational theorist and mathematician. When he was a child, Papert played with gears. As one gear turned, its teeth catching those of a larger gear, he could see and feel that the second gear turned more slowly than the first. "Gears, serving as models, carried many otherwise abstract ideas into my head," he wrote in his 1980 book *Mindstorms.* Papert found that the actions of gears helped him understand differential equations, and the pleasure he experienced working with gears transferred to math. Each equation, he wrote, felt like "a comfortable friend." Working with his hands had helped him into the world of abstract ideas because it connects with what he calls "body knowledge." Grasping the gear, he could feel it turn, could "*be* the gear." This gave him both an affection for the gear and an intuitive sense of how it works.

Something like this was the case for the young Thomas Massie. Building mechanical arms taught him how difficult it is to direct the motions of several mechanical pieces so that the hand would move from one specific point to another. The solution, he was delighted to learn, was trigonometry. Trig's formulas gave him the tools and language he needed to guide mechanical arms. Abstract mathematics, he learned, could describe and even control concrete experience.

Papert loved gears, but he saw their limitations. Such physical machines can help a person learn only a few concepts. A quarter century before Massie, Papert believed computers, using on-screen images and programs, might allow children to explore many different concepts. In those days haptic interfaces with the computer were not available. Now, with haptics, people may be able to draw on the power and flexibility of computers while having hands-on experiences like those that helped Papert understand and love differential equations.

An early example of just such an application is a haptics-enabled program for teaching physics that uses the power of computers without losing the sense of touch. Robert Williams and Meng-Yun Chen of Ohio University and Jeffrey M. Seaton of NASA Langley Research Center designed software for use with inexpensive, low-resolution force-feedback equipped joysticks typically used with video games. These allow students to feel the effects of forces studied in high school physics. For example, forces carried by diagonal braces on bridges can be broken down mathematically into horizontal and vertical vectors. In real life, these vectors cannot be felt separately, but the program can give the student a sense for the relative strength of the forces pushing down or across. In addition to the bridge demonstration, the program can simulate forces involved with pulleys, balls bouncing off paddles, boats being towed, and bullets striking boxes. As students get a feel for these forces, varying the mass, elasticity, and initial velocity of objects, the computer keeps track of their changes and graphs them, allowing them to observe patterns, taking advantage of the computer in yet another of its thinking tool capacities.

Biology has also discovered haptics. Scientists study how proteins fold because understanding alternative conformations can help them understand problems like Mad Cow disease, which involve misfolded proteins. They also want to understand what proteins will be made by a gene and to predict how gene mutations might lead to misshapen proteins and possible disease. DNA guides molecular machinery to string amino acid molecules into long chains. Each amino acid is made up of atoms with different properties. For example, they have different electrical charges, so that when two positively charged atoms come close, they repel each other like the two north ends of magnets. Opposite poles attract. Another important characteristic is how molecules react to water. Some amino acids love it and are attracted to it. They are hydrophilic. Hydrophobic molecules, by contrast, hate water and avoid it. These and other related factors determine how the chain of amino acids will fold into a protein's working form. Once folded, these properties along with the shape of the overall protein determine what it does in the body.

One scientist working with protein folding seems to physically embody, as Papert embodied gears, the proteins she studies. The scientist, Catherine Drennan, reacts strongly when she watches students who are using computer simulations without haptics force proteins into impossible arrangements. Natasha Myers, a Ph.D. candidate at MIT studying the sociology and anthropology of science, describes Drennan's body language. "As she tells the story [of students getting conformations wrong] she contorts her entire body into the shape of the misfolded protein. Arms bent over above her head, her neck crooked to the side, and her body twisting, she expresses the strain felt by the misshapen protein model." She actually exclaims, as if in pain, when students force proteins into incorrect positions.

This feel for the proteins is something she's acquired through years of working with them. As she learned about the forces between atoms, she started to imagine she could actually feel these forces. As a result, working with the molecules felt tangible. Perhaps this is what keeps her interested in something that may seem abstract to novices. Haptics might allow them to feel those forces, and even feel them more precisely than Drennan's imagined forces. Haptics may make the abstract realm of proteins tangible, allowing students to enter more quickly the world of complex molecules as experienced by experts. Once they have a feel for the field, by Papert's reasoning, they might be more likely to enter it. Based on this premise, several researchers at labs around the world have developed prototype systems for simulating the forces in complex molecules.

These uses of haptic technology promise to make the abstract and arcane worlds of experts accessible to beginners. The effect may be not just greater understanding, but also, according to Papert, an emotional attachment that could provide students the motivation to become scientists.

While haptics in education may help make science accessible to more people, Thomas Massie's goal at SensAble was to give people the ability to design new virtual objects that could be manufactured in reality. Right now toy companies use Phantoms to design the next generation of movie tie-ins. Consumers go to Wal-Mart and buy the toys that others had all the pleasure of designing. Massie's goal was for people to be able to go to Wal-Mart and buy an inexpensive but still high quality Phantom packaged with design software. Those with sculpting talent, which Massie thinks is about half of the thousands he has demonstrated the tool to, could immediately start making their own toys, jewelry, and even machines. Those without natural ability would be able to use 3-D clipart to design their own products. Once finished, the designer would click a button to email the design to one of the already existing so-called rapid prototyping services that in just a few minutes could create intricate plastic shapes that snap together to make the finished object. Rapid prototyping machines can even make working gear trains that are already assembled.

Massie spent two years working toward this goal, overseeing development of the software, designing a new Phantom that could be manufactured for less money, even traveling to China to find a good manufacturer. It had been years since he had spent so much time working with his hands, feeling the direct satisfaction of creating something. Massie says this was the best time he'd had since founding the company seven years earlier. He had 1,000 of the inexpensive Phantoms, called Omnis, manufactured and had produced easy-to-use software including a 3-D "printing" service. He used the software to carve and print gargoyle figurines. An employee sculpted an elegant engagement ring and had a wax mold rapid prototyped. That mold was used to cast the ring in platinum. Massie calculated that a person could design a silver pendant with intricate filigree and have it made for about the cost of a DVD movie.

The system was ready to ship. The company even had the boxes and packing peanuts ready. At just that moment Massie walked away. He quit the company, sold his shares, and moved his family to Kentucky, to within a few miles of where he grew up. He cut himself off from the field of haptics, and now works with his hands in the old-fashioned way. He's building himself a timber-framed house.

Why did he leave? On the face of it, Massie left because of a serious disagreement between him and the company's other leaders over the direction SensAble ought to go. He was ready to push ahead immediately, but others thought the cheaper device would undercut profits from their high-end Phantom. They would have to sell a huge number of Omnis to make the company profitable, and Massie's critics cited market research that suggested hobbyists wouldn't buy unless the price was as low as $300. That would be just half the price they could currently offer. Furthermore, switching from high-end sales would mean most of those in the marketing department would lose their jobs. They were geared for wining-and-dining sales to company executives, not mass marketing to consumers.

Massie, on the other hand, believed the future of the company was in sales to hobbyists. It was time to let ordinary people, not just professionals, into the world of haptics. He believed that if people are willing to pay $500 for art software like Adobe Illustrator, they would be willing to pay about the same for a package of software plus the Omni Phantom. He argued. He took a sabbatical hoping the company would come around. But, as he confessed after the dust had settled, he left because he felt he was getting nowhere with his business colleagues.

According to SensAble CEO Curt Rawley, however, the company had and still has every intention of going forward with Massie's mass-market vision. Although some in the company wanted to go only with high-end sales, Rawley says the question was not if, but when, they would be able to sell to hobbyists. Rawley believed they could eventually bring prices down to a range that their market research suggested would sell, and saw this happening over several years. Indeed, since Massie left, the company has started selling the Omni with software for $2,750, an eighth of the cost of the regular Phantom. They have also sold the Omni with a software developer package for just $800, hoping to entice people to write more software for the device. According to Rawley, they continue to work to bring costs down.

This gradual transition to selling cheap Phantoms was the plan Rawley proposed at an off-site meeting that sent Massie packing. Rawley believes Massie left because "Thomas was in a hurry." He also thinks Massie overestimated the potential success of the Omni, and discounted the risks, because of Massie's own love of working with his hands. "He called a lot of shots right. But Thomas is also an engineer at heart. So he loves building things. And so he is very disposed to provide a toolset so that other people can build things. He really has that in his core."

Massie left SensAble, arguably, just when his goal was within sight. Rawley's explanation, that Massie left because of impatience due to over-optimism about the Omni, might be enough to explain Massie’s departure, if it weren’t for one detail that goes beyond company politics. Rawley knew something of what Massie was leaving, but little of what he planned to do. When I asked Rawley what he thought of Massie's current projects, he said, "The only thing I've heard about is putting in roads, building a garage, basically getting on with life in eastern Kentucky." But he suspects Massie is up to something more, "I said, 'So, what are you doing in the garage, Thomas?' But he won't tell me. That's okay. He will some day."

I've been to that garage. It does not contain a secret new project for developing haptics. Instead, it's full of twelve-foot wood beams that

Massie is cutting and chiseling for his new house. Massie left SensAble to go work with his hands. He exchanged simulated touch for the real thing. Was he repudiating haptics? And if so, why?

If Massie's faith in haptics had been shaken, it might have been for good reason. Along with its promise, haptics brings many questions. Ordinarily, for example, touch seems to be a reliable sense. People have seen mirages and even heard voices, but they pinch themselves to be sure they aren't dreaming. Oliver Sacks, the famed neurologist, recounts stories of people who, having lost the ability to feel an arm or a leg, insist that it be amputated, so forceful is the feeling that the arm does not belong to them even though they can *see* it is attached. In these situations the solid sense of touch overrides sight. In haptics-based illusions, however, sight can actually take over. In Massie's first demos while at MIT, the device was not yet well-calibrated. On the screen viewers would see a cube. But the end of the stylus, instead of following a straight path along a side of the cube, followed an arcing path, as if the sides of the cube were curved like a shallow bowl. No one noticed the curve. What they saw on the screen blinded them to what they felt. Touch had ceased to be a reliable indication of the true shape of the virtual object. One of the first questions raised by haptics is whether we can really rely on what has seemed to be the most reassuring of senses.

The Phantom does not only allow people to feel simulated objects, it can also, as the example of the transatlantic touch shows, allow people to seem to feel other people over the Internet.

"Gone may be the days when you can insult another person over the Internet without fear of retribution, or argue with your spouse that cyber-sex doesn't really count as cheating" one web-based columnist wrote, only half tongue in cheek. Joel Jordan, one of the scientists involved in the transatlantic experiment confirmed that the Phantom can indeed do damage, "There are certainly strange aspects to this," he said of the transatlantic touch. "You can hit each other hard enough to leave little bruises, and there are bigger versions of the equipment we're using which could really cause some damage." Relatively easy software fixes could put limits on the force of the device, but this would compromise performance. People who use the Phantom and other devices will need to develop some ground rules for using the new technology.

Similar lists of rules, called "netiquette," are already being worked out by online communities. These rules address things such as the language people should use in certain chat rooms and what sorts of discussions are permissible. Since friendly encounters on the Internet can heat up into romantic relationships, some online groups grapple with questions about what sort of online behavior counts as infidelity. Jim Thomas, a professor of sociology and criminology at Northern Illinois University, cites online conversations in which people try to sort out new boundaries. Many of the discussions turn on the importance of the physical. While some believe that "all forms of internet sex" should be considered cheating, others believe that "in order to be cheating you need to be with that person physically." With haptics, this distinction is no longer clear cut.

So far, SensAble does not market the Phantom as an Internet sex toy, but other companies with rather simpler equipment have. This new market has a name—teledildonics. As the name suggests, the devices are dildos, and more recently, artificial vaginas, that can be controlled over long distances via the Internet. Entrepreneurs have been attempting teledildonics for decades now. Early attempts ranged from complex dentist-chair sized machines to urethane body suits equipped with electrical stimulators that seem vaguely dangerous. Those didn't catch on, but a more recent product, called the Sinulator, has received rave reviews. The first version featured a control panel that one commentator likened to a toy car dashboard. A more recent version looks like a television remote control. It sends signals via the Internet to one of a variety of electromechanical toys for both men and women. The product is marketed as a way for loving couples to stay in touch while physically separated, but other uses are not hard to imagine.

Howard Rheingold, who wrote about the field as early as 1991, sees future teledildonics as a vehicle for new and wonderful experiences of sexuality. Instead of being limited to select areas of the body, he imagines whole body experiences. A suit using "ultra tiny vibrators," he wrote, would be so realistic that you could "run your cheek over (virtual) satin and feel the difference when you encounter (virtual) human flesh." He expects a person will be able to find "one partner, a dozen, a thousand" and interact with them "in ways humans have never before experienced." While he seemed generally excited about the prospects he does wonder about where it all could lead. "If you can experience sexual frissons or deep physical communion with another person with no possibility of pregnancy or VD, what then of conventional morality?"

If haptics can confuse moral boundaries, it can also blur the boundaries between people and machines. If movements can be detected by a machine, broken down into bits and transmitted, they could also be recorded and played back later. Parts of these recordings could be mixed or incorporated into a computer program. The result could be that the person you think you're feeling is really a machine.

Haptics smudges the line between human and machine in other ways. When I tried the Phantom, it was as if my hand reached through the device and into the computer. As it turns out, this feeling of having my reach extended by a tool just calls attention to something that has long been true for humans. Our brains contain maps of our bodies, maps that can be altered by experience. A concert pianist has more of her brain devoted to mapping her fingers and arms than do most other people. This map, however, can be altered in even more radical ways. According to Chris Moore, a neuroscientist at MIT specializing in the sense of touch, the brain can also map tools people use frequently, incorporating them into the body.

The remarkable case of Steven Sharp illustrates the brain's adaptability. In 1992, a malfunctioning hay baler pulled off both of Sharp's arms. When his wounds had healed enough, he began to practice with a prosthetic—a simple machine attached to the stump of one of his arms. He taught himself to throw a bean bag and catch it. Sharp changed a flat tire by himself using that prosthetic. He learned to move a cigarette, burned all the way to a column of ash, from place to place, leaving the delicate column intact. His handed friends tried and failed to do this, though he insisted they could if they would just practice. Sharp even shot a bear in self-defense and skinned it with a pocket knife grasped between the prosthetic's hooks. Immediately after his accident, Sharp had experienced the world as if it were behind a pane of glass. Once he got his prosthesis he could reach into the world. The prosthesis became mapped into his brain as if it were a real arm.

The Phantom is a similar kind of extension, removing the glass wall of the screen to let users reach into the computer and all that it may hold. Like Sharp's mechanical arm, the Phantom blurs the line between human and machine, but more recent work by haptics researchers is making that line disappear. Part of the effort to understand touch involves understanding how the brain directs hands to actively explore objects. As part of this work MIT's Srinivasan, working with Miguel A. L. Nicolelis of Duke University, designed a mechanical arm that a monkey can control just by thinking about it. Nicolelis opened the skulls of owl monkeys and implanted thin wire electrodes. These pick up signals of neurons firing in the brain and transport these signals to a computer, which translates them into directions for a mechanical arm. The monkey, just by thinking, can move the arm. It can also move an identical arm at the same time 600 miles away, linked to the monkey by the Internet.

Andrew Schwartz of the University of Pittsburgh has accomplished a similar feat, only his system reads the monkey's brain so accurately that monkey can use the mechanical arm to feed itself. In a video, the monkey looks relaxed. The motions of the robot arm are remarkably smooth and lifelike.

Early this year, researchers implanted similar electrodes in a human volunteer, Matt Nagle, who had been paralyzed by a stab wound. This system, developed under the direction of John Donoghue of Brown University, is much more rudimentary than the monkey system, and can do nothing Nagle couldn't have done with voice commands or by controlling something with his mouth. But he can direct a cursor on a computer screen, and even draw a rough circle, just by thinking about it.

So far these are one-way set-ups. The monkeys can move the arm, but cannot feel anything with it. Andrew Schwartz looks ahead to a day when sensors on the fingerpads of the mechanical arm can transmit touch-like sensations directly to the touch- and body-sensing areas of the brain. Someday an amputee might be fitted with a new arm, complete with a fully articulated hand and a sense of touch.

As machines become more human-like, humans seem more obviously to be machines. One clear distinction remains, however, between the human machine and the Phantom. The human hand touches the real world, the Phantom reaches into a simulation. Yet brain research suggests even this distinction is not so clear-cut. Our brains constantly simulate the world. They even simulate the body. Immediately after Sharp's arms were pulled off in his accident, he tried to grab a handle on the tractor and drive himself home. He thought he felt his arms reach out. He even sensed the cold of the metal handle in his hand. But of course his arms were not there. He lost his balance and fell to the ground.

Neurologists believe that people with injuries like Sharp's are fooled by simulations that the brain normally manufactures. These simulations predict what the arm and hand will do and what they will feel. It knows how the hand needs to move to reach a target, how it can avoid an obstacle on the way to the target, what position the fingers need to be in to grasp an object, and what the fingers will feel as they grasp it.

One reason to simulate the action ahead of time is to avoid problems with signal delay—the time it takes for a message to go from the brain to muscles and from sensor cells to the brain. This is the same sort of problem that happens when a slow computer doesn't respond quickly enough to clicking on a button to scroll down a page. I keep hitting the button and at first nothing happens. Eventually the screen starts to scroll, but by now I've hit the button too many times, and the screen scrolls past the place I'm looking for. So I start hitting the button to scroll back up. Once more, nothing happens for a while, so again I click too many times. I overcorrect. After a few tries at this, I learn to slow down to let the computer keep up.

The pattern of overshooting and overcorrecting is similar to what would happen if the motion-planning areas of the brain did not work. Under those neurologically flawed conditions, after the brain tells the hand to move toward an object, say an apple, it would wait for a signal that the hand has felt the apple. By the time this signal reaches the brain, however, the hand would have pushed past the apple. The stop signal comes too late. By the time the brain sends the signal to stop, the hand is too far out. The brain tries to send the hand back toward the apple, with the same results. Just as I adapted to the slow computer by slowing down my own clicking, people who lack a well-trained motion planner in their brains would slow down. They would also tend to move jerkily, like a poorly built machines. This is partly why babies, with little motion-planning experience, flail their arms about. With practice, their brains learn better hand-eye coordination.

Once the motion planner is well-trained, it informs relevant parts of the brain to signal the arm to move a certain distance and to expect to feel an apple. But rather than wait for the sensation of the apple to get back to the brain to start the next step, the planner has already sent a signal telling the fingers to close around the fruit at the expected time.

So, what happens if the wind gusts, moving a branch holding the apple, and the hand closes on nothing? That's the second reason for the simulation—it helps the brain learn. The cerebellum compares the simulated sensations with the actual sensations, notes the problem—no apple—and makes adjustments. It might have the eyes watch out for the branch swaying, and if it is, the brain might slow down the movement enough that the signal delay isn't a problem.

Not only is the arm a machine, like a Phantom-equipped computer the brain is continually simulating reality. In Sharp's case, not only did he feel as if his arms were still attached, his motion planner's prediction made him believe he felt the handle with his hand. The Phantom was strange to use because it made a computer simulation feel real. Even stranger is the prospect, based on sound neurological understanding, that our own brains are simulating the world, and that sometimes these simulations can be mistaken for reality. The most reassuring sense, then, is not always a way of firmly grasping reality.

Perhaps the line between flesh and machine can no longer be consistently drawn. Researchers have discovered the mechanisms of touch. The sensations we feel through our old-fashioned flesh and blood arms are actually sensations fed to our brains by an exquisite chemical, mechanical, and electronic machine. It is alive, to be sure, but a machine nonetheless.

Nothing could seem further from the high tech world of haptics than Thomas Massie's farm in the hills of Kentucky, the place he had escaped to when he quit SensAble. I drove my rental car up the gravel lane, mud splattering the sides. I had come to get a better understanding of the man who left a pioneering enterprise just when it seemed poised to fulfill his dream for it. The sky was gray with clouds that had just dropped damp snow on the steep hillsides, creating a high-contrast image of black trees against white slopes. The road ran along the bottom of a steep, narrow valley known locally as a holler, spelled hollow. I drove past cows—red Limousin, white Charolais, and one black Angus bull. The car grumbled along the gravel past barns, work sheds, and a pile of junk including doors from an old Volvo. Then it rattled over a cattle guard made of wood planks set on edge.

Massie's house, a double-wide trailer finished to look like a permanent home, stood a few dozen yards up the slope from the road. He greeted me at the door with a slab of Kentucky twang and a slight smile to match mine. "You must be Kevin." Massie is 34 and looks older than he did in the video of his engineering contest win. But he still looks younger than his years, definitely too young to have retired. He wore jeans and a t-shirt and sturdy metal-framed glasses. He looked like he'd be more at home in the halls of MIT than here in the woods.

I reached for his hand but he flung his arms wide. For a split second it felt like an affront, as if he did not want to touch this journalist until he was sure I could be trusted. But he explained. He was just recovering from being sick, and his whole family had some sort of a bug. I'd be staying there that night, and he wanted to keep me from coming down with it.

And so it was that I had no physical contact with the man who had enabled transatlantic touch. Maybe we could have used a pair of Phantoms.

That evening Massie gave me a tour of the woods and ridges of his farm and Rhonda treated me to smoked pork they had raised and a delicious berry-covered dessert their son called a cheesepie. The next day he seemed fully at home here in the woods. He put on his WoodMizer hat—he has three, given to him after he bought a portable sawmill from the company—and he pulled on tall, camouflaged boots and a pair of safety chaps. That day his slightly worn and scraped fingers grasped fraying logging cables and chisels for stone and solid timber. He felt the side and end grains of the foot-wide wood beams that will become the frame of his new house. He showed me how to turn the end of a beam into a tongue of wood called a tenon that would later slip securely into a mortise. He checked my work with his fingers. "Feel this. It's still raised here. Take it down some more."

A characteristic movement: his controlled, quick throw of a sharp, weighty arm-length chisel against a corner of a tenon, rounding the edge to help it slide more easily into the mortise. At night I watched those same fingers fly on the banjo he's been teaching himself to play.

At the end of the day's work we look up out of the wide doors of the shop. He points out the poetry of it: the finished beams on sawhorses in the foreground, the doorway, itself made of timbers, framing a hillside strewn with logs felled in a major ice storm, logs he'd soon pull down from the hill and transform, sculpting them into something useful.

That day, as I worked out in the woods and in the woodshop, using my hands felt reassuring in spite of what I've learned about the sense of touch. Now as I look out of the shop at the hills, my hands resting on a finished timber, I cannot blame him for wanting to leave the world of computers and simulations, wanting to come to this world of frank reality.

But Massie shows me some things that make me realize that although he has decided to leave the development of haptics to others, his life on the farm is not a repudiation of the field. In one corner of his shop he's walled in an office. Inside are a computer, with a satellite

Internet hookup and not one but two Phantoms on the desk. One, not surprisingly, is in pieces, so I have a chance to peer inside at the cables and counterweights and watch their precise and graceful movements.

Massie hands me a model of his farm, the ridges and hollers built up layer by layer in a rapid prototyping machine. He had used a Phantom and U.S. Geological Survey map to create this model, which he and his kids pour water over to watch it accumulate in a simulated creek bed that runs by their current house. Massie touches the flattened hilltop where his new house will sit overlooking a valley.

Then he opens a file on his computer and lets me feel the turret of his new home rendered in virtual clay.

I remember the way he built his robot arms, looking at his hands, at his tendons moving under the skin, trying to make something like them, and in the process learning more about how his arm works. A similar process is at work here. He has imagined the house he is building, used the computer and haptics to make it solid, to help him understand how he can build it. This vision gets in his head so that when he is out on the hills pulling in the logs, he sees not just logs but the potential posts and beams. For Massie, the Phantom and the chisel are not elements of two different worlds, the high tech and low tech. They both are tools for feeding his imagination and making it reality.

If anything is typical of humans, it is using tools to transform the world, whether those be hands or computers. Our brains are amazingly adaptable. It might not matter whether the tools were part of the original biological kit or are machines used so often that they become as truly wired into the brain as if we had been born with them.

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