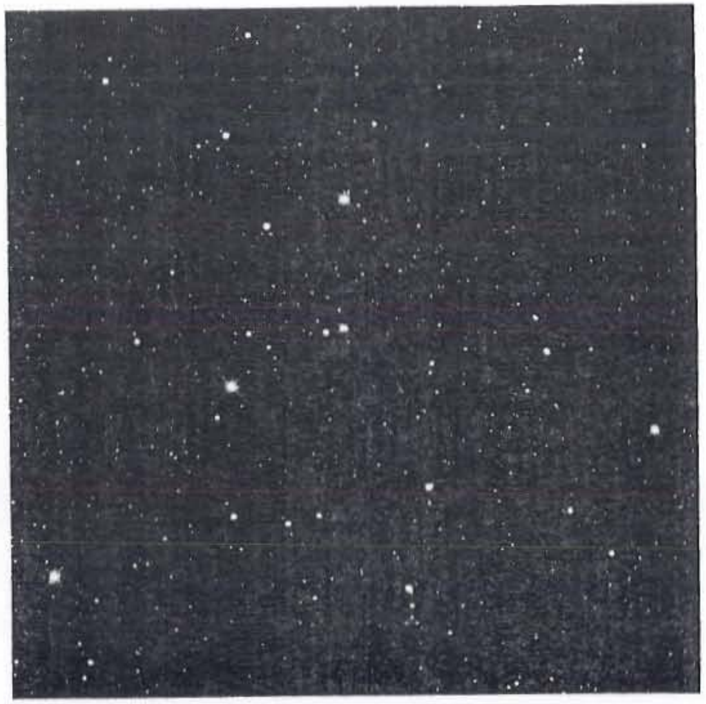
To express the same idea in still another way, I think that human knowledge is essentially active. To know is to assimilate reality into systems of transformations. To know is to transform reality in order to understand how a certain state is brought about. By virtue of this point of view, I find myself opposed to the view of knowledge as a copy, a passive copy of reality. In point of fact, this notion is based on a vicious circle: in order to make a copy we have to know the model that we are copying, but according to this theory of knowledge the only way to know the model is by copying it, until we are caught in a circle, unable ever to know whether our copy of the model is like the model or not. To my way of thinking, knowing an object does not mean copying it—it means acting upon it. It means constructing systems of transformation that can be carried out on or with this object. Knowing reality means constructing systems of transformations that correspond, more or less adequately, to reality. . . . Knowledge, then, is a system of transformations that become progressively adequate. . . . But let us ask what logical and mathematical knowledge is abstracted from. There are two possibilities. The first is that, when we act upon an object, our knowledge is derived from the object itself. . . . But there is a second possibility: when we are acting upon an object, we can also take into account the action itself, or operation if you will, since the transformation can be carried out mentally. In this hypothesis the abstraction is drawn not from the object that is acted upon, but from the action itself.

—Jean Piaget, *Genetic Epistemology*

STARS

Mitchel Resnick



When I was growing up in a suburb of Philadelphia, there was a small field on the side of our house.[1] On summer evenings, I would go to the "side lot" (as we called it), lie on my back, and stare into the sky. My eyes would dance from star to star. But it wasn't so much the stars that held my attention. Rather, it was the space between, around, and beyond them. At an early age (maybe seven or eight), I had started to wonder about all that space. Does it go on forever? If not, where does it end? How does it end?

Every answer that I could think of seemed equally absurd. I could not imagine the universe going on forever. But how could it end? If there is a wall at the end of the universe, what is on the other side? These questions frustrated and fascinated me. Of course, I came across many other questions that I couldn't answer. But for most questions, even if I didn't know the answer, I could at least imagine that there *was* an answer. Questions about the "end of the universe" took on a special status for me. These were questions where I couldn't even imagine any answer. No answer seemed possible.

As I grew older, I became interested in puzzles and paradoxes. I spent many hours trying to sort out the sentence: *This sentence is false.* If the sentence is true, then it must be false. But if it is false, it must be true. Again, a puzzle for which I couldn't even imagine any answers.

In school, I was attracted to math and physics, two fields filled with paradoxes and counterintuitive ideas. I became fascinated by an object that my high-school physics teacher showed us. The object was remarkably simple: two wheels and an axle, with a pin hanging down from the middle of the axle (not quite hitting the ground), and a string at the end of the pin. The teacher asked: What happens when you pull on the string? Since the string is attached to the end of the pin, it seems that the pin should come toward you. At the same time, it seems that the wheels should come toward you. Both can't be true: if the pin comes toward you, the wheels move away; if the wheels come toward you, the pin moves away. Another paradox! But this object was different from the stars of my childhood: you could hold it in your hands and test it out. Indeed, I went home, took apart an old toy truck, and made my own version of the puzzle, testing pins of different lengths. Even after I "knew" the answer, I loved tugging on the string and thinking about the paradox.

In college, majoring in physics, I was determined to develop a better understanding of what I now thought of as my Ultimate Paradox—the paradox of a universe that can't go on forever but can never end. In physics courses, I learned how to derive and manipulate the equations of general relativity, the field most directly related to my paradox. It wasn't the equations that really interested me, they were just a foundation, a jumping-off point, for thinking about the paradox itself. I tried to approach it through new thinking strategies, through new intuitions and metaphors: I learned that the universe might curve back on itself, just as the land on Earth curves back on itself as you travel all the way around the globe. But what does that mean? How can three-dimensional space "curve back on itself"? How could I envision that? How could I "feel" that?

During college, I had planned to attend graduate school in physics. But at the end of senior year, I decided to work as a journalist instead. I worried that physics graduate school would be filled with too many equations and too few qualitative insights. I was still fascinated with the mysteries and paradoxes of science. I hoped that as a journalist, specializing in science and technology, I would be able to share my fascination with others. For five years, I covered universities and high technology companies around Boston and then Silicon Valley. I enjoyed my work, but something was missing. I didn't feel the same level of intellectual excitement that I had felt in college. I had lost contact with my obsession. I began to recognize the importance of having obsessions.

Then, in 1982, I wrote a cover story for *Business Week* magazine about research in the field of artificial intelligence. I talked with many leading researchers in the field. I became increasingly interested in questions about the mind. How can a mind emerge from a collection of mindless parts? It seems clear that no one part is "in charge" of the mind (or else it too would be a mind). But how can a mind function so effectively and creatively without anyone (or anything) in charge?

At last, I had a new Ultimate Paradox, a new obsession. I wasn't so much interested in the details of neuroscience, or even in traditional research in artificial intelligence. Rather, I wanted to develop qualitative ways to think about the idea of emergence. I became interested not only in minds but also in other systems in which complex patterns emerge from simple interactions among simple parts. I became particularly interested in natural selection and evolution, hoping to gain a better understanding of how today's sophisticated life forms evolved from a few simple chemicals. For me, there was something intriguing and beautiful about this self-organized emergence of order from disorder, of complexity from simplicity. I developed an emotional investment in this idea. Few things got me more upset than listening to creationists attacking the idea of evolution, attacking the idea that complexity can arise from simple pieces.

Around this time, I came to MIT for a year as a Knight Science Journalism Fellow. During the year, I studied with Sherry Turkle, who studied the emotional power of things we think with, and Seymour Papert, who described how a particular object, gears, had changed his way of thinking in childhood. Papert had fallen in love with gears and, in the process, with mathematics.[2] Most important during that year was the way I came to see the computer in a new light. For me, the key insight was not that the computer itself is an evocative object (although surely it is for many people), but rather that the computer can be used to *create* evocative objects. And those new evocative objects could be used to help people learn new things in new ways. In designing the Logo turtle, for example, Papert had explicitly attempted to make an evocative object to help students become engaged with mathematical ideas and mathematical thinking. Just as the young Papert had fallen in love with mathematics through gears, children could now fall in love with mathematics through the turtle.

The idea of creating evocative objects for educational purposes is not a new idea. When Friedrich Froebel started the world's first kindergarten in 1837, he carefully designed a set of physical objects—blocks, balls, beads—that became known as Froebel's gifts.[3] As children playfully experimented with Froebel's gifts, they learned important ideas about number, shape, size, color. This approach has stood the test of time, and it continues as the basis for kindergartens around the world today.

The computer provides an opportunity to expand Froebel's approach, making possible a wider and more diverse range of evocative objects for education. I felt a new sense of mission: I could use the computer to create evocative objects for exploring my new Ultimate Paradox, the paradox of a complex whole arising from simple parts. I wanted to create objects that would enable me to explore the paradox, but also to help others explore it as well. I decided to use Papert's turtle as the basic building block. But instead of a single turtle, I created thousands of turtles. And I developed a new language, called StarLogo, that enabled students to program each of the individual turtles, then observe the patterns that emerge from all of the interactions.

Students have used StarLogo to explore a diverse range of phenomena. They have turned turtles into birds to explore how flocking patterns arise; into cars to explore how traffic jams form; into ants to explore how foraging patterns emerge; and into buyers and sellers in a marketplace to explore how economic patterns form. It has given me great satisfaction to see students become engaged with my Ultimate Paradox. For some, it has become an obsession, as it was for me.

Over the past twenty years, my research has continued to revolve around the creation of evocative objects for education. Working with the LEGO Company, I've embedded electronics inside LEGO bricks, so that children can make their LEGO constructions come alive—sensing, reacting, and even dancing with one another. I aspire for these "programmable bricks" to serve as a Froebel gift for the twenty-first century. Just as the stars of the night sky inspired, intrigued, and provoked me as a child, my hope is to create new objects that help others find their own obsessions.

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