TECHNOLOGY and POWERFUL ideas

The real value of computers is in helping us understand the powerful ideas that force us to change our ways of thinking

BY ALAN KAY

PHOTOGRAPH BY AARON GOODMAN

A few years ago, researchers from the National Science Foundation (NSF) decided to visit a Harvard commencement and ask questions of the graduating seniors and some of the faculty. The questions had to do with simple, observable scientific phenomena—what causes the seasons, for example, or the phases of the moon. Of the 23 graduating Harvard seniors, 21 had serious misconceptions about both the seasons and the phases of the moon. NSF researchers made a video of this little experiment and used it to show how common scientific misconceptions are, even among educated people.

When I first saw this video, I kept waiting for the researchers to ask what, to me, was the obvious next question. They never did, so I tried the same experiment with a group of graduate students at UCLA. I went through the same routine questions, and I got roughly the same results: About 95 percent had serious misconceptions about the seasons and the phases of the moon. Most of them thought the seasons were the result of the earth's elliptical orbit—when we're closer to the sun, they said, it's summer, and when we're farthest away, it's winter.

But then I asked the question that NSF hadn't asked: "When it's summer in North America, what season it is in South America and Australia?" Everyone knew the answer was winter. Then I just waited while it slowly dawned on them that the change in seasons could not possibly be caused by a change in distance from the sun. (In fact, the earth's tilt on its axis causes the seasons.)

The same thing happened with phases of the moon. Most of the people thought the phases of the moon were caused somehow by the earth getting in the way between the sun and

Alan Kay is a Disney Fellow and vice president of research at Walt Disney Imagineering in Glendale, Calif.

the moon. That, of course, is what happens in an eclipse of the moon. (The phases of the moon have to do with the relation of the sun, earth, and moon; depending on where the moon is in its orbit, one sees more or less of its illuminated half.) So I asked the graduate students, "Well, have you ever seen the sun and the moon in the sky at the same time?" And of course, they all had, and there was another pause while they came to the realization that their theory didn't stand up.

What this little experiment shows is not a crisis in science education. In fact, this is not a science problem at all so much as it is a problem about thinking processes. All of these people knew something that contradicted the theory they were forming, but they couldn't get at that knowledge because it was in a different compartment, as it were.

We all have many private universes inside our heads, and one of the biggest problems humans have faced over time is our inability to connect these separate universes of knowledge into a coherent whole. It is an especially challenging problem now, with the rush to "technologize" education. If we don't find ways to help people learn to make connections, all the school technology we're pouring money into will wind up as no more than vocational training, with no real education attached.

The power of stories

One way of looking at the problem is to use an image created by Arthur Koestler, a great novelist who became a cognitive scientist toward the end of his life. What usually happens when we're trying to think about things, he said, is that we tend to stay within a certain belief structure. Imagine that belief structure as a level plane. We could move vertically in our thoughts, but in fact, there are powerful forces that keep us focused on the task at hand, focused on the ideas we've already had and on the way we learn those ideas. Every time a vertical thought breaks out of the plane, it usually is quashed.

But every once in a while when we're relaxed and out of the normal context of "work"—maybe in the shower, maybe just back from jogging, maybe dreaming just before dawn—suddenly one of those vertical thoughts breaks through, and we see that what we had been thinking about could be looked at in a completely different way.

Koestler calls this bisociation; educators call it nonspecific transfer. Educators know it is extremely difficult to teach children something in such a way that they will be able to apply it in a domain that is analogous to but not the same as the domain in which they learned it. Children are quite good at finding analogy if you tell them one exists, but most of them have no inner mechanism that causes them to look for similarities and analogies, to jump out of the plane when they're thinking about something and make a connection across planes.

That presupposes other planes to connect to, of course. In other words, you have to have lots of different kinds of knowledge learned in lots of different kinds of ways in order to have something to make analogies to and cross-connections to (which is one reason general education, as opposed to vocational training, is so important). And you have to *learn* to make cross-connections, because it doesn't seem to be built in naturally to the way humans think about the world.

Instead, as the NSF experiment shows, kids are learning science and most other subjects the way people learn proverbs: It doesn't matter if one contradicts another so long as it explains the phenomenon at hand. If you come home from a trip and your significant other is glad to see you, the explanation is, "Absence makes the heart grow fonder." But if you come home and your significant other is not particularly happy to see you, the explanation is, "Out of sight, out of mind."

Oral societies want to rationalize what is happening right now, and they do it with a little story called a proverb. When one proverb contradicts another, it doesn't matter—just as it doesn't matter that the movie you liked last night contradicts the movie you liked last week. The important thing about stories is how good they are right now. Stories happen in the here and now; they create their own environment. Even when they purport to be about general knowledge, what really matters is how well they satisfy the listener.

Most of us, including scientists, learn best through stories. We are wired to learn this way because, for hundreds of thousands of years, the most important ideas of our culture have been passed along through stories. In fact, cognitive psychologists know we are predisposed to judge a statement as being more true if it rhymes.

Other ways of thinking

Over the last thousand years, however, other ways of thinking have been invented. One is mathematics. Although other ancient cultures had ways of numbering things and thinking about patterns, it was the Greeks who took an unfocused, unstructured discipline and turned it into a separate way of thinking. One of the most important things about the Greek invention of mathematics was that it was not simply about demonstration: It also involved contradiction and argument.

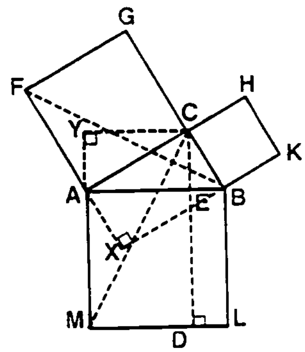
More recently, beginning in the 17th century, a third way of thinking evolved in sci-

WE ALL HAVE MANY PRIVATE UNIVERSES INSIDE OUR HEADS. THE PROBLEM IS OUR INABILITY TO CONNECT THEM INTO A COHERENT WHOLE.

38

ence and politics, one that can be called ecological thinking or systems-level thinking.

Our country was built on these new ways of thought. Consider Thomas Paine's pamphlet "Common Sense," a 40-page reasoned argument against monarchy that exemplifies the mathematical way of thinking. "Common Sense" had a pivotal place in the creation of our country: Instead of letting the king be law, Paine said, let us make the law be king. Paine's pamphlet changed people's minds about most of what they believed about government, paving the way for yet a new way of thinking and creating an environment in which the U.S. Constitution could be written.



GEOMETRIC PROOF OF THE PYTHAGOREAN THEOREM

Diagram by Emily Mann, an eighth-grader at Mark Twain Middle School, Fairfax County, Va.

The Constitution is not a story: It is a recipe or systems description for a complicated mechanism, an ecology with millions of not completely agreeable parts—the citizens—that will work for hundreds of years without breaking. One of the great breakthroughs in human thought was to realize that it is better to let people live as much as possible according to their own dictates. Instead of writing laws or rules about how people should live, it is better to include in the systems description a mechanism for resolving disputes and misfits between different parts of the system.

As this example suggests, many of the most important things that constitute the fabric of our civilization have nothing to do with the story form. Modern science is not a story. American politics is not a story. It did not arise from rhetoric (though politicians want to revert to rhetoric); instead, it arose from an attempt to build a rational system that would work in spite of misfits.

These are very hard ideas, and that is why they were inventions.

Writing was an invention. Our species learns how to talk spontaneously—that's wired into us—but many cultures have never had a writing system. Printing was an invention. Mathematics was an invention. Democratic concepts such as fairness and justice, which we think of as the cornerstones of our civilization, were inventions. Every one of them is hard to learn, or they would not have had to be invented.

We can learn many things as children in a village culture. We can learn how to live our lives successfully. We can learn what the culture believes. We can learn how to hunt and fish and farm. We can learn a lot of things simply by watching others. But school was invented so people could learn the hard things, the things we don't learn naturally. School was invented so we could learn the created things that actually require us to change what's inside our heads, to learn what Seymour Papert calls powerful ideas.

And if that's the case, we should be thinking about technology as more than an aid to education. We should be thinking about something much stronger than that. Let me suggest a couple of ideas.

Triangles and bacteria

At the dawn of the invention of mathematics, Pythagoras and his followers found an interesting relationship by looking at a right triangle surrounded by the squares of its sides: If you draw three more triangles around the C square, it is easy to rearrange them so you can fit the A square and the B square and the four triangles into that larger square. That is, the sum of the areas of the squares drawn on the two legs is equal to the area of the square drawn on the hypotenuse. (See the figure.) This beautiful proof is what is called a preliterate proof—a highly satisfying, easy to understand demonstration, and definitely the proof children should be exposed to.

But shortly thereafter, someone used Pythagoras' theorem to come up with the astounding fact that no matter what system of measurement you use for the sides, that system of measurement will not measure the hypotenuse of some triangles exactly. In mathematical terms, we would say that there is no fraction n/m that will give you the exact length of the hypotenuse. This is not a proof that can be demonstrated; this proof must be done by contradiction and by argument.

It is said that the person who first came up with this proof was drowned because he had completely overturned the contemporary concept of rational thought. The Greeks did not go beyond "rational" numbers—that is, numbers that can be expressed as the ratio of two integers—and this proof introduced irrational numbers. (A stronger proof shows that if the square root of a number is not an integer—the square root of 4 is 2, the square root of 9 is 3, but the square root of 6 or 7 or 8 is not an integer—then it is also not a fraction, and that is true for all numbers.) You might think that with all the fractions that exist between each integer, you would be able to find the fractional number for, say, the square root of 6, but you simply cannot.

This branch of Greek mathematics, then, went a short way and ran into an intractable problem. That, I believe, is one reason the Greeks went on to become more interested in geometry than in algebra. They might have drowned the person who devised this proof, but they weren't able to drown the idea.

Now, let's turn from mathematics to biology. Consider a single bacterium like the millions we have inside us. The bacterium contains about a hundred gigabytes of information processing, about the equivalent of 50,000 desktop computers of a few years ago. Now consider that this bacterium is only about 1/500th the size of the cells that make up our body tissue, so within each cell is the equivalent of about 25 million desktop computers—about one-quarter of all the computers on the Internet. And we have between 10 trillion and 100 trillion of these cells in our bodies

The real shocker is that not a single atom in your body has been there for longer than seven years. In fact, about 90 percent of the atoms in your body are recycled every couple of weeks. For example, no red blood cells that are in your body now are more than 100 days old. As biological organisms, we are simply patterns that organize energy and matter into forms that look like us. We give off energy and matter so that the organizational pattern that is us moves along through time and space, but none of the atoms or the energy that we had seven years ago go with us. Millions of cells in our body are dying every day, but billions of things are going more right than wrong, and that's why we are able to exist longer.

These new ways of thinking are not just interesting from the scientific standpoint; they also have to do with understanding how complicated organizations, such as companies, countries, and school districts, operate. Science and math, in other words, are not just about the seasons of the year and the Pythagorean Theorem. They are about something much more interesting and much more important, and that is how we think about the world. As Danish physicist Niels Bohr put it, "Science is not there to tell us about the world; science is there to tell us about how we can talk about the world."

The uses of technology

So what, after all, are computers good for? First come a class of uses I call red herrings. For example, computers can imitate in a nicer way old structures for representing things, like paper, which gives us word processors. And with spreadsheets, computers can carry out the kinds of calculations we've done in accounting systems over the last several hundred years. Computers can also be connected in networks, giving us the equivalent of libraries.

All of these uses, I believe, represent a desire on the part of a future-shocked public to see a new technology only as a better version of an old one. This happens all the time: Thomas A. Edison invented the motion picture camera in 1895, but it took 20 years before anybody realized you could move the camera while you were filming or that you could cut and splice the film and create montages.

The same thing was true with printing. In the early years of the printing press, the Catholic Church did not think to suppress it because it seemed to be doing a good job of automating what the monks had been toiling for many years to do—producing religious texts. But within 50 to 75 years, the church was under attack by ideas spread through the printed word. First came Erasmus and Martin Luther, then Copernicus, Galileo, Kepler, Hobbes, and Newton. All of a sudden the entire world was different. The Catholic Church was no longer a temporal power; nationalism arose, and something even more striking than nationalism began to emerge: the urge toward different forms of government constructed on arguments transmitted by the press.

As we look into the future of education, we should bear two things strongly in mind. First, the computer will not always be used as it is used today, which is as a paper imitator. At some point in the future, everything we're trying to teach kids about computing today in most schools will be totally obsolete. In fact, I think it's obsolete right now, because the urge to computerize schools is 99 percent vocational and only 1 percent educational. How else can we explain such graduation requirements as being able to use a word processor or a spreadsheet?

Think about what literacy actually is. Literacy begins with *ideas*, and literature evolved as a way of communicating those ideas. Computer literacy, by extension, cannot possibly be about learning how to put a disk in a machine, and it cannot possibly be about learning a spreadsheet. Computers are really for helping us understand systems that are too complicated to think about in classical ways, such as political systems or the AIDS epidemic. They are really for letting children build models of complicated ideas and understand these powerful ideas in a direct way at a much earlier age than they would have without the aid of the computer.

THE MOST POWERFUL WEAPON WE HAVE FOR EXPLORING THIS NEW FUTURE IS THE ONE BETWEEN OUR EARS.

About 30 years ago, when we were first starting to think about how computers and education might go together, we noticed that students were not learning calculus very well. Traditionally, calculus is taught in high school in a classical form that relies on algebra. We computer people knew there was a direct way of teaching the powerful ideas of calculus to fifth-graders by using Seymour Papert's Logo Turtle program, but schools weren't using this approach. Despite many compelling presentations and demonstrations of Logo, elementary school teachers had little or no idea what calculus was or how to go about teaching real mathematics to children in a way that illuminates how we think about mathematics and how mathematics relates to the real world.

These are important issues—not because we want children necessarily to become mathematicians or scientists, but because clear thinkers understand that they cannot know everything, that they must scaffold knowledge in many different ways to put it in a representational form that can be transmitted to others. And the computer can help do that. With computers, children can play with and understand complicated structures at a young age.

It won't happen immediately, though. Over the next few years, the urge for access will dominate everything else in school technology. The push to connect schools to the information highway is taking precedence over the question of content. Most of the important ideas in our civilization are not on the Internet yet, but they are already available in free public libraries. The haves and have-nots during these coming years will not be the people who do or do not have access to the Internet. The real gap will be between those who are discerning about the information they access and those who are not—between those who use technology to help them understand powerful ideas and those who do not.

If all we do is connect schools to the Internet without considering the kinds of thinking processes students need in order to learn from the information they access, we are fooling ourselves. All the technology we put in schools is no more than the emperor's new clothes unless we attend to the content we want children to learn with the technology and the kinds of thinking we want them to be capable of at various ages. After all, the most powerful weapon we have for exploring this new future is the one between our ears—providing it's loaded. ■