The Center of "Why?"

Alan Kay

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2004 Kyoto Prize Commemorative Lecture

(adapted from the oral presentation Nov 11, 2004)

by Alan Kay

Dedicated to Yahiko Kambayashi: a wonderful human being, advancer of civilization, colleague and friend. 1943-2004

The Inamori Foundation asked us to look back into our past to talk about our motivations, inner feelings and philosophy. This has been quite a challenge! The old mechanical fortune teller in a Thornton Wilder play says: "I tell the future: nothing easier," then asks "…but who can tell the past?"

The future is somewhat easier to tell because it hasn't happened yet. We can be vague about it and still be in the right neighborhood, but the past is messy because it has happened; it is very detailed and the details all mesh together so it's difficult to make even long talks coherent because so many things have to be left out.

"I tell the future: nothing easier. But who can tell the past?"
     -- Thornton Wilder

Books and more Books

    I think the most important thing that happened to me in my entire life happened very early: learning to read fluently several years before I went to school. My earliest memories are of books. It is almost impossible to read widely and not encounter many different perspectives on the same ideas, even for childish reading. For example, one of the earliest adult books I read all the way through – perhaps around the age of four or five – was my father's copy of Edith Hamilton's Mythology. The most important part of this book (and fortunately I got to the end!) was the very last section on Norse mythology that provided an interesting comparison with the mostly Greek myths presented in the front of the book.

    For the first time I got a sense that different groups made up different stories for the same topics. More importantly, there was more than one point of view, and they could all be written down, so there was no particular reason to accept anything that was written down (or spoken) at face value; more was needed. A few years later I realized, because the word "not" could be added to any assertion, that one could say anything in language – that is: language didn't contain what was actually going on in the universe. A deeper realization came further on: there might be limitations in language itself and our ability to represent ideas and think about them that could preclude us from actually understanding the foundations of our situation.
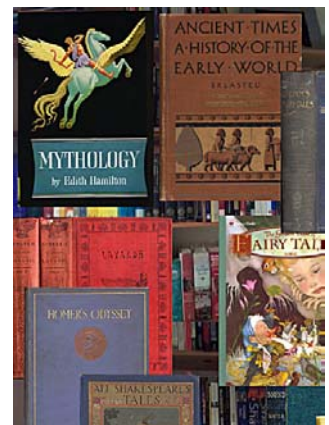

About 4 years old

Books at home were rich and interesting

The "One Book"

I had already read many books by the time I was old enough to go to school. But I was surprised to find that in school there was just **One Book** about each subject: The **Text Book** that the teacher used for the **Final Authority** for all opinions and questions. I had started first grade a year early at the age of 5 and was quite small for my age, so we can imagine a tiny child with a little high-pitched voice continually raising his hand and saying "But I read in a book that it's not what you said, but could be this way". Pretty quickly I realized that the teacher did NOT want to discuss any of these interesting ideas AT ALL. In fact she seemed to get angrier and angrier the more I raised my hand. I couldn't articulate it at the time, but it was clear that this school was not interested in ideas, especially mine. But, through books, I found that if I wanted to learn something, I could do it myself, and so school was only somewhat painful, not completely painful.


School Books were limited and boring

9 Years Old: A different view of learning.

But in 4th grade the teacher, Miss Mary Quirk, was quite different from the start. And there was something very different in her classroom. There was an old dining table towards the back on the right hand side that was completely covered with various kinds of junk: tools, wires, gears, batteries, and books.

Mary Quirk, my 4th and 6th grade teacher
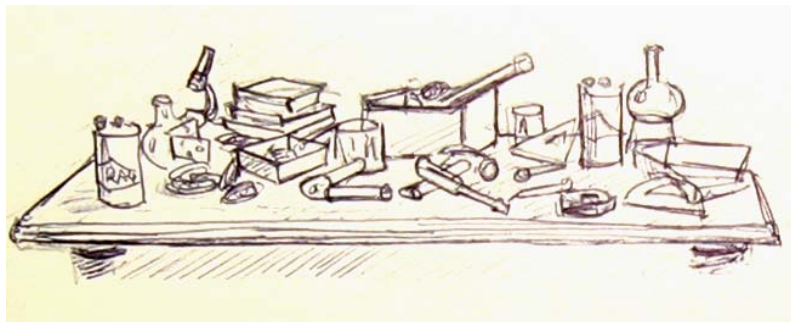
Miss Quirk never mentioned this table. Eventually, I started to poke around to see what was on it. As a confirmed book rat I first looked at the books. One of them was about electricity and looked very interesting. That afternoon during an English class I set up my English book with the smaller electricity book behind it, and the large dry cell battery, nail, wire, and paper clips behind that. I wound the bell wire around the nail as it showed in the book, connected the ends of the wire to the battery, and found that the nail would now attract and hold the paperclips!

I let out a shriek: "It works!" The class stopped. I hunched down expecting some form of punishment as had often happened to me in my previous school. But Miss Quirk did nothing of the kind. She stopped the class and asked, "How did you do that?". I explained about the electricity book and showed my electromagnet holding the paper clips. She said: "Wow, that's

great! What else is in the book?" I showed her that the next project was to make a telegraph with the electromagnet! She asked if others in the class were interested in this, and some were. She said, OK later this afternoon we'll have time for projects and you all can work together to do the next things in the book. And that's just what happened!

This happened many times. Children would find stuff on the table that really interested them and made something. Miss Quirk would get the child to show it and see who else was interested to work on it. Pretty soon about half of our class time was devoted to these self chosen projects. We started showing up earlier and earlier for school in the hopes we could spend more time on them. She was always there. We could never beat her to class!

Most of my ideas about how elementary school education should be done are drawn from the way Miss Quirk ran her classroom. She took subjects that would be interesting to the children and integrated real mathematics, science and art together for her curriculum.

Still later when I lucked into a terrific grad school at the University of Utah, my first thought was that this was just like 4th grade! And then I realized that Mary Quirk had made 4th grade just like a great graduate school! This is a critical insight. Children are in the same state of *not knowing* as research scientists. They need to go through many of the same processes of discovery in order to make new ideas their own. Because discovery is really difficult and has taken hundreds of years, the difference is that children have to be scaffolded carefully (but not using the Socratic method, it "leads the witness" too much). Instead the scaffolding has to be set up as close encounters and careful but invisible sequencing to allow the children to make the final leaps themselves. This was the genius of Mary Quirk. It was interesting that we never found out what she knew. She was *focused on what we knew and could find out*.

About 10 years old

10 Years Old: Do Vacuums Really Suck?

One of the local department stores had a pneumatic tube system for moving receipts and money from counters to the cashier's office. I tried to figure out how they worked and asked the clerks about it. They knew all about it. "Vacuum", they said, "Vacuum sucks the canisters, just like your mom's vacuum cleaner". But how does it work, I asked? "Vacuum", they said, "Vacuum, does it all". This was what most adults called "an explanation"!

So I took apart my Mom's Hoover vacuum cleaner to find out how it worked. There was an electric motor in there, which I had expected, but the only other thing in there was a fan! How could a fan produce a vacuum, and how could it suck?

We had a room fan and I looked at it more closely. I knew that it worked like the propeller of an airplane, but I'd never thought about how those worked. I picked up a board and moved it. This moved air just fine. So the blades of the propeller and the fan were just boards that the motor kept on moving to push air.

But what about the vacuum? I found that a sheet of paper would stick to the back of the fan. But why? I had heard that air was supposed to be made up of particles too small to be seen. So when you got a gust of breeze by moving a board, you were

knocking little particles one way and not another, like rowing with an oar. But where did the sucking of the paper on the fan and in the vacuum cleaner come from?

Suddenly it occurred to me that the air particles must be already moving very quickly and bumping into each other. When the board or fan blades moved air particles away from the fan there were less near the fan and the already moving particles would have less to bump into and would thus move towards the fan. They didn't "know" about the fan, but they appeared to.

The "suck" of the vacuum cleaner was not a suck at all. What was happening is that things went into the vacuum cleaner because they were being "blown in" by the air particles' normal movement, which were not being opposed by the usual pressure of air particles inside the fan!

When my father came home that evening I exclaimed "Dad, the air particles must be moving at least a hundred miles an hour!" I told him what I'd found out and he looked in his physics book. In there was a formula to compute the speed of various air molecules at various temperatures. It turned out that at room temperature ordinary air molecules were moving much faster than I had guessed: more like 1500 miles an hour! This completely blew my mind! I'm pretty sure this was the first time I ever thought like a scientist and was able to resist commonsense and exert enough will to do an actual experiment about a phenomenon that really interested me.
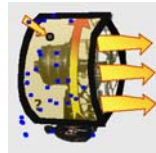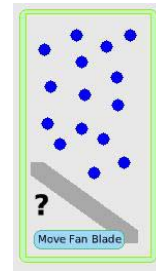
Painting and Music

My mother was an excellent draftsman and played the piano, so I also got interested in art and music.

A few weeks ago while playing the pipe organ in my house with the great music flowing through me, I realized that I did not like the original lecture I had sent to the Inamori Foundation. I was playing and feeling this wonderful music but had not tried to explain that the answer to "why?" for me is the "music of computing". I changed this talk so I could try to explain why and how many scientists, mathematicians, and technologists are attracted to the aesthetic nature of these fields.

The Center of "Why?" is Art

Art is "all the stuff that people make", and this includes our beliefs (which we like to call "reality"). Most people don't think of science or technology as Art, but all three of these areas are actually art forms. The Fine Arts we are most familiar with are on the left hand side and adding technology and science makes the three categories of prizes given by the Kyoto Prize committee.

Arts and their Ultimate Critics
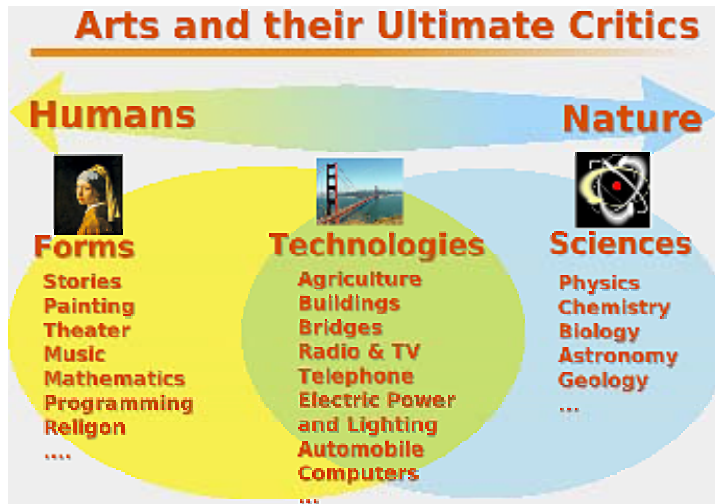
One way to look at this vast area is to consider the ultimate critics of each art form. Most of what people call "Art" is the shaping of forms, and the ultimate critics are human beings. The forms are quite arbitrary and have no connection to the physical universe. For example, we can say: "It is the case that: blah blah blah", and we can also insert a "not" into every sentence so we can say: "It is <u>not</u> the case that: blah blah blah". So we can say anything which is almost the same as saying nothing.

At the other extreme, on the right hand side, we have the sciences whose ultimate critic is Nature. Our opinions and hopes don't matter over here, because Nature is just the way it is, not the way we'd like it to be. The *arts of science* are to find ways not to be fooled, to make the invisible more visible, and to create theories that are the best maps we can make of what we can't get at directly. Science is very tricky because we have to use representation systems like mathematics, stories and computing that have no intrinsic relation to what's out there in Nature (and we have to use our own easily fooled brains!).

In the middle we have creations that have to heed Nature – such as bridges and airplanes – that we'd like to not break easily! But they also have visual forms that we'd like to be pleasing. The Technologies are very interesting art forms: they combine the traditional Arts with the new scientific Arts!

Artists

One of the great human traits is the ability to Love so deeply that one desires to merge with one's beloved. It is the greatest experience in life to have this happen and be reciprocated. Artists are people who can enter into Love with the expressing of ideas and feelings as well as with other humans. Portraying Art as an Act of Love is the only way I know how to describe what the process feels like.

Glass blowing is an interesting example of an art form that that is also a technology. A Venetian glassblower friend of mine once told me that if he could he would eat the molten blobs of glass on the end of his glassblowing pipe! I understand completely what he meant by that: he wanted to *become* his Art. The myth of Pygmalion falling in love with his creation applies strongly to such people.

No other reason is needed for doing Art. Pascal said: "The Heart has its reasons that Reason cannot know". *Artists <u>can't not</u> do their Art*: this is their basic personality trait.

Modern "Glass Blowing"

Glass is made from sand which is mostly silicon dioxide. Computer chips today are also mostly made from silicon, and here is a modern "glassblower" – Bob Noyce, one of the inventors of the integrated circuit.

Bob Noyce
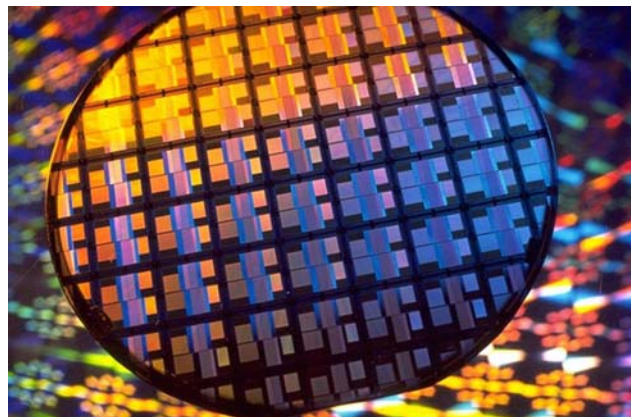
We can see that the silicon wafers are quite pretty physically, but their real beauty is more like the beauty of the printing press: it's the patterns that are impressed on the material that carries the real art – and again like the printing technologies, the patterns can be very subtle and far reaching.

Science is trickier!

Living organisms are shaped by evolution to survive, not necessarily to get a clear picture of the universe. For example, frogs' brains are set up to recognize food as moving objects that are oblong in shape. So if we take a frog's normal food – flies – paralyze them with a little chloroform and put them in front of the frog, it will not notice them or try to eat them.

It will starve in front of its food! But if we throw little rectangular pieces of cardboard at the frog it will eat them until it is stuffed! The frog only sees a little of the world we see, but it still thinks it perceives the whole world.

Now, of course, **<u>we</u>** are **<u>not</u>** like frogs! Or are we?

**We Are More Like Frogs Than We Would Like To Think!**

When Shakespeare had Puck say "What Fools these Mortals be!": he meant not so much the modern connotation that we are idiots, but instead that we are all easily fooled. In fact, we like to be fooled! Much of the literary, theatrical and magical arts are possible because we are able to be fooled and like to be fooled.

But we are also easily fooled when we are trying not to be, for example when we are trying to learn about universe, or even just to draw. The great drawing teacher Betty Edwards always shows these two tables on the first day of her art course, and explains to the students that the reason people have difficulty drawing is not because they can't move their hands carefully, but because their brains are too eager to recognize objects in the world rather than the shapes made of light.

Betty Edwards

To illustrate this, she tells them that the table tops are exactly the same size and shape. No one believes here. She then moves the top from one table, rotates it and shows that it exactly fits on the other table. I've been doing this example hundreds of times and I still can't see this!
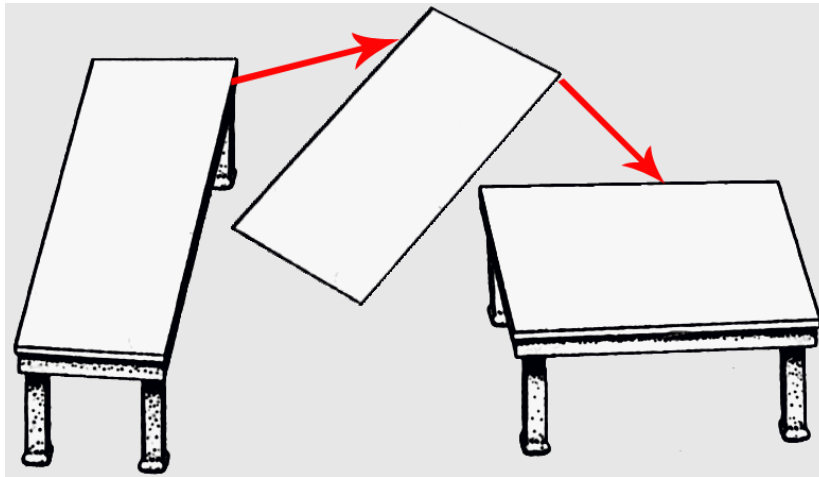

Amazingly, the size and shape of the two table tops is exactly the same!

What artists do to get around these problems is to use measuring instruments to get a more accurate sense of what's out there. And this is what scientists do also. There's a nice saying from the Talmud: We see things not as <u>they</u> are, but as <u>we</u> are. That is, whenever we're looking out into the world, we're always seeing ourselves, we're not really seeing what's out there. We have to learn very carefully how to see what's out there.

Science is a relationship between representations and "what's out there?"

Here are two maps, both with lots of detail, both convincingly drawn.
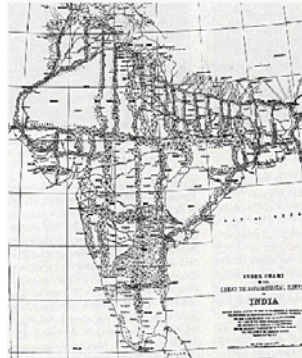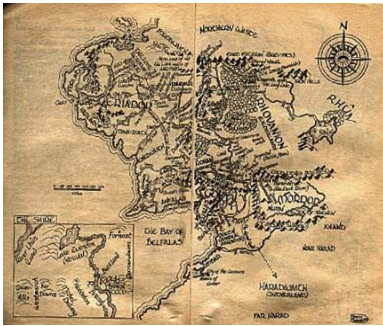

On the right is one of India made in the 19th century carefully made by English surveyors. The other on the left is of Tokein's Middle Earth where the action of the fantasy "Lord of the Rings" takes place.

There is no way we can tell from just looking at these maps which ones are "real" and which ones are made up. We need other processes to help – these other processes are the Art of Science.

We can also start getting the idea that the maps are not going to be an actual depiction of reality, but a kind of "accurate as possible" depiction of the shadows that we can pick up with our senses and with the aid of instruments.

Let's take gravity as our phenomenon and represent it as a bunny rabbit. The shadow of the bunny is what we can experience and measure about gravity on Earth.
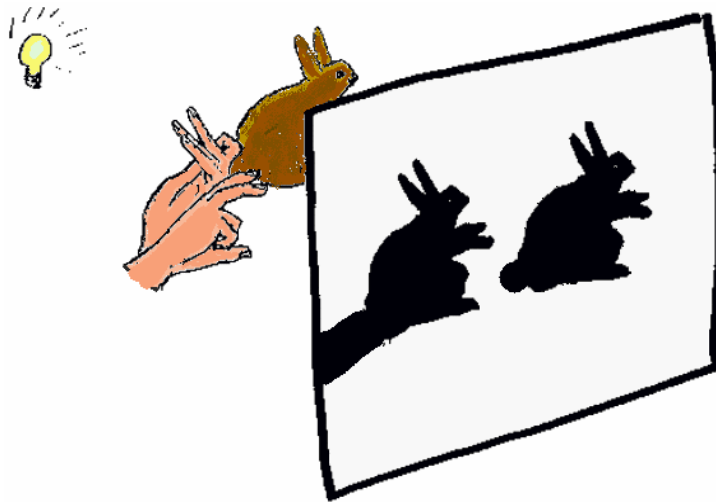
We can then try to make a model that will cast the same shadow. Here we make a hand shadow puppet – think of it as Newton's Theory of Gravity – that makes a pretty good shadow bunny in most places. Newton used Mathematics to make his model, but if we look carefully enough we can see that the shadow of the real bunny has a round tail and the Newton model has an arm sticking out!

The "arm on the bunny" took a while to find, but the orbit of the planet Mercury is not in accord with Newton's theory, so Newton's model is not as perfect as we'd hoped.
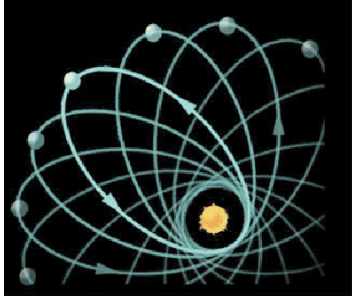
The orbit of Mercury precesses in a way that Newton's model doesn't predict (highly exaggerated)

Einstein had to take a very different approach from Newton in order to put the round tail on the human shadows.

He said something that we should try to remember every moment of our lives: "You should be careful to distinguish what is true from what is real". He meant that we can make "true" things in languages – especially mathematics – because it is only about itself, and can be made very consistent. But when we try to apply mathematics and other representational systems to "what's out there", we depart from actual truth and have to make do with approximate mappings.

The importance of science is partly how well it is able to do with careful approximations. The representations are still story-like but a qualitatively new kind of story. If we look at this in the larger sense, it means that for efficiency sake, evolution set us up to think that our perceptions and beliefs are reality and we act that way. In the last few hundred years using science we've found over and over again that our perceptions are not accurate: we are constantly fooling ourselves. This means that a very good strategy for life, is to insert slow thought between perception and quick action because our initial perceptions and reactions are often wrong and dangerous.

The ability of the Scientific Arts to "make the invisible a little more visible" has been quite remarkable. By the 18th century, people in Europe delighted in carrying around pocket globes that depicted the Earth as it would be seen from space even though the internal combustion engine and airplanes had not been invented yet.

200 hundred years later, when we finally did go out into space and turned a camera back on the Earth, there were no surprises. How was it possible to know this in the 18th century? In part because the very notion of what it meant to "know and find out" had changed.

The most important invisible thing today is ourselves. Most people live in stories made up by them and their societies, and they call these stories "reality". We are the most dangerous force on Earth, to ourselves and the environment. It is the main aim of

education to provide not information or techniques, but a better set of perspectives for better seeing the invisible.

You can't learn to see until you realize you are blind. Education is to help people realize they are blind and show them how to see a little.
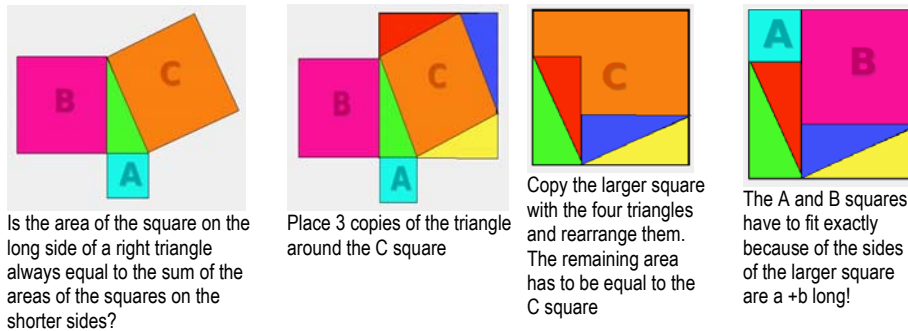
The Beauty of Mathematics

Now let's take a look at the several kinds of beauty in mathematics: both internal, as a set of harmonious relationships, somewhat like music, and in the ways it has been used to depict the external universe.

For example, Newton's theory of gravitation is very beautiful, and how he arrived at it was quite beautiful. The poet Keats said "Beauty is Truth, and Truth Beauty". And many thought that Newton's theory was True because it was beautiful and worked so well. But in spite of its beauty and usefulness – we use it today to accurately send spaceships around the solar system – the orbit of Mercury and many other recent observations show that it is not the whole story about gravity. Einstein's theory, which is also quite beautiful, supplies more of the story, but not all of it.

Many of these beautiful mathematical theories are difficult to explain to a general audience. But some can be understood much more directly.

For example, the proposal of Pythagoras is quite startling. There are many proofs of it, including this one, which might be the original from 2500 years ago.

$$F = G\frac{mM}{d^2}$$

$$E = mc^2$$

$$e^{i\pi} + 1 = 0$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} + \tfrac{1}{c}\dot{\mathbf{B}} = 0$$
$$\nabla \times \mathbf{B} - \tfrac{1}{c}\dot{\mathbf{E}} = \tfrac{4\pi}{c}\mathbf{j}$$

$$A^2 + B^2 = C^2$$

Is the area of the square on the long side of a right triangle always equal to the sum of the areas of the squares on the shorter sides?

Place 3 copies of the triangle around the C square

Copy the larger square with the four triangles and rearrange them. The remaining area has to be equal to the C square

The A and B squares have to fit exactly because of the sides of the larger square are a +b long!

We can surround the C square with 3 more of the triangles to make a larger square whose area is the C square plus 4 triangles. We copy this and move the triangles. The odd shaped orange area still has to be the area of the C square. We see that we can move the A and B squares to exactly cover this area. Bingo!

We can reflect that this will work for any right triangle regardless of shape.

This is very beautiful!

The Beauty of Computing

One of the parts of computing is a special kind of mathematics, and one of the earliest beautiful creations in this new art came in the late 1950s when John McCarthy – one of my heros, and a Kyoto Prize Laureate who is here today – found a very compact and new mathematical way to write down the relationships of a very powerful programming language.

John McCarthy

When I first understood this as a student in the 60s I was quite overcome by the beauty and power of this way of looking at things. I thought of this as the Maxwell's Equations of computing! It had a huge effect on the way I thought about many things. To me, this is the essence of what a computer science should be!

I spent quite a bit of the last few months trying to find a way to explain the meaning of John's short program to this Kyoto Prize general audience, but wasn't successful. Like much other great and beautiful mathematics, it is not that it is hard, but there is a fair amount of context that is needed to follow the arguments. In fact, most of the professional computing world today does not yet understand the implication of this half page of Art from 40 years ago and this has really held back the entire field.

An easier work of great computer art to appreciate – a kind of parallel to the geometry example - is Ivan Sutherland's "Sketchpad: A man-machine graphical communication system" from the early 60s. It was the first example I saw in graduate school that showed how special, different and important computers could be.

Ivan Sutherland
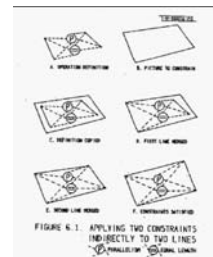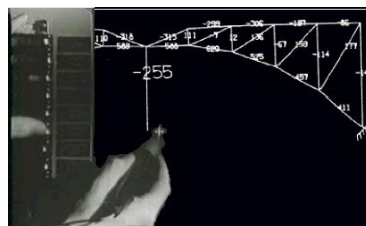
What it could do was quite remarkable, and completely foreign to any use of a computer I had encountered. The three big ideas that were easiest to grapple with were: it was the invention of modern interactive computer graphics; images were described

by making a "master drawing" that could produce "instance drawings"; control and dynamics were supplied by "constraints", also in graphical form, that could be applied to the masters to shape and inter-relate parts. It was the first to have clipping and zooming windows—one "sketched" on a virtual sheet about 1/3 mile square!

Just by sheer lucky chance, grad school at the University of Utah in 1966 was one of about 15 Advanced Research Project Agency projects (sponsored by the US government) that were engaged in what they called the "ARPA Dream": the destiny of computing was to become an interactive intellectual partner and intercommunications medium for everyone on Earth.

Work was afoot to create an "intergalactic network" (now called the Internet) that would link all of the computers on the planet. There was quite a challenge of scalability, since no one had ever built such a network for data.

Dave Evans, Head of the University of Utah Computer Science Department, and my mentor.
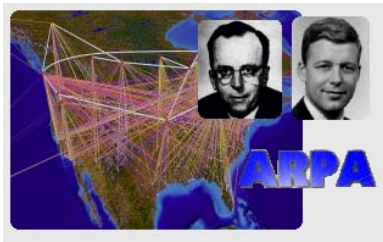
JCR Licklider "Lick", Bob Taylor, and The ARPAnet
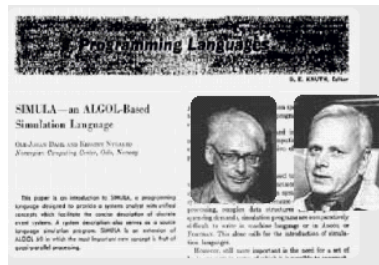
The Simula paper, Dahl and Nygaard

Right after seeing Sketchpad, I was introduced to an little known simulation language Simula from Norway and gradually realized that it was a very powerful way to program Sketchpad-like structures.

My undergraduate concentrations had been in pure mathematics and molecular biology, and I suddenly saw the analogies between biology, mathematics, computer graphics and networking.
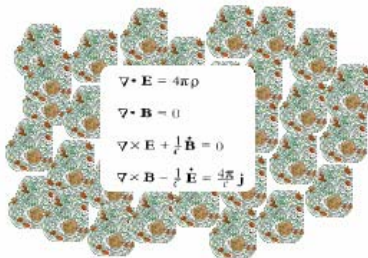
Math and Biology
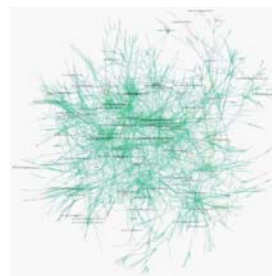
Abstract universal computing as recursively embedded computers sending messages to each other

This gave me a mental image that everything in computing could be represented by little computers communicating with each other.

I designed a system that could do this and started experimenting with it. When someone asked me what I was doing, I said "object-oriented programming". Now I wish that I'd come up with a more suggestive term!

Doug Engelbart and "Thought Vectors in Concept Space"

While I was working on objects, Utah was visited by the amazing Doug Engelbart. His notion of the ARPA dream was that the destiny of oNLine Systems (NLS) was the

"augmentation of human intellect" via an interactive vehicle navigating through "thought vectors in concept space".
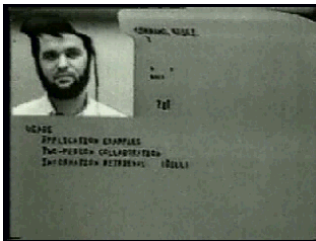

Doug Engelbart, the father of personal computing using his system NLS

NLS controls showing the first mouse and a chord keyboard for the left hand.

What his system could do was incredible. Not just hypertext, but graphics, multiple panes, efficient navigation and command input, interactive collaborative work, etc.


Immersive collaborative screen sharing in 1968!

Having a meeting using NLS as communications and shared context

An entire conceptual world and world view. The impact of this vision was to produce in the minds of those who were "eager to be augmented" a compelling metaphor of what interactive computing should be like.

Two other amazing works of computer art that had recently been created were my vote for the first personal computer – the LINC of Wes Clark (one of the design requirements be that it be shorter than the person using it!) – and the first pen-based system, the beautiful GRAIL system from RAND Corporation.
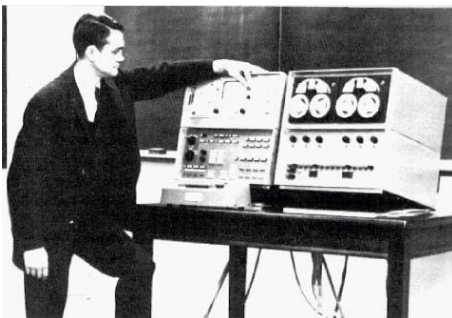
Wes Clark and his LINC personal computer, ca. 1962

The RAND tablet (1964) and the GRAIL system, ca, 1967-9

So this was a very Romantic time when my mentor Dave Evans introduced me to his friend Ed Cheadle who was working on "a little machine" to fit on a desktop and interact with engineers. I suggested we try to make it work for professionals in many

fields, and that was the start of a pleasant collaboration on the FLEX Machine that we termed a "Personal Computer".

Here is a self-portrait drawn on its own display. It had windows and pen based tablet input, and looks pretty familiar.
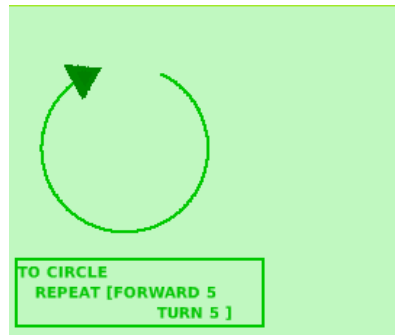
While we were working on the FLEX machine, I started visiting interesting uses of interactive computers for end-users, and the most startling visit was to Seymour Papert's early work with children and LOGO.

Ed Cheadle and Alan Kay: FLEX machine self portrait, ca 1968

Seymour Papert, with an early turtle and some eager children

The program to draw a circle in LOGO is so simple that children can invent it.

Papert was a mathematician who had also studied with the child cognitive psychologist Jean Piaget. He had a great insight: that the special nature of the computer could bring quite of bit of real and important mathematics within the reach of children, and would create a Mathland, where mathematical language would have great meaning for children.

This completely blew my mind! I thought this was the greatest idea anyone had ever had for what the computer was really good for, and I immediately started to think about a computer like the Flex machine, but for children.

On the airplane back to Utah I drew a little cartoon showing two children learning physics on their children's computer – which I called a Dynabook – by making the game of Spacewar, using a special programming language as a new kind of highly expressive and powerful mathematics.
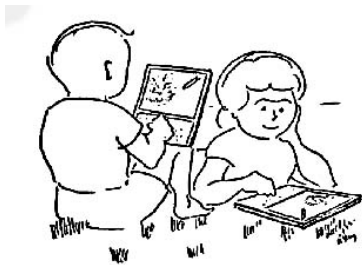
I had been thinking of computers as tools, but this made me realize that the computer is a medium of expression – like reading and writing amplified by the printing press.

I had been a professional musician and so I also made the connection to this as a *new kind of instrument whose music is all ideas*.

We have intimate relationships with the media that represent our ideas and this insight had a great effect on me.

Then, at Xerox PARC in the early 70s, about two dozen of us young ARPA computer scientists got a chance to really invent personal computing and networking on a much larger and more practical scale.

I went there to try to make a practical version of a children's computer – an "interim Dynabook – until the real Dynabook technology came along. Here are sketches of ideas from 1970 and 1971.

We have intimate relationships with our tools for art, shouldn't this also be the case for computers?
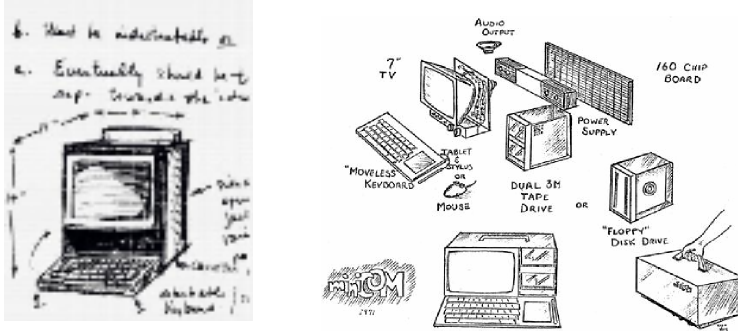
In the meantime, there was the need for a new kind of object oriented language that could be programmed by young children.

I had been thinking about it, but was interrupted by a hallway bet about "how large would a description of the world's most powerful computer language be?"

Having understood John McCarthy's LISP by then, I said "Half a page!" They said "Prove it". Two weeks later I had this for the kernel of a new kind of object-based language, using some of John's techniques, but put in directly executable form.

Xerox PARC in 1972

Dan Ingalls

The kernel of Smalltalk. How small powerful "computer math" can be.

One month later my colleague Dan Ingalls had programmed this into one of our minicomputers and we suddenly had a working, very high level, simple and powerful dynamic object language!

Chuck Thacker

And a few months after that, we suddenly had an interim Dynabook: the Alto personal computer, built by Chuck Thacker and jointly designed by him and a few more of us, including Butler Lampson.

Butler Lampson

Gary Starkweather

Bob Metcalfe

Dave Boggs

Gary Starkweather had just created the first workable laser printer and it was incredible even by today's standards: a page a second at 500 pixels/inch.

Bob Metcalfe and Dave Boggs were just starting the Ethernet to connect all this together.

And Dan Ingalls and I were shortly joined by computer scientist and educator Adele Goldberg to start making experiments for children. A major milestone was putting the first Altos in a school in 1975.

Adele Goldberg with the first Alto classroom in 1975

Adele Goldberg

Over the next few years of the mid 70s, more than a thousand Altos were built and put into use. This was a very serious experiment!

As Butler Lampson has pointed out, no one else was interested in personal computing at the time, so we had the entire field to ourselves for quite a few years. Much of this work was done by about 25 people, and two keys to success were the ability of these scientists to (a) cooperate with each other when this was a good idea – much of this is due to the lab manager, psychologist Bob Taylor – and (b) to be really simple about how they went about bringing reality to these grand ideas.

Bob Taylor

What Children Can Do

Now let's leave the past and take a look at what children can do today with their "dynamic media for creative thought". In fact, I'm using a little two pound laptop – just as we thought 35 years ago we would have by now – to give this presentation.

One way to think about children is that they all are artists until they're talked out of it by society, and if you want to educate children, try to keep their artistic motivations intact, don't try to be too practical with them at first. Instead, try to get them really interested in ideas. As Einstein said "Love is a better Teacher than Duty!"

A project that nine, ten and eleven year old children really love is to design and make a car they would like to learn how to drive. They first draw their car (and often put big offroad tires on them like this).

So far this is just a picture. But then they can look "inside" their drawing to see its properties (for example where the car is located and heading) and behaviors (the ability to go forward in the direction it is heading, or change its heading by turning. These behaviors can be pulled out and dropped on the "world" to make a script which can be set "ticking" by clicking on the clock. The car starts moving in accordance with the script. If we drop the car's pen on the world, it will leave a track (in this case a circle), and we see that this is Papert's LOGO turtle in disguise – a turtle with a costume and easy ways to view and control it.
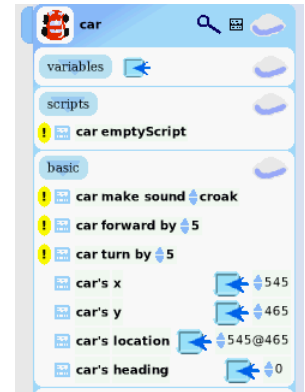
To drive the car, the children find that changing the number after **car turn by** will change its direction. Then they draw a steering wheel (the very same kind of object as the car, but with a different costume) and see that if they could put **steer's heading** right after **car turn by …** this might allow the steering wheel to influence the car. They can pick up **steer's heading** (the name for the heading numbers that the steering wheel is putting out) and drop it into the script. Now they can steer the car with the wheel!

The children have just learned what a variable is and how it works. Our experience indicates that they learn it deeply from just this one example.

They quickly find that it is hard to control the car. They need to introduce a "gear" into the wheel's connection to the car. They can get the needed advice from a teacher, parent, friend, or from a child thousands of miles away via the mentoring interface over the Internet. They open the expression in the script, and divide the numbers coming out of the steering wheel by 3. This *scaling* makes turns of the steering wheel have less influence. They have just learned what divide (and multiply) are really good for.

Maria Montessori would recognize what just happened. The children think they are playing (and they are), but they are playing in an environment that has 21st century toys that embody 21st century ideas. They play for their own reasons – and children differ in why they play, and what they want to play at – but they all learn the powerful 21st century ideas, and even more important: they start learning the most powerful ways of thinking about the ideas.

Jenni's Big Race, … err, Pig Race

Then we turned the kids loose to think up a project all by themselves. Jenny liked to introduce her slant on things whenever possible (her cars we done as pencils with wheels), and she decided that it would be really fun to make a pig race.

The start of the Pig Race

Here is her narrative as she explained her project for the Squeakers DVD.

> Here we go for the annual pig race. It looks like it's a rough time today. The pink pig crashing into the wall.
> (I also have a watcher here that tells me what speed they're going.)
> Oh and the blue pig's coming in the lead. I have my own pig. I named it Jackson. And usually it loses, But, oh look the black pig is catching up, leaving the white pig in the dirt!
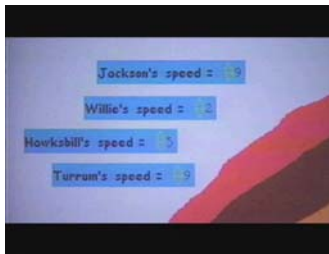

The race. How does Jenny get the pigs to stay in their lanes?

Jenni, Age 11

She wanted a real track for her pigs and needed to figure out how to keep each pig in its lane. She had a wonderful idea that the nostrils of her pigs would be perfect as sensors to tell when it was trying to escape its lane!

Watchers showing the speed of the different pigs

Jackson pig winning

Quite a bit of doing is "just doing", so it is a good idea to also reflect on what just happened. One way to do this is to have the objects leave trails that show what they were doing over time.

If the speed is constant then the trail of dots is evenly spaced, showing that the same distance was traveled in each little tick of time.
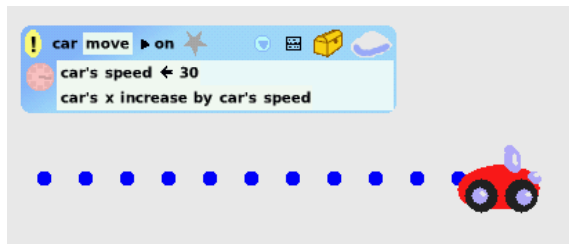
If we increase the speed each tick of the clock, we'll get a pattern that looks like this. This is the visual pattern for uniform acceleration.
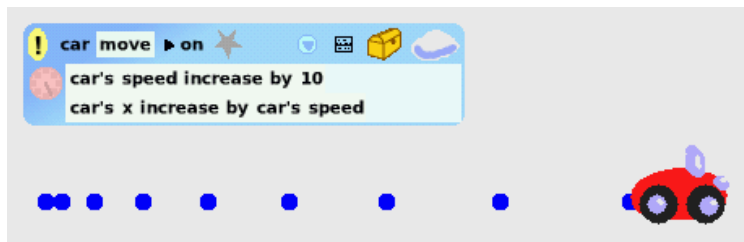
If we change to speed to be random each time, we will get an irregular patter of distance traveled for each tick.

```
! car move ▸ on ✴
    car's speed ← random 40
    car's x increase by car's speed
```
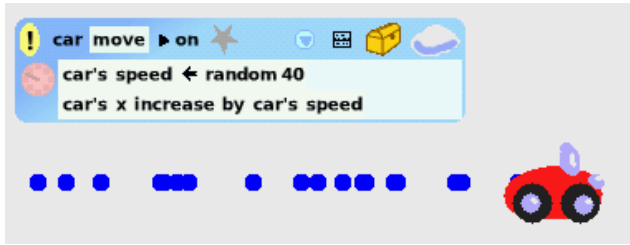
Random speeds are great for races!

Real Science With Children

So far we've been doing mathematics. To do science we have to look at the outside world. A nice example for 11 year olds is to investigate what happens when we drop objects of different weights.
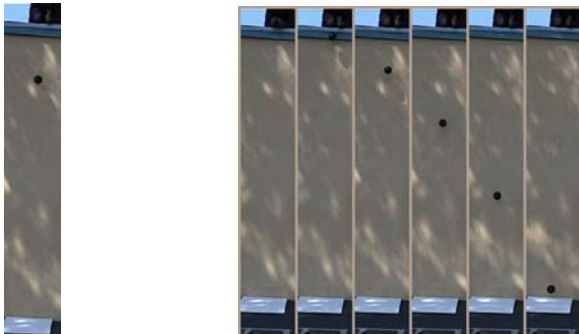
The children think that the heavier weight will fall faster. And they think that a stopwatch will tell them what is going on.

But it is hard to tell when the weight is released, and just when it hits.

In every class, you'll usually find one "Galileo child". In this class it was a little girl who realized: well, you don't really need the stop watches, just drop the heavy one and the light one and listen to see if they hit at the same time. This was the same insight that Galileo had 400 years ago, and apparently did not occur to any adult, (including the very smart Greeks) for our previous 80,000 years on this planet!

To really understand in more detail what is going on with gravity near the surface of the Earth, we can use a video camera to catch the dynamics of the dropping weight.

We can see the position of the ball frame by frame, $1/30^{th}$ of a second apart. To make this easier to see we can just pull out every fifth frame and put them side by side:

The "Galileo Girl" explains a simple way to see if different weights fall at the same or different speeds.

Another good thing to do is to take each frame and paint out the non-essential parts and then stack them. When the children do this, most of them will immediately say "Acceleration!" because they recognize that the vertical spacing pattern is the same as the horizontal one they played with using their cars several months before.

The stacked up frames that reveal the acceleration pattern

But, what kind of acceleration? We need to measure.

Some children will measure directly on the spread frames, while others will prefer to measure the stacked frames.
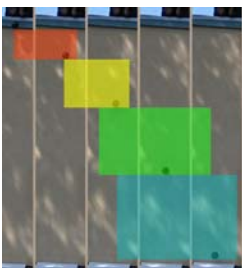
The translucent rectangles help because the bottom of the balls can be seen more accurately, The height of a rectangle measures the speed of the ball at that time (speed is the

distance traveled in a unit of time, in this case about $1/5^{th}$ of a second).

When we stack up the rectangles we can see that the difference in speed is represented by the little strips that are exposed, and the height of each of these strips appears to be the same!

These measurements reveal that the acceleration appears pretty constant, and they made such scripts for their car months ago. Most quickly realize that since the ball is going vertically that they have to write the script so that it is the vertical speed that is increased and the vertical position **y** that is changed. They paint a small round shape to be the simulated ball, and write the script:
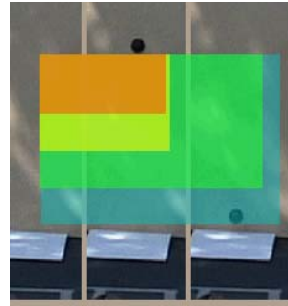
Now, how to show that this is a good model for what they have observed? 11 year-old Tyrone decided to do as he did with his car months before: to leave a dot copy behind to show that the path of his simulated ball hit the very same positions as the real ball in the video.

Here is what he had to say when explaining what he did and how he did it for the Squeakers video:

> And to make sure that I was doing it just right, I got a magnifier which would help me figure out if I had it - if the size was just right.
>
> After I'd done that I would go and click on the little basic category button and then a little menu would pop up and one of the categories would be Geometry, so I clicked on that.
>
> And here it has many things that have to do with the size and shape of the rectangle. So I would see what the height is… I kept going along the process until I had them all lined up with their height.
>
> I subtracted the smaller one's height from the bigger one to see if there was a kind of pattern anywhere that could help me out. And my best guess worked: so in order to show
>
> that it was working, I decided to make – to leave – a dot copy (so that it would show that the ball was going at the exact right speed. And acceleration.)

An investigative work of beauty by an 11 year-old!

By the way, in the United States about 70 percent of the college kids who are taught about gravity near the surface of the Earth fail to understand it. It's not because the college kids are somehow stupider than the fifth graders, it's because the context and the mathematical approach most college kids are given to learn these ideas are not well suited to the ways they can think.

Now that the kids have captured gravity, they can immediately make many games. In Lunar Lander, the gravity script that the children have just created will pull down the spaceship and crash it if it moves too fast. The rocket motor script can oppose gravity and a careful pilot can balance them to land the spaceship safely!
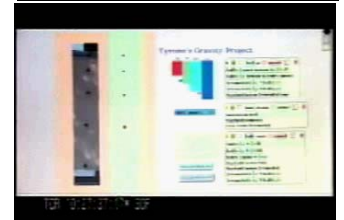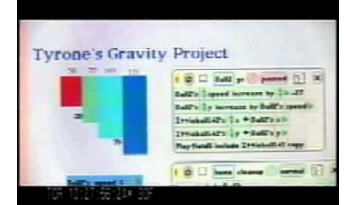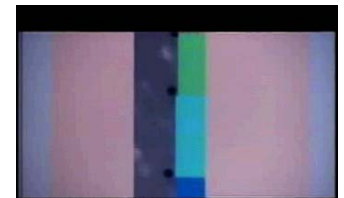
The Beauty and Importance of Complex Systems

We are all very aware now that one of the simple things that computers can do is to copy things quickly and cheaply.

Because of this we can explore very complex systems by just scripting the behavior of one item and making many copies. For example, if we make lots of little dots, we can explore the behavior of contagious processes, such as rumors and disease. Here the scripts are very simple, and cause a dot to change color when it collides with an "infected" dot. The size of the arena for collisions determines the delays between collisions, and allows us to explore matters of life and death, such as really understanding the characteristics of epidemics: fast deadly ones like typhoid which are very noticeable, and slow deadly ones such as AIDS (which is deadly in part because the onset of an AIDS epidemic is not dramatic). A poor understanding of slow deadly epidemics in many parts of the world is one of the main causes of the AIDS disaster. People have to reach beyond their common sense into the "uncommon sense" of models for disasters in order to help their imagination spur them to early action. The computer will eventually create an even larger change in how humans think about ideas than the printing press.
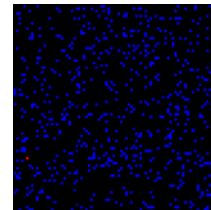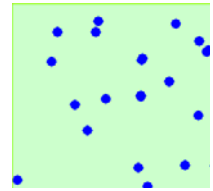
Lots of Things in the Universe are Springy!

Now, for the last set of ideas I'd like to show how easy observations of the real world plus very simple models plus the great power of the computer to do many simple things very quickly can reveal a whole new world of art and science.

One of the problems with classical science is that it reused common words – like know, theory, force, etc. – for very new ideas. New words should have been chosen.
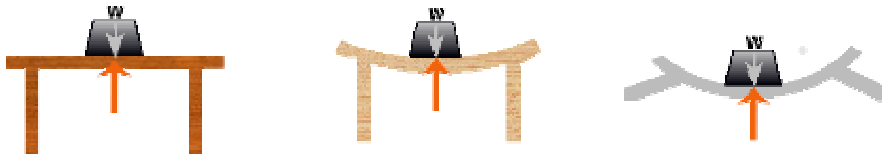
For example, the weight of an object is thought of in science as a force in the direction of the source of gravity. But if we place a weight on a sturdy table so that it moves no further, most people do not think of the table exerting an upwards force that balances the downward force of the weight.

If we try a table made from a flimsy wood, like balsa, we will see the table bend until it either breaks or is able to exert a balancing upwards force.

If we try this on a paper table, it will simply collapse down to the floor which exerts the upwards force.
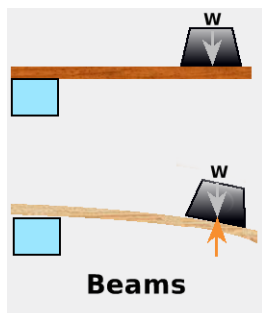
Beams have the same characteristics. And all these are examples of "springy things".

If we look at a spring with a weight hung on it we can measure how much it stretches until it is able to balance the force.
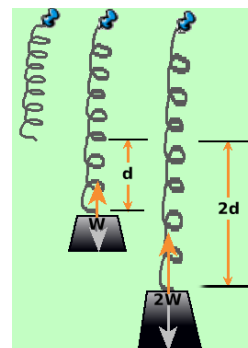
If we put on twice the weight most springs will stretch very close to twice as much. This gives us a way to simply describe the force of the spring: it is proportional to the length it is stretched.

Now we can use the ideas about acceleration and speed we learned from the falling weight. But the acceleration is not constant now because it is proportional to the stretch of the spring. What can we do?

What is really nice here is that we can get the computer to compute very small little movements in which we can pretend the acceleration is constant. Then we can measure the stretch of the spring and do this again. This gives us a very simple but good model of the spring, and is a great example of how easy it is for young children to learn the ideas of calculus with the environment of a computer.
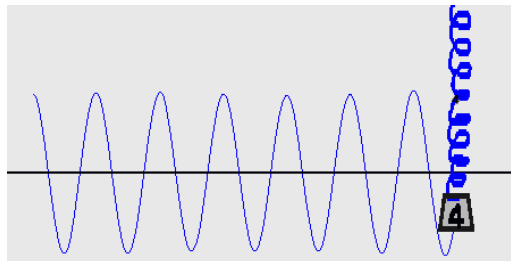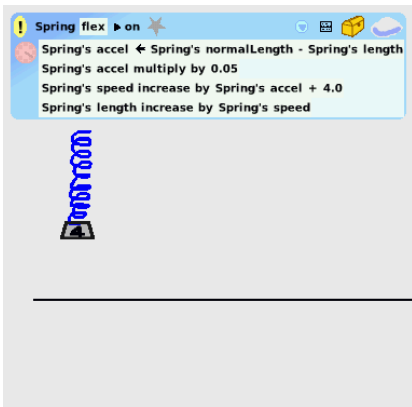

To plot what the spring does, we turn on its pen and move it sideways

Even better, once we've made one spring, we can get the computer to copy it over and over to get more springs.

Here is a movie all engineers see in college of a bridge with a 100 mile an hour wind blowing across it. It is quite startling to see how elastic the steel bridge is!

Let's make a simple bridge from two springs and a weight. If we turn on gravity and the spring models we see this: If we turn on the wind, we see that it will find a balance. But if we gust the wind but turning it on and off, we start to see behavior like the bridge.
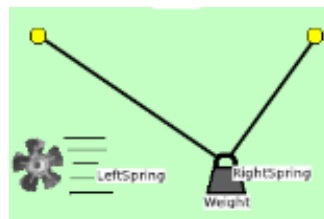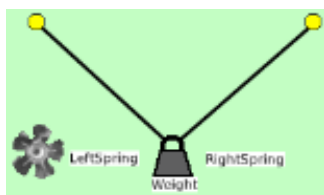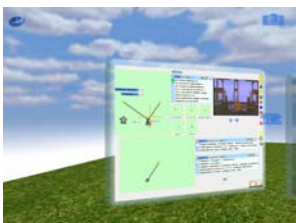

Tacoma Narrows Bridge in the wind

Tacoma Narrows Bridge shaking itself apart because it was too springy and started to resonate in the wind

But now let's make a real bridge! Since real bridges are in our 3D world, we need a 3D world to make our model – and we see that we've been in a 3D world the whole time!
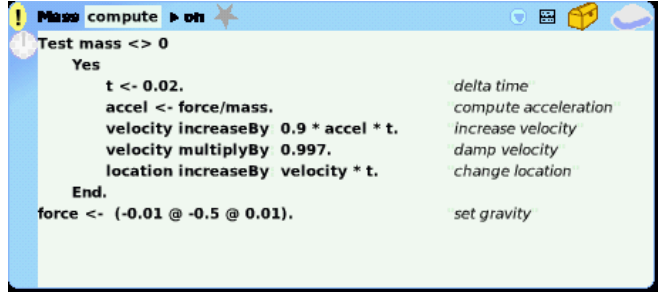

We are really in a 3D Computer World

Manifest a 3D bridge

But now let's make our bridge work. This structure is the same as the simple one we built with two springs and a mass, but now we are using the power of the computer to make many copies of the springs and the weights to make a bridge structure.

Let's first turn on gravity. This will make the bridge sag a bit – notice that it is a bit springy.

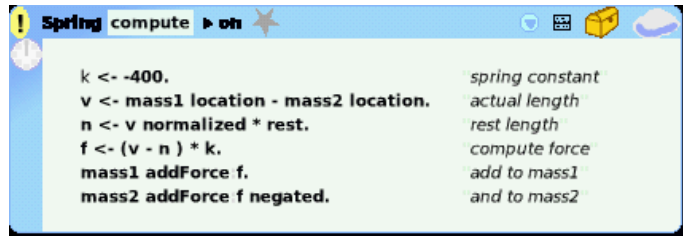Turning on gravity to affect the masses in the bridge

The gravity script

```
Mass compute ▶ on
Test mass <> 0
    Yes
        t <- 0.02.                                  delta time
        accel <- force/mass.                        compute acceleration
        velocity increaseBy  0.9 * accel * t.       increase velocity
        velocity multiplyBy  0.997.                 damp velocity
        location increaseBy  velocity * t.          change location
    End.
force <-  (-0.01 @ -0.5 @ 0.01).                    set gravity
```

Now let's look at the script for the springs. Let's make them more springy by changing the stiffness number to -400.

Making the bridge structure springy

The spring script

```
Spring compute ▶ on
    k <- -400.                                      spring constant
    v <- mass1 location - mass2 location.           actual length
    n <- v normalized * rest.                       rest length
    f <- (v - n ) * k.                              compute force
    mass1 addForce f.                               add to mass1
    mass2 addForce f negated.                       and to mass2
```

We can see the bridge sag and bounce a little more.

Now we'll turn on a gusting wind that is like the one that started the suspension bridge in the movie oscillating. This has a few more details, but is still easy and small.

The simulated bridge really starts oscillating violently, very similar to the movie of the real bridge! Let's move around to the side so we can look down it. It is so flexible and elastic that it looks kind of like a cloth fabric to me. And that pops up an idea. Let's detach one end of the bridge, gradually put a texture on
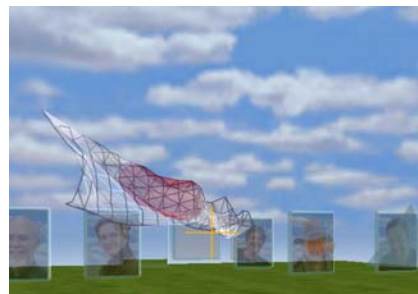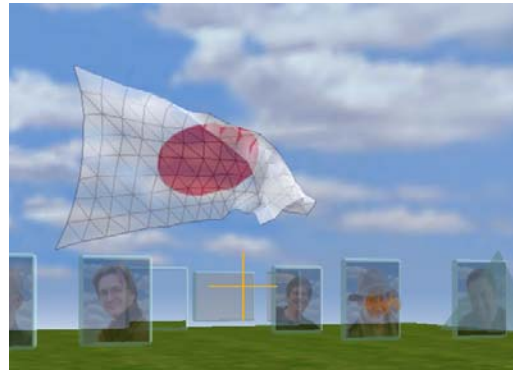

The wind starts the bridge oscillating

it, and see what happens in the wind and gravity.
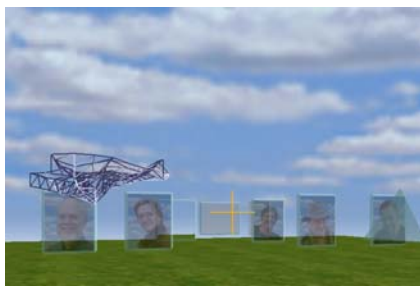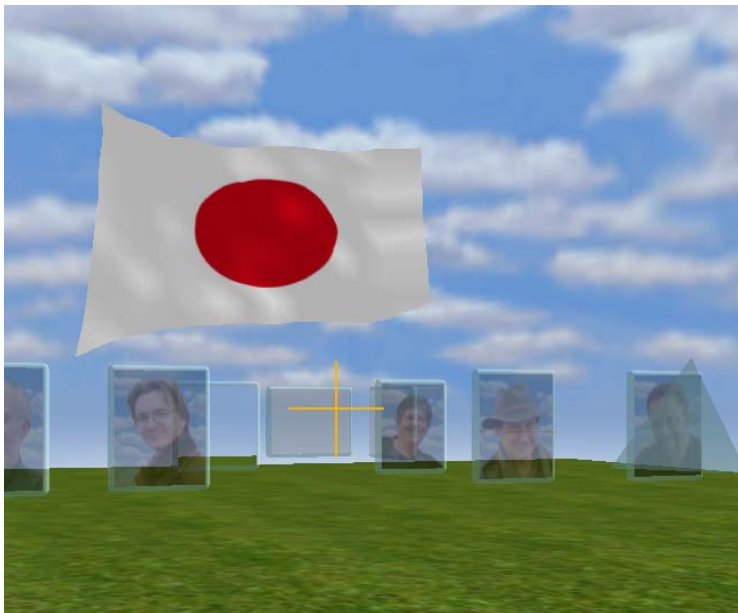

From the side with strong wind

The bridge unfolding and starting to show a texture

We get a nice surprise! It's a flag!

The texture becomes more intense and the structures fade

Surprise! A bridge and a flag are the same kind of physical object!

Cesare Pavese said: "To know the world, one must construct it". We can see that Computing is a new kind of Romantic Art Form where we make our ideas as Art, and the understanding of these ideas is Art.

The Greeks said that the Fine Arts were the imitation of Life – but we see that the Fine Arts of Computing are the *Imitation of Creation* itself! It is this Romance that attracts children to build their ideas and helps them learn to think better than most adults do today.

This is our Romance and this my answer to the question "why?".

Thank you.