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Embedded Microworlds for a Multiuser Environment

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Abstract

This paper describes a possible set of software learning activities called "microworlds." The microworlds could be stand-alone "construction kits" for single users or teams of users, or located as pockets of activity within a networked multiuser environment. The design of the microworlds is such that exchanges of objects between the microworlds and of ideas among the users enhance the power of the kits as environments for learning.

The microworlds described here are for learning about an aspect of motion study, balance. They are also for learning about an aspect of topology, the spatial relationships between vertexes, edges, and faces of three-dimensional shapes. Users construct dinosaur skeletons and mobiles for experiments with balance, and polyhedra for explorations in topology. The mobiles in changed scale can become items of jewelry, and the polyhedra in changed scale can become landscapes along which the dinosaurs can teeter.

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Embedded Microworlds for a Multiuser Environment

This paper describes a possible set of software learning activities called "microworlds." These microworlds could be functional as stand-alone "construction kits," useful as learning environments for single users or for teams of users. The microworlds could also be implemented as pockets of activity within a networked multiuser environment. Connection to a thematically related MUD-style context would provide continuity and built-in possibilities for young people to work collaboratively.[1] Furthermore, the added opportunities to show and discuss constructions with others would enhance the power of these kits as environments for learning.

Microworlds provide specifically designed tools and objects that children can use to construct things they care about. In the course of this constructing, because of focuses and properties of the tools and objects, the children can develop better understandings of the topic of the microworld. Such topics often include basic principles of science and mathematics. The microworlds described here are for learning about an aspect of motion study, balance. They are also for learning about an aspect of topology, the spatial relationships between vertexes, edges, and faces of three-dimensional shapes.

In this century, the field of topology has become increasingly appreciated as a set of concepts and methods for genetics research, theoretical physics, and other sciences. Euler's formulation for describing polyhedra, a basic tenet of topology, is the basis of one of the microworlds described here. The other two focus on motion study, chosen because of its primacy in the field of physics and in the everyday experiences of young people. Balance is one of the fundamentals in this domain.

Among the proposed activities are assembling and animating mobiles and dinosaur skeletons as means of exploring principles of balance. Children can also create colorful polyhedra, which in changed scale become landscapes for the animated dinosaurs. The three microworlds are interrelated in concept, theme, and technical base. These relationships reflect the sense that understandings developed by working and playing in one microworld will tend to support ideas encountered in the others.

There is a strong emphasis here on the importance of design. Functionalities are included not just because they are technically feasible, but because they contribute to a design premise and focus. One of the challenges of microworld design is to find the right balance between design focus and technical facilities to keep the user engaged.

These microworlds are intended to spawn learning and foster conditions for intellectual growth, but they are also tools for learning research. In addition to describing instantiations of a particular approach to learning environment design, this paper considers means of evaluating the learning that takes place. Both of these approaches constitute changes from current educational practice, changes that are sorely needed if we are to encourage the growth of thinking skills necessary for productive living in the 21st century.

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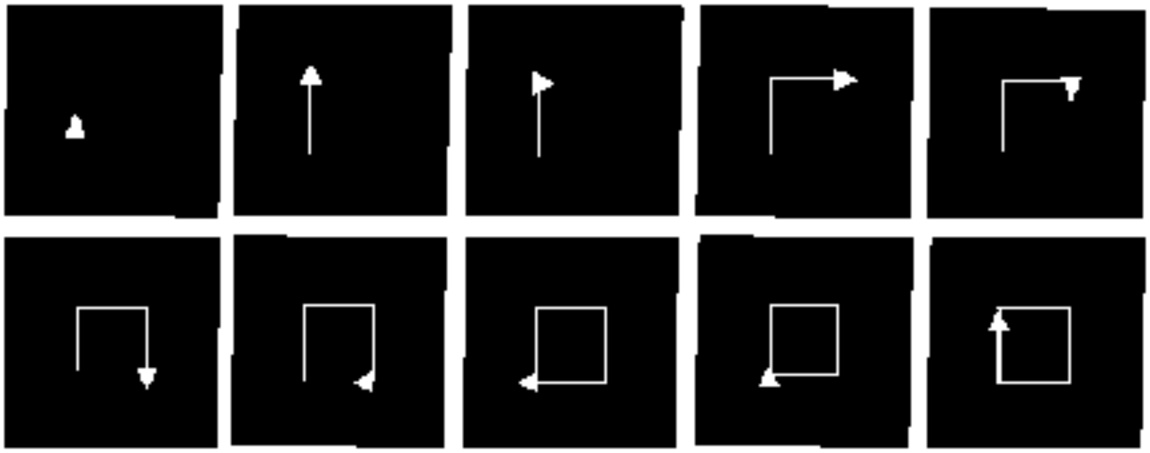
[1] I use the term "MUD" broadly, to include the ideas of MOO and MUSE, as well as other such environments that will emerge as technologies progress. (MUD means "Multi-User Dungeon, Dimension, or Domain"; MOO means MUD Object-Oriented; and MUSE means Multi-User Simulation Environment.")

The Idea of Embedded Microworlds

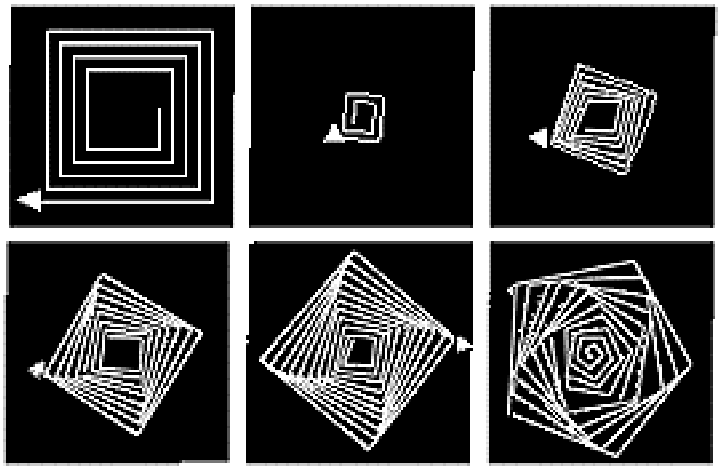
The term "microworld" was introduced by Papert (1980) in his classic book, *Mindstorms*, to describe learning activities and environments of a particular kind. Objects and elements of microworlds are designed to embody fundamental properties of a conceptual domain. By working with the elements, people can get in touch with core ideas and develop understandings of the domain.

The microworld of Turtle Geometry is an example. In this microworld, children can draw pictures by directing the movements of a graphical object (that in some versions looks like a turtle). The turtle has two properties: a position and a heading. By creating pictures through manipulations of these two basic properties, children can come to understand the concept of vector.



From S. Papert, Mindstorms: Children, Computers, and Powerful Ideas. *New York: Basic Books, Inc., 1980.*

This building-block idea can, in turn, help in developing further understandings – of angles, the geometries of squares and spirals, etc.



Like Turtle Geometry, the microworlds described here are simple in principle but rich in possibilities for playful, thoughtful activity. Additionally, they could complement other interactions within a multimedia MUD-style environment. Such an environment could provide a social and technical context for the constructive activities. The microworlds could be spatially located – that is, "embedded" – within the graphical domain.

In "The Lessons of Lucasfilm's Habitat," Morningstar and Farmer (1991) describe their experiences in designing and implementing a base for a graphical online community. Some of their discoveries are strikingly consonant with principles of good learning environment design: "It seems to us that the things that are important to the inhabitants of such an environment are the capabilities available to them, the characteristics of the other people they encounter there, and the ways these various participants can affect one another" (p.274). They conclude that "one of the goals of a next generation Habitat-like system ought to be to permit far greater creative involvement by the participants without requiring them to ascend to full-fledged guruhood to do so" (p.295).

Embedded microworlds are one kind of provision for creative involvement and enriching the range of capabilities within the environment, transforming it into a *learning environment.* It is through the act of making something, of *constructing* something personally meaningful, that connections between new ideas and existing understandings can happen. In this model of learning, knowledge is something that grows from what a person already understands. It isn't something that can just be "poured" into the head or "transferred" from one person to another.

Papert has elaborated on this principle in his discussion of "constructionism" (Harel & Papert, 1991). The word is a play on Piaget's term "constructivism," adopted "to capture the sense in which the child must make and remake the basic concepts and logical thought-forms that constitute his intelligence. Piaget prefers to say that the child is inventing rather than discovering his ideas. ... The ideas in question do not preexist out there in the world, only awaiting their discovery by the child: each child must reinvent them for himself. By the same token, since the ideas have no a priori external existence, they cannot be discovered by simple exposure; rather, they must be constructed or invented by the child" (Gruber & Vonèche, 1977, p. xxxvii).

Papert's extension of this view is that the child's inventing of the ideas can be facilitated by actually constructing an object in the world. Microworlds are domains in which this sort of construction can happen in a particularly focused way. The design challenge is to provide focuses in terms of content, what the learner already knows, and what the learner likes. As Papert (1980) observes, "Anything is easy if you can assimilate it into your collection of models. If you can't, anything can be painfully difficult."

Users of microworlds are engaged in activities that can help them to think about certain phenomena. But the learners also have feelings about these things. If they don't like what is being presented, or how it is being presented, they won't spend time with the idea – and growth takes time. One of the challenges in microworld design is to develop a context in which people will want to spend time needed in order to learn. Time spent as a matter of requirement, in an attempt to satisfy some other person or agenda, is less likely to result in real learning, learning that lasts and lends itself to application in new situations. As Einstein said, "Love is a better master than duty."

Microworlds are environments can engender learning, but they can also help in doing research on how learning happens. We can observe, document, and analyze how learners use software tools, how they describe their actions, and how their thinking changes over time. Learning is a developmental process: "The understanding of learning must...refer to the genesis of knowledge. What an individual can learn, and how he learns it, depends on what models he has available. This raises, recursively, the question of how he learned those models. Thus the "laws of learning" must be about how intellectual structures grow out of one another and about how, in the process, they acquire both logical and emotional form" (Papert, 1980, pp. vi-vii).

Thinking of learning in terms of the growth of intellectual structures helps in meeting the challenge of microworld design. In Turtle Geometry, for example, vectors and angles are fundamentals of the topic domain, and understandings of these fundamentals are basic intellectual structures with which the learner works and plays. By using microworld tools to manipulate representations of fundamental ideas, the learner develops deeper understandings of the topic. The conceptual structures grow, becoming more refined, elaborate, and connected with other domains.

Thus, in designing microworlds, we need to examine the topic domain in order to identify what aspects of it to represent. Mathematics and science are broad categories of knowledge that we can think of as being composed of subcategories, each of which can be further subdivided. Coming to understand a domain involves a process of building up from core ideas. Children develop many core understandings on their own.

"Piaget has taught us that we should understand how children learn number through a deeper understanding of what number is. ... Imagine a microworld in which things can be ordered but have no other properties. The knowledge of how to work the world is...the mother structure of order" (Ibid., p. 159). In everyday play, by making sequences and groups of things, children develop a concept of "order," which contributes to a broader understanding of "number."

They also know a lot about how their bodies move through space. "Every preschool child has amassed on his or her own special mathematical knowledge about quantities, about space, about the reliability of various reasoning processes, elements that will be useful later in mathematics class. The enormous quantity of this "oral" mathematics constructed and retained by every child has been well documented by...Piaget" (Papert, 1993, p. 16).

Furthermore, "Piaget's work on genetic epistemology teaches us that from the first days of life a child is engaged in an enterprise of extracting mathematical knowledge from the intersection of body with environment. ...whether we intend it or not, the teaching of mathematics, as it is traditionally done in our schools, is a process by which we ask the child to forget the natural experience of mathematics in order to learn a new set of rules (Papert, 1980, pp. 206-07). Turtle Geometry is one offering of a world in which children can bring their "body knowledge" to bear in learning about an aspect of mathematics. They can imagine themselves as the turtle, turning this way and that in order to set a heading for making a vector, a line, an angle, or a figure.

Two of the microworlds described here, tentatively titled, "Them Bones" and "Life on the Edge," lend themselves to a similar strategy of projecting one's self and one's knowledge of movement into another world and onto an object of one's own creation. All three of the proposed microworlds – Them Bones, Life on the Edge, and "Mobilize" – lend themselves to experiments with motion.

Papert has pointed out that schools usually postpone motion study until taking a course in physics. Yet, young children have experimented with motion from before the time they learned to walk. When they do study physics, the material is presented in the reverse order from how it was originally encountered: in school courses, the study of statics usually precedes dynamics. But for children, dynamics come first. Feynman (1963, 5-1) also asserts the primacy of this subject: "The study of *motion*, which is basic to all of physics, treats with the questions: where? and when?." Children experiment with these fundamental questions from an early age.

The microworlds proposed here offer ways to address topics in science and math to things children already know and care about. By working and playing in these environments, children can experiment with their own theories of balance, spatial relationships, and topological properties.

Edwards (1994) provides a survey of activity in the realm of microworld design. Her report examines microworlds for learning about mathematics and physics. Examples include topic domains such as fractions, geometry, proportion, functions, numeric representation, and Newton's laws, including simulations of velocity and acceleration. Edwards's analysis probes the nature of representation, how specific ideas from these topic domains can be "embodied" in computer programs so that extraneous elements do not distract the learner from the focus topic. Her descriptions are influencing the design of Them Bones, Mobilize, and Life on the Edge.

Another category of ongoing research that informs this work is the set of inquiries into Nintendo and other video games as a force in children's lives (e.g., Jenkins, 1993; Kinder, 1991; Provenzo, 1991). Our microworlds will not make use of the tiered, competitive framework that characterizes most video games; however, they may bear a certain family resemblance because of their highly interactive nature and multimedia forms. Ideally, these microworlds will capture some of the fascination that children have for video games through lively, engaging interfaces and activities that encourage thoughtful experimentation.

Video games also play a role in social binding and contribute to children's technological savvy. The microworlds described here should serve similar functions, particularly when embedded in a larger MUD, but will also provide the means to study roles of technology in learning processes. The research that accompanies the development effort will focus carefully on how members of demographic groups that typically shy away from math, science, and technology may make use of the microworlds.

Embedded Microworlds for Math and Motion Study

Imagine one example of a graphical MUD that incorporates speech, agent, and digital video technologies: the "Zircus," part zoo and part circus. This is an imaginary world, currently portrayed through a video of the same name (Strohecker, 1994). In the Zircus, animals are not trained to perform unnatural tricks, but roam freely through familiar terrains, in the spirit of the well designed zoos. Visitors are not mere spectators, but creators of acrobatic routines, juggling sequences, and other circus arts. Friends from all over the globe can see themselves represented in cartoon-like form – often, forms that they themselves design. As they wander through various landscapes and interiors, these new-age "pen pals" can converse in different languages with each other and with resident characters ("agents"). The visitors can also compose and send messages to one another, often drawing from a multimedia database, and invent their own creatures to dwell in the Zircus. Most of the visitors are probably young people, but that is not a rule.

This imaginary environment anticipates a platform that brings together real-time, networked 3D graphics; speech recognition and generation; natural language processing; artificial agents; various input devices; and high-level software for constructing animations and audio/video sequences. The microworlds described here would not require this full range of capabilities. They would depend on music and other sounds; 2D still images; and facilities for manipulating, grouping, and animating the images. The input mechanism could be as straightforward as point-and-click. However, one could easily imagine later versions in which the images are represented as 3D objects and the input is gestural or relies on now-experimental devices.

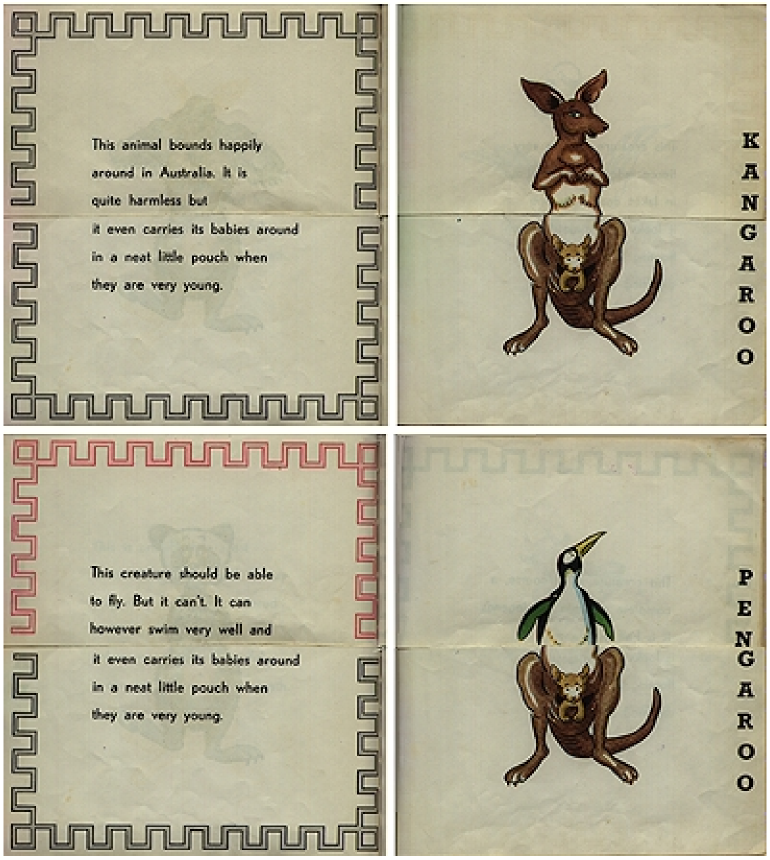
The Zircus scenario is a plausible context, both technological and cultural, in which microworld-style activities can be embedded. With its reliance on animals as characters, companions, and objects of interest, the context is well suited for explorations in math and science. Representations of animals can present opportunities for experimenting with motion study and locomotion, systems study and physiology, environmental study and ethology. Together with language study, such topics form key focuses for interactions.

Thematically related tools and smaller contexts – embedded microworlds – could enable construction of animations, audio/video sequences, and simulations. A Zircus visitor might try on virtual stilts in the circus tent and see how changes in their lengths affect balance. He or she might slip through a hatch door in the floor to discover an underground workshop where Muybridge still images can be edited into sequences showing animal gaits. Outside, the visitor might find dinosaur bones that can be assembled into skeletons that seem to come to life, moving according to algorithms that test for balance and structural integrity. An initial mockup of this microworld does exactly that.

Them Bones

Young people can use this software "creature construction kit" in thinking about balance, an aspect of motion study. With this kit, they can put dinosaur bones together and then test the skeletons to see if they can balance while standing or moving. The software calculates a center of mass and uses it in a simple test for static balance. These representations evolved through a series of considerations in microworld design.

Creature construction can be a good way to develop and test hypotheses about how animals move. But when does it makes sense to construct a creature? Centaurs and mermaids are ancient examples of composite creatures, animals pieced together from parts of disparate beings. People have used all kinds of media to imagine new animals in this way – among them, books, wooden blocks, and software toys.



This animal bounds happily around in Australia. It is quite harmless but it even carries its babies around in a neat little pouch when they are very young.

KANGAROO

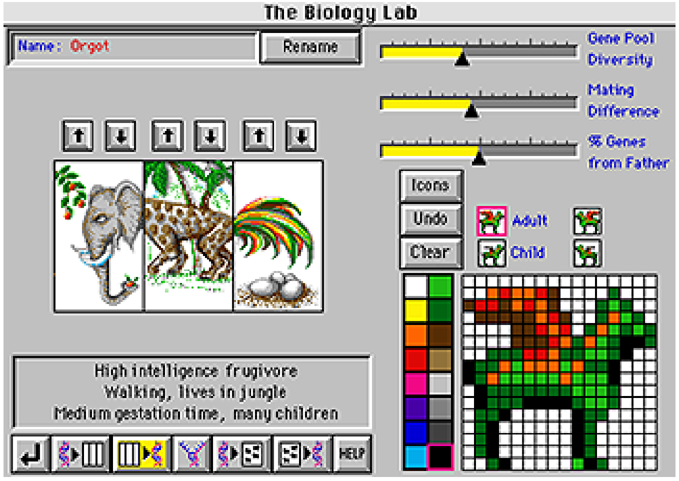
This creature should be able to fly. But it can't. It can however swim very well and it even carries its babies around in a neat little pouch when they are very young.

PENGAROO

From J. Riddell, Hit or Myth: More Animal Lore and Disorder. *NY: Harper and Rowe, 1949.*

The kangaroo blurb reads, "This animal bounds happily around in Australia. It is quite harmless but it even carries its babies around in a neat little pouch when they are young." The pengaroo blurb: "This creature should be able to fly. But it can't. It can however swim very well and it even carries its babies around in a neat little pouch when they are young."

SimLife's Biology Lab uses a similar approach for making new creatures, but adds features that help to make it a learning environment for ecology and genetics: users can modify the species genome, gene pool diversity, degree of difference between parental genes, and number of paternal genes. While these capabilities may help in learning about genetics, sliced-animal creature construction could work against it.



The Biology Lab

Name: Orgot

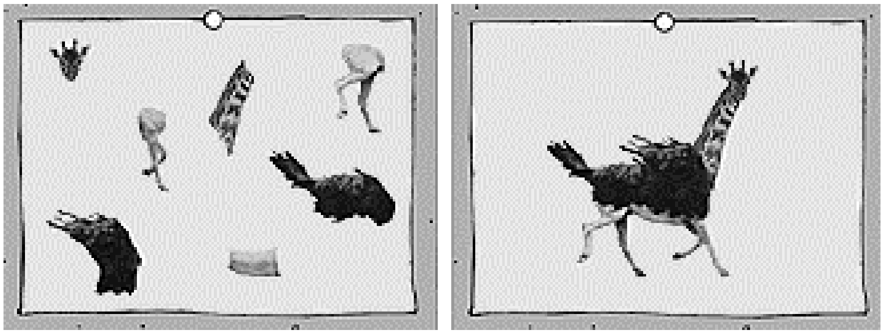
High intelligence frugivore
Walking, lives in jungle
Medium gestation time, many children

From K. Karakotsios et al., SimLife: The Genetic Playground. *Orinda: Maxis, 1992.*

Among the ideas presented through the Zircus scenario are premises and a context for a creature construction kit that could become a microworld for learning about balance. The video shows a composite creature that is part giraffe, part ostrich, and part horse. One design idea for how to make the animal was to pull and stretch a clay-like form into the shape of a creature.

From preparatory materials for a video produced by C. Strohecker, Zircus: An Environment for Learning, Playing, Doing, Saying. *Cambridge, MA: Mitsubishi Electric Research Labs, 1993.*

The idea seemed fun, but no more satisfying than the sliced-animal approach. Another idea, of assembling the creature from various body parts, seemed just as fantastic and slightly macabre.



From follow-ons to a video produced by C. Strohecker, Zircus: An Environment for Learning, Playing, Doing, Saying. *Cambridge, MA: Mitsubishi Electric Research Labs, 1993.*

SimLife suggests a promising direction by beginning to use an evolutionary model. Genetic algorithms offer promise as tools for understanding biological systems, but we were striving to provide a more direct, concrete kind of involvement with animal forms.

Fortunately, there is a time when it does make sense to put animal pieces together, and that is when they're bones.

From D. Norman, The Illustrated Encyclopedia of Dinosaurs. *NY: Crescent Books, 1985.*

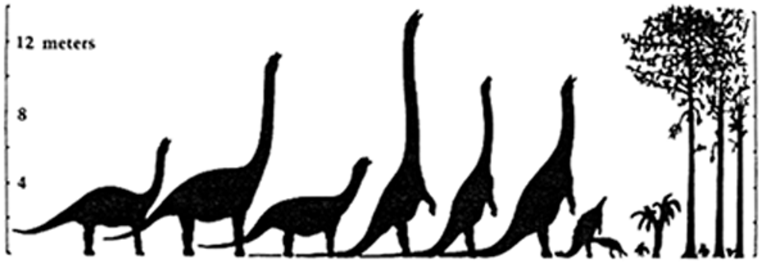
Paleontologists, of course, assemble dinosaur skeletons in the course of their work, but they are not the only ones who have discovered the learning and exploratory potentials of this medium. Missouri teenager Tabitha Mountjoy describes her work with bones from a cat, which included both scientific and artistic motivations:

> This last fall I have been putting a cat skeleton together. It has been fascinating and very enlightening. I found the skeleton in some tall weeds about two months after the cat died. (She had been a barn cat.) Because the cat was in the weeds and it had just rained, I could not find all of the bones. The bones I was missing were long thin bones, like ribs or thin leg bones. Before I had started this project of assembling the bones into a skeleton, I had no idea how many different parts there are to a single bone. For example, I had always thought that the leg bone was just a bone. Inside the bone, however, is marrow, and outside the bone is parieostum.
>
> Since I found the cat, and no one else had touched her, it was sort of like an archaeologist's find. It was a strange feeling to be digging for remains in the mud because previously, I would never have picked myself out to be the type to do something with dead animal parts. However, when Amory [her sister] held the skull in her hand and remarked that this pile of skin, fur, and bones was all that was left of our cat, I became intrigued. Bending down, I found the lower jaw and fitted the pieces together. It looked so mystical. I held the jaw open and the teeth were jagged. They looked like they could come alive. The soul of the animal had really left its mark.
>
> After I found as many bones as I could, and I had separated the skin and fur from them, I began to put the pieces together. It was exactly like putting together a puzzle, a skill I had started before I was able to talk. I put the head, backbone, and tail together with glue.
>
> However, ever since I first picked up the head, the bones had a mystical meaning for me. By the time I had finished putting the backbone together, I was looking for a way to give the whole thing more meaning than just a skeleton. So when I found a white feather, I knew that the skeleton needed to become a spirit symbol. I made a cross stand out of leg bones and put the feather on the head. I am still looking for flowers to go in the eyes and mouth.
>
> Making this spirit symbol has been a great creative release for me. I have never been in a classroom with dissection going on, but I do have friends who are in high school and

> dissect frogs, mice, and other animals. Even though my project with the cat and dissections in a classroom both have to do with anatomy, it is hard for me to see them as the same type of things. I think that it is sad that so many kids are forced to do dissections without being able to use their imagination because there is so much *room* for imagination with an animal. It would be interesting to see what different kids would come up with other than merely putting the animal together or taking it apart exactly as it was.
>
> For example, last month I carved a miniature arrow out of wood and made a stand for it out of the cat's rib bones. Also, I started making a necklace for a friend out of one of the leg bones made into long beads. Mother and I had been in an ethnic shop downtown and we had seen old bones with the marrow taken out of them and that had been dyed with natural materials. I asked an employee how they had gotten the bones to look the way they did. She said they had cut off the ends of the bones and boiled them in water to remove the marrow. Then they had dyed the bones with bark or berries. I went home and began this process using one of the cat bones. So far, it has worked really well. All I have to do now is dye the bone and put it on a string. The possibilities of things you can make from bones are endless.
>
> – From Grace Llewellyn, ed., *Real Lives: 11 Teenagers Who Don't Go to School.* Eugene: Lowry House, 1992.

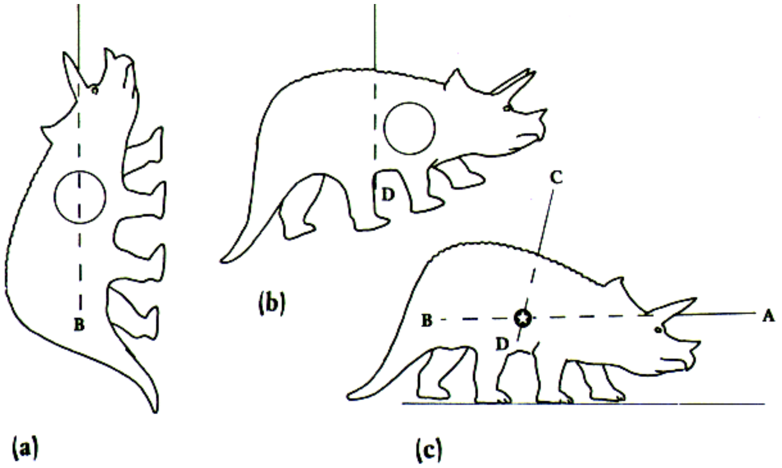
Tabitha's explorations with bones included imaginative ventures and experiments with creative expression, in addition to inquiries of a more scientific nature. Even when remaining within the paleontologist's or archaeologist's perspective, there are endless ways in which bones can be combined as reconstructed skeletons. Interpretations of available data vary, and those doing the assembling do not necessarily take into account all of the structural characteristics that would have made the creature viable.

Alexander (1989) has acknowledged this sort of concern in applying knowledge of physical dynamics to the study of dinosaurs and other animals. He specifically addresses the issue of balance. One consideration is how the necks and tails of extremely large animals can serve as balancing devices in foraging.



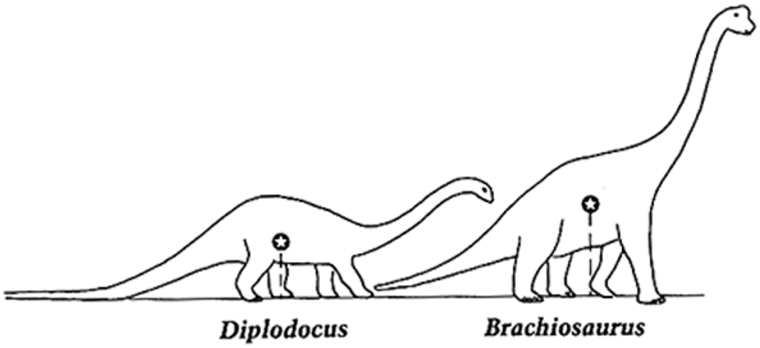
From R. McN. Alexander, Dynamics of Dinosaurs and Other Extinct Giants.
NY: Columbia Univ. Press, 1989.

Because the creatures he studies are extinct, Alexander's techniques are sometimes a bit unorthodox. In an attempt to locate the center of mass for triceratops, Alexander worked with a plastic model from the museum store of London's Museum of Natural History. These models are based on accepted conceptions of dinosaurs' forms and proportions, and Alexander considers them to be good replicas. He went so far as to drill a hole in the model to simulate the air pocket of the lungs. Then the procedure became a simple matter of suspending the model along vertical and horizontal axes, and marking their intersection.



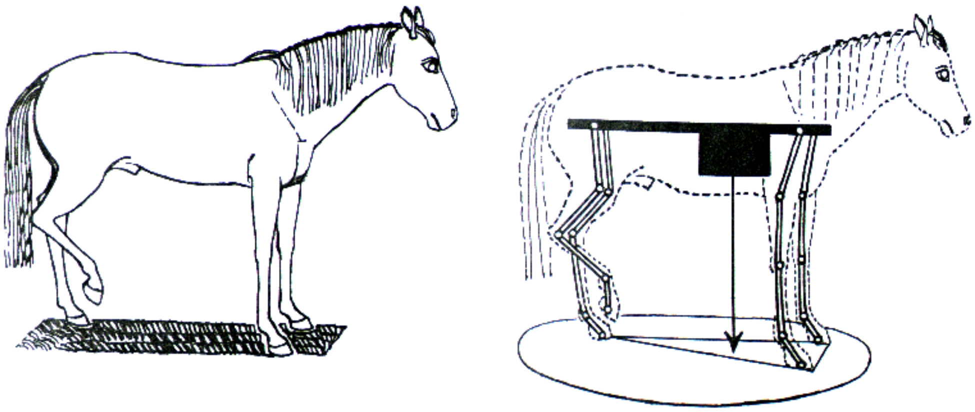
From R. McN. Alexander, Dynamics of Dinosaurs and Other Extinct Giants. *NY: Columbia Univ. Press, 1989.*

Alexander also considers the relationship between location of the center of mass and an animal's posture.



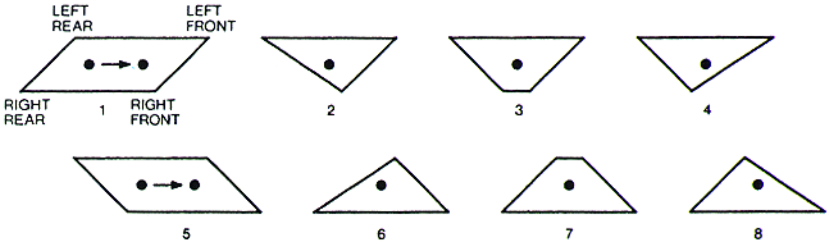
From R. McN. Alexander, Dynamics of Dinosaurs and Other Extinct Giants. *NY: Columbia Univ. Press, 1989.*

Gray (1953) shows how a vertical line projected from an animal's center of mass to the ground identifies the center of gravity. In order for the animal to maintain its balance, this point must lie within a polygon formed by joining points of contact with the ground. Because a horse usually stands with its center of gravity lying closer to its forefeet, it can stand with one hind foot off the ground. Gray explains that this frontward positioning of weight is an adaptation for rapid movement.



From J. Gray, How Animals Move. *Cambridge: Cambridge Univ. Press, 1953.*

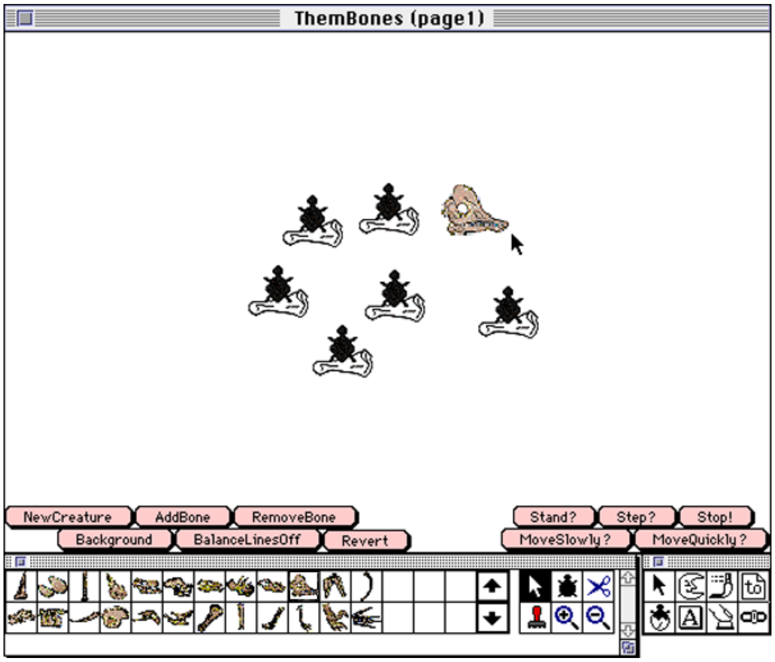
Raibert (1986) refers to McGhee and Frank (1968) in illustrating how the projection of the center of mass falls within polygons formed by the feet in a statically stable gait. A supporting foot is at each vertex of the changing polygons in the course of the animal's movement.



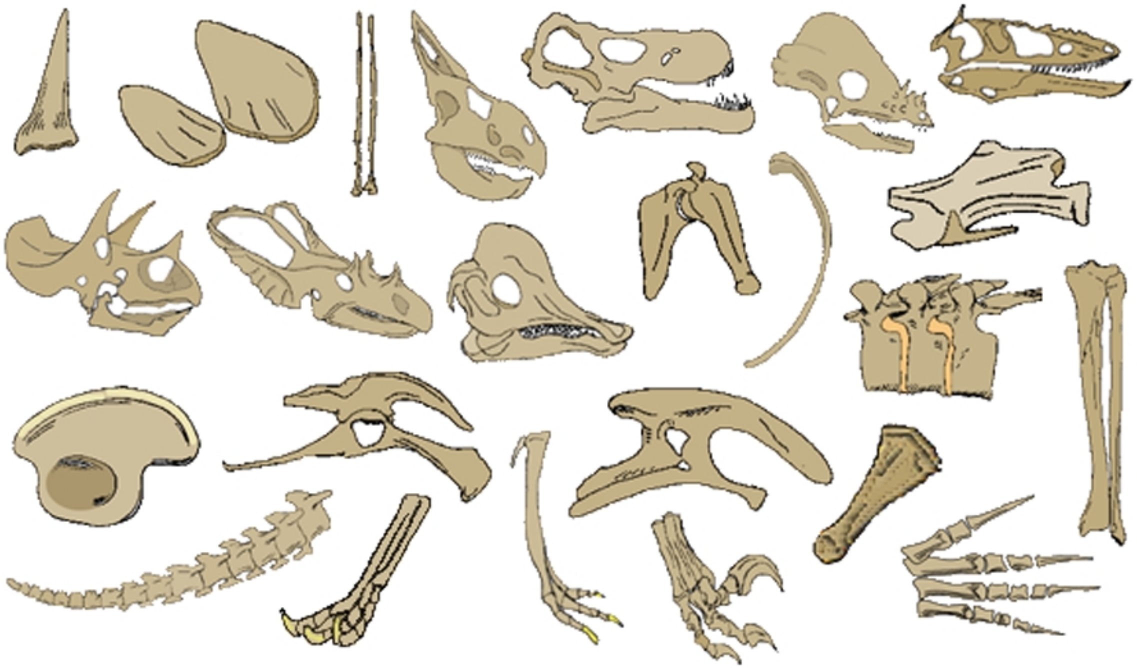
From M. Raibert, Legged Robots that Balance. *Cambridge MA: MIT Press, 1986.*

The relationship between a creature's center of mass and its supports is the crux of the tests for balance in the Them Bones microworld. The current mock-up is implemented in MicroWorlds Project Builder, a software environment from Logo Computer Systems, Inc. (LCSI). (The term "microworld" in this paper applies to a specific theoretical and design approach rather than a specific environment for implementation. However, both usages stem from work with Seymour Papert.) LCSI MicroWorlds is a good system for mock-ups and prototypes, but final implementations need to be in a more general, lower-level software environment.

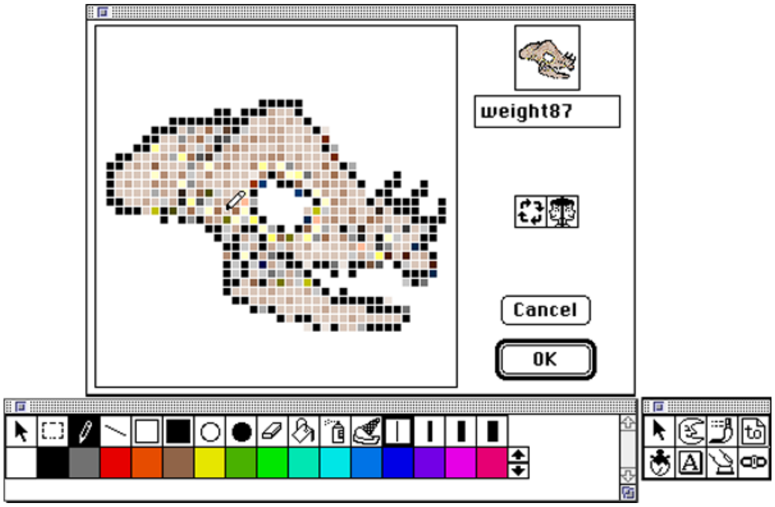
MicroWorlds provides a programming interface and supports for pictures and sounds. Users interact with Them Bones much as they would with other projects developed in this environment. However, instead of "hatching" turtles that can be changed into various shapes, users "add bones" and replace the resulting turtle-bone icons with bone-shapes. In this way, users amass whatever pieces they would like their skeletal creatures to have.



There are 24 pieces in the kit, including 3 dorsal spikes, 7 skulls, a shoulder girdle, a rib, single and triple vertebrae, a set of tailbones, a hip, two pelvises, a femur, a radius and ulna, a forelimb, a talon, a claw, and a set of digits. This collection is by no means exhaustive, but provides for rich possibilities in developing varied and interesting creatures. A child who wanted to make a facsimile after a dinosaur picture in a reference book would find most, if not all, of the needed parts.

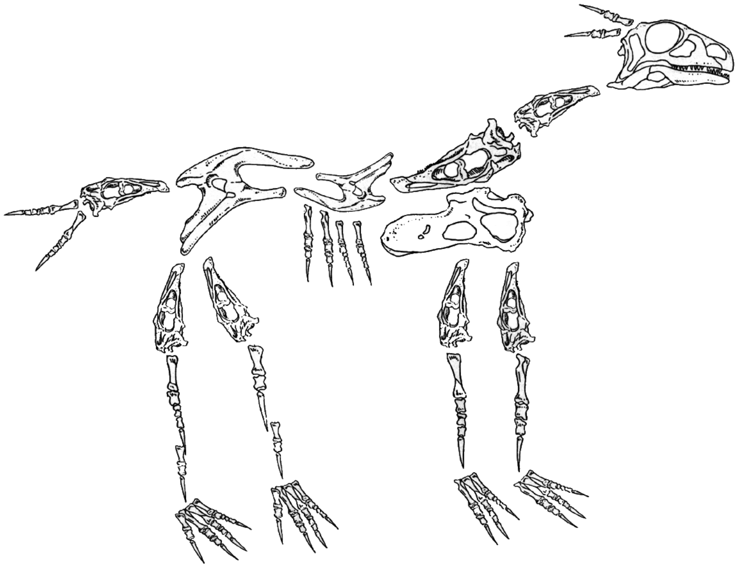


The MicroWorlds shapes editor enables modification of existing bones or creation of new ones. There are tools for selecting, cutting, copying, pasting; adding pixels, lines, and open and filled squares and circles, of different weights and colors; erasing, filling, spray-painting, and undoing. Bones can be rotated clockwise by 90-degree increments and flipped around a vertical axis.



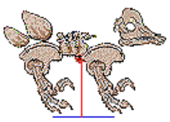
To increase the orientation possibilities, a duplicate of each bone is provided in 45-degree rotation. Thus, each piece can take any of 8 rotational positions. Bones can also be enlarged or reduced in size, and stamped into the background as permanent images.

Despite such variety, it's worth noting that acceptable skeletons can be made from just a few parts. This plausible-looking fellow is composed of only three kinds of bones – pelvises, skulls, and digits:

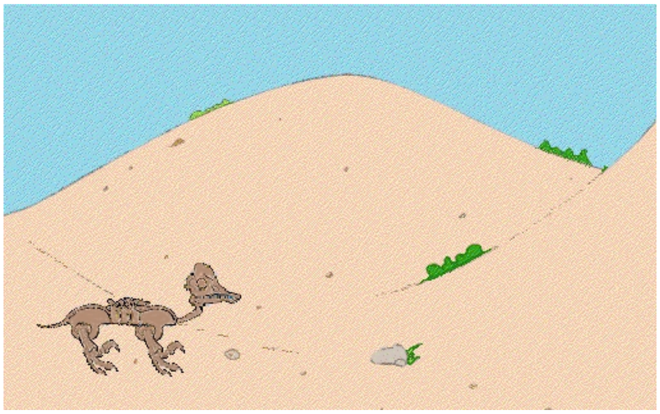


Skeletons created in the existing version of Them Bones tend to be fanciful but are often carefully crafted. Several of the children who have used the prototype have wanted even more degrees of freedom than the software currently provides for orienting bones.

After adding (and possibly removing) bones and fashioning a skeleton, users have a number of choices. They can see if the creature balances while standing, stepping, or moving at either of two speeds. They can do these balance tests with the "balance lines" on or off; these are the markings that show where the center of mass is and how it projects relative to the base.



Other functions allow users to stop a given movement, revert the creature to its original pose and position, and bring in a background picture to complete the scene. Skeletons move to music selected according to tempo, variations of a public-domain folk tune known by such names as "Them Bones" and "Dry Bones" ("...the knee bone's connected to the thigh bone, the thigh bone's connected to the hip bone...").



Because of how the creatures look and how they move, it's easy to project personality onto them and become attached to them. They tickle our sense of *animism;* they seem to be alive and to invite attention. Engaging with them is important for learning with them.

Beyond the prototype, a new implementation should enable creation and movement of creatures with greater numbers of bones, as in these wanna-be's that users have made:

Consistent with premises of microworld design, each object in the construction kit is characterized by a few simple properties: it has its own center of mass, a mass value (or weight), and a position. These three properties are used in calculating whether a skeleton will maintain its structural integrity and balance.

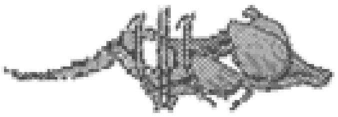
Position, of course, is determined by the user. It is expressed as the x- and y-coordinates of the bone's center. This point is determined generally for now, as the center of the 40-pixel square in which each bone is rendered. Weights are assigned as values within 10 and 99, but the weight of a bone changes as it is enlarged or reduced.

To calculate the center of mass for the composited creature, the program uses these values as follows:

$$\frac{(x,y)_{\text{elements composited thus far}} * \text{mass}_{\text{elements composited thus far}} + (x,y)_{\text{next element}} * \text{mass}_{\text{next element}}}{\text{mass}_{\text{elements composited thus far}} + \text{mass}_{\text{next element}}}$$

The program also designates upper and lower ranges for the creature, which are important structurally and for movement. The lower range goes from the creature's lowest y-coordinate to a y-level just below the center of mass; the upper range goes from this level to the highest y-coordinate. The lower part is interpreted as a collection of legs that move separately, according to built-in gait patterns; the upper part moves as a single entity.

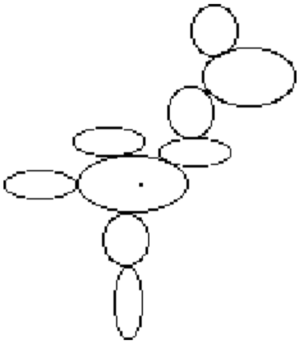
If the cumulative weight of the lower portion is insufficient to support the weight of the upper part, the creature collapses (with appropriate sound effects). Similarly, if a balance test fails, the creature falls. The user can see if a creature can balance while it is standing, stepping, moving slowly, or moving quickly. These balance tests consist of determining a base at ground level, calculating the creature's center of mass, and projecting the center onto the base. To form the base polygon, the program connects the points where the legs make contact with the ground. If the projection (a vertical line) falls within this polygon, the creature stands or moves successfully. If not, it crashes.



For movement sequences, the program designates left and right legs to move according to specific gait patterns. For a creature facing right, the designations are as follows, proceeding from left to right:

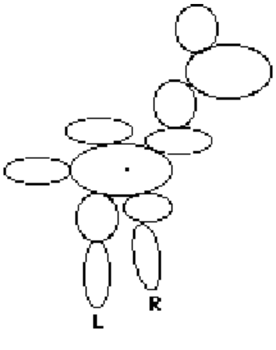
2 legs	**L**eft, **R**ight
3 legs	**L**eft**H**ind, **R**ight**H**ind, **F**ore
4 legs	**L**eft**H**ind, **R**ight**H**ind, **L**eft**F**ore, **R**ight**F**ore
5 legs	**L**eft**H**ind, **M**id**H**ind, **R**ight**H**ind, **L**eft**F**ore, **R**ight**F**ore
6 legs	**L**eft**H**ind, **R**ight**H**ind, **L**eft**M**iddle, **R**ight**M**iddle, **L**eft**F**ore, **R**ight**F**ore
many legs	**L**eft1, **R**ight1, **L**eft2, **R**ight2, **L**eft3, **R**ight3, **L**eft4, **R**ight4, **L**eft5 ...

Gait patterns for two speeds are as follows. They derive from analyses by Muybridge (1957), Hildebrand (1965, 1976), and Pearson (1976). The patterns show which legs get lifted and in what sequence. As a creature moves, its legs go up, over, and back down by amounts that differ for the slow and quick sequences. Ellipses indicate that the sequence repeats until it encounters a stop condition. The program are also has provisions for special cases of creatures with more than 6 legs.



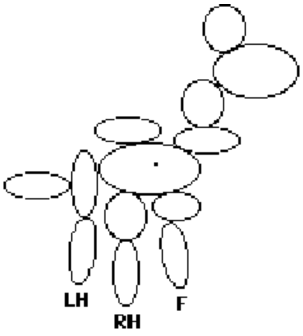
1 Leg

Slow:	*Quick:*
repeated up-and-down action	faster repeated up-and-down action



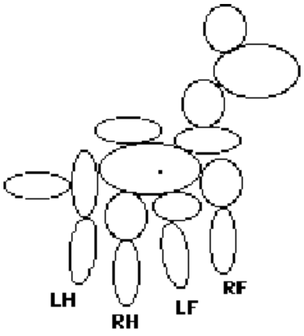
2 Legs

Slow:	*Quick:*
L R...	faster L R...



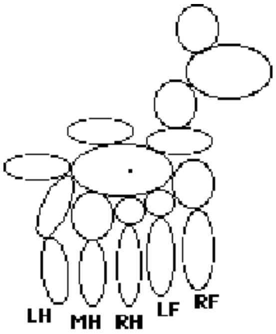
3 Legs

Slow:	*Quick:*
LH	F
RH	all
F...	LH, RH...



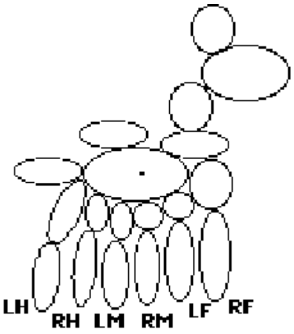
4 Legs

Slow:	*Quick:*
LH	LH, RF
LH, LF	all
LF	RH, LF
LF, RH	all...
RH	
RH, RF	
RF	
RF, LH...	



5 Legs

Slow:	*Quick:*
LH	LH, MH,
LH, LF	RH
LF	all
LF, MH	LF, RF
MH, RH	all...
RH	
RH, RF	
RF	
RF, MH	
MH,LH...	



6 Legs

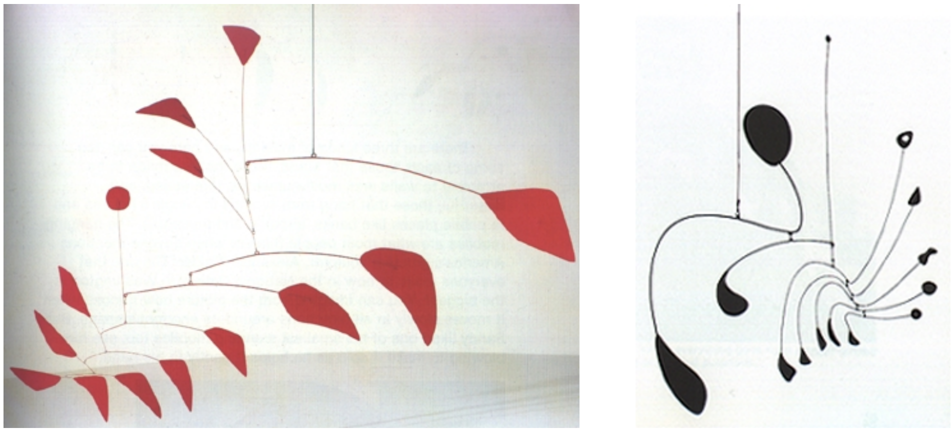
Slow:	*Quick:*
LH	LH, RM, LF
LH, LM	all
LM	RH, LM, RF
LM, LF	
LF	
LF, RH	
RH	
RH, RM	
RM	
RM, RF	
RF	
RF, LH	

The user can stop the sequence, reverse direction, or revert the creature to its initial pose and position. The next implementation may include several ways to improve the functionality. The creatures might leave footprints, their tracks providing visualizations of gait patterns. Children may be able to apply textures such as skin or feathers. Creatures and animations may be saved and exchanged with friends.

Several computational changes could improve the program's operation, and in some instances, the environment's potential as a learning environment. For example, calculating a center of mass for each bone rather than using a general position for these centers would improve the overall calculations. Using elastic rather than geometric similarity for bone magnifications would better approximate scaling relationships (e.g., Thompson, 1992). Leg length relative to body size could determine speed. The placement of a creature's center of mass could also affect movement: for example, if a creature with its center close to the forefeet stopped suddenly, it would flip forward rather than simply crashing. All of these are considerations for a new implementation.

Mobilize

Mobilize is also a microworld for learning about principles of balance. This environment could share algorithms with Them Bones, but the construction kit would have different parts – for assembling mobiles.

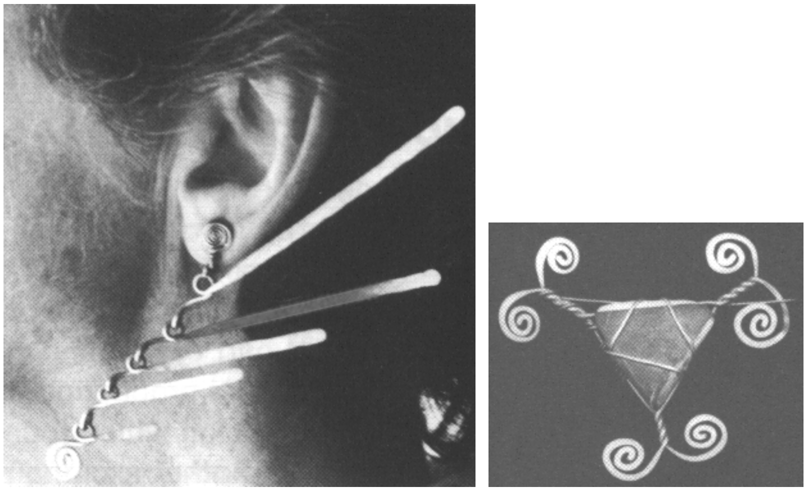


From J. Lipman & M. Aspinwall, Alexander Calder and His Magical Mobiles. *New York: Hudson Hills Press with the Whitney Museum of American Art, 1981.*

Mobiles present interesting variations on themes brought up by Them Bones. The two microworlds share a focus on the role of center of mass in balancing. In Mobilize, however, the consideration is relative to an inverted fulcrum rather than a base. This difference can become a powerful conceptual tool for children who use both microworlds. It provides opportunities for working with and thinking about the concept in more than one way, thereby coming to understand it deeply.

Another difference is that Mobilize would allow construction of objects that have many local centers rather than just one. This difference could push forward some of the questions that Them Bones begins to pose about how the location of a creature's center relative to the rest of the body can affect gait. Each microworld provides a different way to address the relationship between location of the center of mass and the object's movement.

Multiple approaches to a topic are also a way of addressing individual learning styles. Already, based on informal checks, we have some evidence that there are people who prefer to spend time thinking about mobiles rather than dinosaurs. Some of those individuals might especially appreciate a scaling facility that would enable Mobilize to double as a jewelry design kit.



From J. Lipman & M. Aspinwall, Alexander Calder and His Magical Mobiles.
New York: Hudson Hills Press with the Whitney Museum of American Art, 1981.

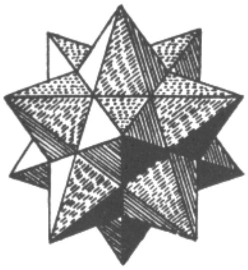
In addition to the work of Alexander Calder, Brand's (1994) software for mobile design will provide inspiration for this microworld.

Life on the Edge

Three avenues of thought contribute to the rationale for this microworld. One has to do with its mathematical premise; another, with psychological considerations to make thinking about this abstract premise easier; and the third, with relating the microworld to Them Bones through shared objects and functions.

In plane geometry, the number of sides of a polygon is always equal to the number of angles it inscribes. This characteristic helps us to classify polygons as triangles, quadrangles, pentagons, and so on. Such classification is not as straightforward for polyhedra, though. The number of faces alone may not be sufficient to differentiate one from the next. Euler solved this problem by introducing the concepts of *vertex* and *edge.* Besides the number of faces, the number of points and lines on the surface of a polyhedron determines it character.

In Euler's language, the classification formula for polygons is $V = E$; the number of vertices equals the number of edges. For polyhedra, the relationship is $V - E + F = 2$; the number of vertices, minus the number of edges, plus the number of faces, always equals 2. Why would this be? Euler's formulation for describing polyhedra is a basic tenet of topology, yet few people appreciate the relationships between the 0-dimensional vertexes, 1-dimensional edges, and 2-dimensional faces.

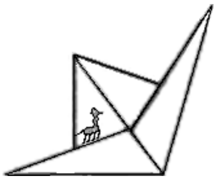


From I. Lakatos, Proofs and Refutations: The Logic of Mathematical Discovery.
Worral, J., & Zahar, E. eds. Cambridge: Cambridge Univ. Press, 1976.

The third microworld would focus on intuitive exploration of these relationships. Children would be able to construct colorful polyhedra and see them in different views. An excellent precedent for this work is a system by Eisenberg & Nishioka (1994) that enables children to design polyhedral forms in the computer, print flat versions of them, and fold the cut printouts into origami shapes.

The microworld would borrow a strategy from Piaget et al. (e.g., Piaget & Inhelder 1967; Strohecker 1991). In thinking about a complicated object such as a knot or a polyhedron, it helps to imagine oneself as a tiny creature crawling along the surface. (The classic version is a small ant.) This technique encourages spending time and focusing on details that are relevant in understanding the topology. Imagining oneself to be so small as to be surrounded by aspects of the object can engender a style of thinking in which the child becomes very much a part of a system that includes both the object and the child. The knot or polyhedron is no longer an external, bland object, but something that the child can "enter," experience, and come to know.

Life on the Edge would incorporate a facility for young people to use this strategy. In addition to constructing various polyhedra, children would be able to import skeletal creatures made in Them Bones to walk along the edges and faces.



It should be satisfying to see a creature of one's own making move in an environment of one's own creation. In addition to providing opportunities for learning about topology, and for *learning about* learning about topology, this environment should enable further study of roles of affect in learning.

Embedded Microworlds for Learning and Learning Research

Microworlds are tools for learning, but they are also tools for doing research on how learning happens. The design of microworld objects and tools is based on concepts fundamental to the topic domain, so users' thinking tends to have a particular focus. Their actions and explanations pertain to basic intellectual structures. These structures grow and change in the course of working in the microworld.

Because developmental processes happen in different ways and at different paces for different people, the primary task of learning research is to dwell on the activity and discussion of individual learners. The psychological method of clinical interview helps to bring to the surface and clarify individuals' processes of thinking and feeling. Both are relevant to how and what the individual learns.

Because humans are social and much learning happens though exchanges with others, anthropological and ethnographic techniques are also important. In particular, the method of participant observation is crucial in creating an honest, open, and supportive context for work that can yield in-depth data about learning processes.

The techniques of participant observation and clinical interview are well described in Piaget (1951), Turkle (1984), and Berg and Smith (1985). They are like petri dish and microscope in enabling study of social interactions, conceptual growth, and other issues relevant to evaluating learning engendered by the microworlds.

Whether or not Them Bones, Mobilize, and Life on the Edge are embedded in a MUD, they will help to focus research on issues of learning about balance and topological relationships; learning about one's own learning styles and strategies; identity; authorship and attribution; effects of affect; roles of technology in learning processes; and how members of demographic groups that typically shy away from math, science, and technology use the microworlds and deal with the concepts they embody.

A larger MUD context would add to possibilities for gathering data on these issues and would also strengthen the focus on the social context of learning. Researchers typically strive to create a social context and a lengthy program for constructive activities (e.g., see Harel and Papert, 1991). A MUD with embedded microworlds would greatly facilitate these features of an effort in learning research.

Learning takes time. In fact, some of the thinking that the microworlds engender may not show up as applicable learned material until years later. Papert (1980), who has described microworlds as "incubators for knowledge," has discussed this phenomenon in personal terms: he believes that his fascination with and learning about gears as a two-year-old eventually enabled his adult understanding of differential equations and other mathematical relationships.

Nevertheless, there is much we can glean in the short term. Microworlds such as the ones described here are well honed tools that we can use in furthering our understandings of how people learn.

Bibliography

Abelson, H., & diSessa, A. 1980. *Turtle Geometry: The Computer as a Medium for Exploring Mathematics.* Cambridge: MIT Press.

Ackermann, E. K. 1987. "Pathways Into a Child's Mind: Helping Children Become Epistemologists." "Science Learning in the Informal Setting" symposium, Chicago Academy of Sciences. Available through Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.

Alexander, R. M. 1988. *Elastic Mechanisms in Animal Movement*. New York: Cambridge Univ. Press.

Alexander, R. M. 1989. *Dynamics of Dinosaurs and Other Extinct Giants.* New York: Columbia Univ. Press.

Austin, Howard. 1976. "A Computational Theory of Physical Skill." Ph.D. diss., Massachusetts Inst. of Technology.

Beilin, H., & Pufall, P. B., eds. 1992. *Piaget's Theory: Prospects and Possibilities.* Hillsdale: Lawrence Erlbaum.

Berg, D. N., & Smith, K. K. 1985. *Exploring Clinical Methods for Social Research*. Beverly Hills: Sage Publ.

Beth, E. W. 1965. *Mathematical Thought: An Introduction to the Philosophy of Mathematics.* Dordrecht: D. Reidel Publ.

Beth, E. W. 1966 [1964, 1959]. *The Foundations of Mathematics: A Study in the Philosophy of Science.* New York: Harper & Row.

Beth, E. W., & Piaget, J. 1966. *Mathematical Epistemology and Psychology.* Mays, W., trans. Dordrecht: D. Reidel Publ.

Bettelheim, B. 1977. *The Uses of Enchantment: The Meaning and Importance of Fairy Tales.* New York: Vintage Books.

Bourbaki, N. 1966. *Elements of Mathematics: General Topology.* 2 vols. Reading: Addison-Wesley.

Brand, M. 1994. *Explanation-mediated Vision.* Ph.D. diss., Northwestern Univ.

Bruckman, A. 1991. "Identity Workshop: Emergent Social and Psychological Phenomena in Text-Based Virtual Reality." Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.

Courant, R., and Robbins, H. 1978 [1969, 1941]. *What is Mathematics?* Oxford: Oxford Univ. Press.

Curtis, P. 1992. "Mudding: Social Phenomena in Text-Based Virtual Realities." *Proceedings of the 1992 Conference on Directions and Implications of Advanced Computing, Berkeley.* Also available as Xerox PARC technical report CSL-92-4.

Damarin, S. K. "On the Necessity of Finding New Ways to Address the Women and Math Problem." Unpublished draft, Ohio State Univ.

Duckworth, Eleanor. 1987. *The Having of Wonderful Ideas: Essays on Teaching and Learning*. New York: Teachers College Press, Columbia Univ.

Edwards, L. 1994. "Microworlds as Representations." Santa Cruz: Crown College, Univ. of CA.

Eisenberg, M., & Nishioka, A. 1994. "HyperGami: A Computational System for Creating Decorated Paper Constructions." To appear in Proceedings of the Origami Science Meeting, Otsu, Japan.

Ericsson, K. A., and Simon, H. A. 1984. *Protocol Analysis: Verbal Reports as Data*. Cambridge: MIT Press.

Erikson, E. H. 1963 [1950]. *Childhood and Society*. New York: W.W. Norton.

Fisher, S. S. 1993. "Menagerie." *Computer Graphics Visual Proceedings*. ACM SIGGRAPH.

Frampton, K. 1992 [1980]. *Modern Architecture: A Critical History*. London: Thames & Hudson.

Geertz, C. 1973. *The Interpretation of Cultures*. New York: Basic Books.

Gentner, D., and Stevens, A. L., eds. 1983. *Mental Models*. Hillsdale: Lawrence Erlbaum.

Gillette & Lockley, eds. 1989. *Dinosaur Tracks and Traces*. Cambridge: Cambridge Univ. Press.

Gilligan, C. 1982. *In a Different Voice: Psychological Theory and Women's Development*. Cambridge: Harvard Univ. Press.

Goodman, F. L. "Why Might Games Be Taken Seriously By Educators?" Unpublished paper, School of Education, University of Michigan, Ann Arbor.

Gray, J. 1953. *How Animals Move*. Cambridge: Cambridge Univ. Press.

Gruber, H. E., & Vonèche, J. J., eds. 1977. *The Essential Piaget*. New York: Basic Books.

Hadamard, J. 1945. *The Psychology of Invention in the Mathematical Field*. New York: Dover Publ.

Harel, I. 1988. "Software Design for Learning: Children's Construction of Meaning for Fractions and Logo Programming." Ph.D. diss., Massachusetts Inst. of Technology.

Harel, I., & Papert, S., eds. 1991. *Constructionism*. Norwood: Ablex.

Hayles, K. 1995. "Embodied Virtuality: Or How to Put Bodies Back into the Picture." *Immersed in Technology*. Moser, M. A., ed. MIT Press.

Higginson, W. 1978. "Language, Logic and Mathematics: Reflections on Aspects of Education and Research." *Revue de Phonétique Appliquée* 46-47:101-30.

Hildebrand, Milton. 1960. "How Animals Run." *Scientific American* May: 148-157.

Hildebrand, Milton. 1965. "Symmetrical Gaits of Horses." *Science* 150: 701-708.

Hildebrand, M. 1976. "Analysis of Tetrapod Gaits: General Considerations and Symmetrical Gaits." *Neural Control of Locomotion*. R. M. Herman, S. Grillner, Stein, P. S. G., & Stuart, D. G., eds. New York: Plenum Publ.

Hildebrand, M. 1980. "The Adaptive Significance of Tetrapod Gait Selection." *Americal Zoologist* 20: 255-267.

Honey, M. 1990. "Play in the Phallic Universe: An Analysis of Adolescents' Involvement with a Fantasy Role Playing Computer Game." New York: Center for Children and Technology, Bank Street College.

Jacob, E. 1987. "Qualitative Research Traditions: A Review." *Review of Educational Research* 57, 1: 1-50.

Jenkins, H. 1993. "x Logic": Repositioning Nintendo in Children's Lives. *Quarterly Review of Film and Video* 14, 4: 55-70.

Karmiloff-Smith, A., & Inhelder, B. 1975. "If You Want to Get Ahead, Get a Theory." *Cognition* 3, 3: 195-212.

Kegan, R. 1982. *The Evolving Self: Problem and Process in Human Development.* Cambridge: Harvard Univ. Press.

Keller, E. F. 1985. *Reflections on Gender and Science*. New Haven: Yale Univ. Press.

Kinder, M. 1991. *Playing with Power in Movies, Television and Video Games: From Muppet Babies to Teenage Mutant Ninja Turtles.* Berkeley: Univ. of California Press.

Kliman, M. 1987. "Breaking the Law: Competing Perspectives in Children's Thinking about the Balance Scale." Master's thesis, Massachusetts Inst. of Technology.

Kliman, M. 1987. "Children's Learning about the Balance Scale." *Instructional Science* 15: 307-40.

Lakatos, I. 1976. *Proofs and Refutations: The Logic of Mathematical Discovery.* Worral, J., & Zahar, E. eds. Cambridge: Cambridge Univ. Press.

Lampert, M. 1988. "The Teacher's Role in Reinventing the Meaning of Mathematical Knowing in the Classroom." Research Series no. 186. East Lansing: Inst. for Research on Teaching, College of Education, Michigan State Univ.

Latour, B. 1987. *Science in Action.* Cambridge, MA: Harvard Univ. Press.

Laurel, B., Strickland, R., and Tow, R. 1994. "Placeholder: Landscape and Narrative in Virtual Environments." *Computer Graphics* 28:2, 118-126.

Lave, J. 1988. *Cognition in Practice: Mind, Mathematics, and Culture in Everyday Life.* Cambridge: Cambridge Univ. Press.

Lévi-Strauss, C. 1966 [1962]. *The Savage Mind.* Chicago: Univ. of Chicago Press.

Lipman, J., & Aspinwall, M. 1981. *Alexander Calder and His Magical Mobiles.* New York: Hudson Hills Press, Whitney Museum of American Art.

Llewellyn, G., ed. 1992. *Real Lives: 11 Teenagers Who Don't Go to School.* Eugene: Lowry House.

McCulloch, W. S. 1961. "What is a Number, that a Man May Know It, and a Man, that He May Know a Number?" Alfred Korzybski Memorial Lecture 1960. *General Semantics Bulletin* 26/27: 7-18.

McGeer, Tad. 1990. "Passive Dynamic Walking." *International Journal of Robotics Research* 9,2: 62-82.

McGhee, R. B., & Frank, A. A. 1968. "On the Stability Properties of Quadraped Creeping Gaits." *Mathematical Biosciences* 3:331-351.

McKenna, M., & Zeltzer, D. 1990. "Dynamic Simulation of Autonomous Legged Locomotion." *Computer Graphics* 24, 4: 29-38.

McMahon, T. A. 1975. "Using Body Size to Understand the Structural Design of Animals: Quadrupedal Locomotion." *Journal of Applied Physiology* 39, 4: 619-627.

McMahon, T. A. 1985. "The Role of Compliance in Mammalian Running Gaits." *Journal of Experimental Biology* 115, 263-282.

Morningstar, C., & Farmer, F. R. 1991. The Lessons of Lucasfilms' *Habitat. Cyberspace: First Steps.* Benedikt, M., ed. Cambridge: MIT Press.

Motherwell, L. 1988. "Gender and Style Differences in a Logo-Based Environment." Ph.D. diss., Massachusetts Inst. of Technology.

Muybridge, Eadweard. 1957. *Animals in Motion.* New York: Dover Publ.

Oldenburg, R. 1989. *The Great Good Place: Cafés, Coffee Shops, Community Centers, Beauty Parlors, General Stores, Bars, Hangouts and How They Get You through the Day.* New York: Paragon House.

Papert, S. 1971. "Teaching Children to be Mathematicians vs. Teaching About Mathematics." Artificial Intelligence Memo no. 249, Logo Memo no. 4. Cambridge: A. I. Laboratory, Massachusetts Inst. of Technology.

Papert, S. 1971. "Teaching Children Thinking." Artificial Intelligence Memo no. 247, Logo Memo no. 2. Cambridge: A. I. Laboratory, Massachusetts Inst. of Technology.

Papert, S. 1973. "Uses of Technology to Enhance Education." Artificial Intelligence Memo no. 298, Logo Memo no. 8. Cambridge: A. I. Laboratory, Massachusetts Inst. of Technology.

Papert, S. 1980. *Mindstorms: Children, Computers, and Powerful Ideas.* New York: Basic Books.

Papert, S. 1980. "Redefining Childhood: The Computer Presence as an Experiment in Developmental Psychology." Amsterdam: North-Holland Publ.
Papert, S. 1984. "Microworlds: Transforming Education." *The Computer Culture*. Evans, S. H., & Clarke, P., eds. Indianapolis: White River Press.
Papert, S. 1984. "New Theories for New Learnings." *School Psychology Review*, Oct.
Papert, S. 1986. "Beyond the Cognitive: The Other Face of Mathematics." Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Papert, S. 1986. *On Logo.* "Thinking": Tape 3, New Mindstorms videotape series. St. Louis: Media Microworlds.
Papert, S. 1987. "A Critique of Technocentrism in Thinking about the School of the Future." "Children in an Information Age: Opportunities for Creativity, Innovation, and New Activities" conference, Sofia, Bulgaria.
Papert, S. 1987. "Using Computers to Combat Illiteracy: Towards a Constructionist Theory of Creative Learning." A Proposal to the MacArthur Foundation. Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Papert, S. 1988. "Objects-to-Think-With." Unpublished course syllabus, Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Papert, S. 1988. "One AI or Many?" *Daedalus: Journal of the American Academy of Arts and Sciences* 117,1:1-14.
Papert, S. 1990. "A Unified Computer Environment for Schools: A Cultural/ Constructionist Approach." Proposal to the National Science Foundation. Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Papert, S. 1991. "A Teachers' Learning Collaborative: A Model for the Appropriation of Science by Elementary Teachers." Proposal to the National Science Foundation. MIT Media Lab in cooperation with the Science and Whole Learning Teachers Collaborative.
Papert, S. 1991. "New Images of Programming: In Search of an Educationally Powerful Concept of Technological Fluency." Proposal to the National Science Foundation. Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Papert, S. 1993. *The Children's Machine: Rethinking School in the Age of the Computer.* New York: Basic Books.
Papert, S., & Associates. 1987. "Learning at the Zoo: A Design for an EcoLearning Center at the St. Louis Zoo." Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.
Pearson, K. 1976. "The Control of Walking." *Scientific American*, pp. 72-86.
Perkins, D. 1986. *Knowledge As Design.* Hillsdale: Lawrence Erlbaum.
Peterson, I. 1988. "Shareware, Mathematics Style." *Science News* 2 Jan: 12-13.
Piaget, J. 1951 [1929]. *The Child's Conception of the World.* Tomlinson, J. & Tomlinson, A., trans. New York: Humanities Press.
Piaget, J. 1962. *Play, Dreams, and Imitation in Childhood*. Gattegno, C., & Hodgson, F. M., trans. New York: W. W. Norton.
Piaget, J. 1965 [1952, 1941]. *The Child's Conception of Number*. New York: W. W. Norton.
Piaget, J. 1970 [1946]. *The Child's Conception of Movement and Speed*. Holloway, G.E.T., & Mackenzie, M. J., trans. New York: Basic Books.
Piaget, J. 1970. *Genetic Epistemology*. Duckworth, E., trans. New York: Columbia Univ. Press.
Piaget, J. 1970 [1968]. *Structuralism.* Maschler, C., ed., trans. New York: Basic Books.
Piaget, J. 1971 [1970]. *Psychology and Epistemology*. Rosin, A., trans. New York: Grossman Publ.
Piaget, J. 1976 [1974]. *The Grasp of Consciousness: Action and Concept in the Young Child.* Wedgwood, S., trans. Cambridge: Harvard Univ. Press.

Piaget, J. 1985 [1975]. *The Equilibration of Cognitive Structures: The Central Problem of Intellectual Development*. Brown, T., & Thampy, K. J., trans. Chicago: Univ. of Chicago Press.

Piaget, J., & Inhelder, B. 1967 [1956, 1948]. *The Child's Conception of Space.* Langdon, F. J., & Lunzer, J. L., trans. New York: W. W. Norton.

Polkinghorne, D. 1983. *Methodology for the Human Sciences: Systems of Inquiry*. Albany: State Univ. of New York Press.

Polya, G. 1973 [1957, 1945]. *How to Solve It: A New Aspect of Mathematical Method*. Princeton: Princeton Univ. Press.

Provenzo, E. F. 1991. *Video Kids: Making Sense of Nintendo.* Cambridge: Harvard Univ. Press.

Raibert, M. 1986. *Legged Robots That Balance.* Cambridge: MIT Press.

Raibert, M., Chepponis, M., & Brown, Jr., H. B. 1986. "Running on Four Legs As Though They Were One." *IEEE Journal of Robotics and Automation* RA-2, 2: 270-82.

Rheingold, H. 1993. *The Virtual Community: Homesteading on the Electronic Frontier.* Reading: Addison-Wesley.

Rich, C., Waters, D., Schabes, Y., Strohecker, C., Freeman, B., & Roth, M. 1994. "Demonstration of an Interactive Environment for Collaboration and Learning." *IEEE Computer* 27, 12.

Rich, C., Waters, D., Schabes, Y., Freeman, B., & Roth, M. 1994. "An Animated Online Community with Artificial Agents and Spoken Interaction." *IEEE Multimedia* 1, 4.

Schön, D. 1983. *The Reflective Practitioner.* New York: Basic Books.

Sorkin, M., ed. 1992. *Variations on a Theme Park.* New York: Hill & Wang.

Shapiro, D. 1965. *Neurotic Styles*. New York: Basic Books.

Sims, Karl. 1987. "Locomotion of Jointed Figures over Complex Terrain." Master's thesis, Massachusetts Inst. of Technology.

Sims, Karl. 1994. "Evolving Virtual Creatures." *SIGGRAPH 94 Computer Graphics Proceedings.* Assoc. for Computing Machinery.

Skemp, R. R. 1971. *The Psychology of Learning Mathematics*. Harmondsworth: Penguin Books.

Soloway, Elliot. 1991. "How the Nintendo Generation Learns." *Communications of the ACM* 34,9: 23-26.

Strohecker, C. 1990. "Knot-Tying: A Constructionist Environment for Topology." *Constructionist Learning.* I. Harel, ed. Epistemology & Learning Group, Media Lab, Massachusetts Inst. of Technology.

Strohecker, C. 1991. *Why Knot?* Ph.D. diss., Massachusetts Inst. of Technology.

Strohecker, C. 1992. "Elucidating Styles of Thinking through Learning about Knots." *Constructionism.* Harel, I., & Papert, S., eds. Norwood: Ablex.

Strohecker, C. 1992. "Ideas for a System Supporting Users' Learning of a Foreign Language." MERL Note 92-19. Cambridge: Mitsubishi Electric Research Labs.

Strohecker, C. 1993. "A View of Learning Environments." MERL Note 93-17. Cambridge: Mitsubishi Electric Research Labs.

Strohecker, C. 1994. "The 'Zircus' Concept Sketch for a Learning Environment and Online Community." MERL Technical Report 94-22. Cambridge: Mitsubishi Electric Research Labs.

Strohecker, C. 1995. "A Model for Museum Outreach Based on Shared Interactive Spaces." Internat. Conf. on Hypermedia and Interactivity in Museums, San Diego.

Suchman, L. 1987. *Plans and Situated Actions.* Cambridge: Cambridge Univ. Press.

Thompson, D'Arcy. 1992. *On Growth and Form.* New York: Dover Publ.

Thulborn, R. A. 1989. "The Gaits of Dinosaurs." Cambridge: Cambridge Univ. Press.

Turkle, Sherry. 1984. *The Second Self: Computers and the Human Spirit.* New York: Simon & Schuster.

Turkle, S. 1990. "Romantic Reactions: Paradoxical Responses to the Computer Presence." *Boundaries of Humanity: Humans, Animals, Machines*. Sousna, M., & Sheean, J., eds. Berkeley: Univ. of California Press.

Turkle, S., & Papert, S. 1990. "Epistemological Pluralism: Styles and Voices Within the Computer Culture." *Signs* 16,1. Chicago Univ. Press.

Turkle, S. 1984. *The Second Self: Computers and the Human Spirit.* New York: Simon & Schuster.

Watzlawick, P., Weakland, J., & Fisch, R. 1974. *Change: Principles of Problem Formation and Problem Resolution*. New York: W. W. Norton.

Winnicott, D. W. 1971. *Playing and Reality.* London: Tavistock Publ.