Behavioral Kinetic Sculpture

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June 1996

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences at the
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Abstract
As we enter the 21st century our culture has been significantly changed by the arrival of the internet and the proliferation of personal computing and digital communications. As the decades progress, we will find ourselves interacting with machines more and more frequently, but what will be the qualities of these interactions? Through integrating information processing technologies into kinetic sculpture we are able to explore new methods and properties of interaction. The concepts and experiments presented in this thesis as behavioral kinetic sculpture are the intellectual progeny of cybernetic art as evolved over the last thirty years through the development of interactive software, behavioral robotics, artificial life, and modern sculpture. This thesis defines the concept of behavioral kinetic sculpture as a unique category of expression through providing context, terminology, and a conceptual structure for its discussion and evaluation. This is supported through discussing the author's experiments in interaction and the behavioral kinetic sculpture, *Trundle*.

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Associate Professor of Design and Computation
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Behavioral Kinetic Sculpture

Casey Reas

Thesis Reader: Bruce Blumberg
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Behavioral Kinetic Sculpture

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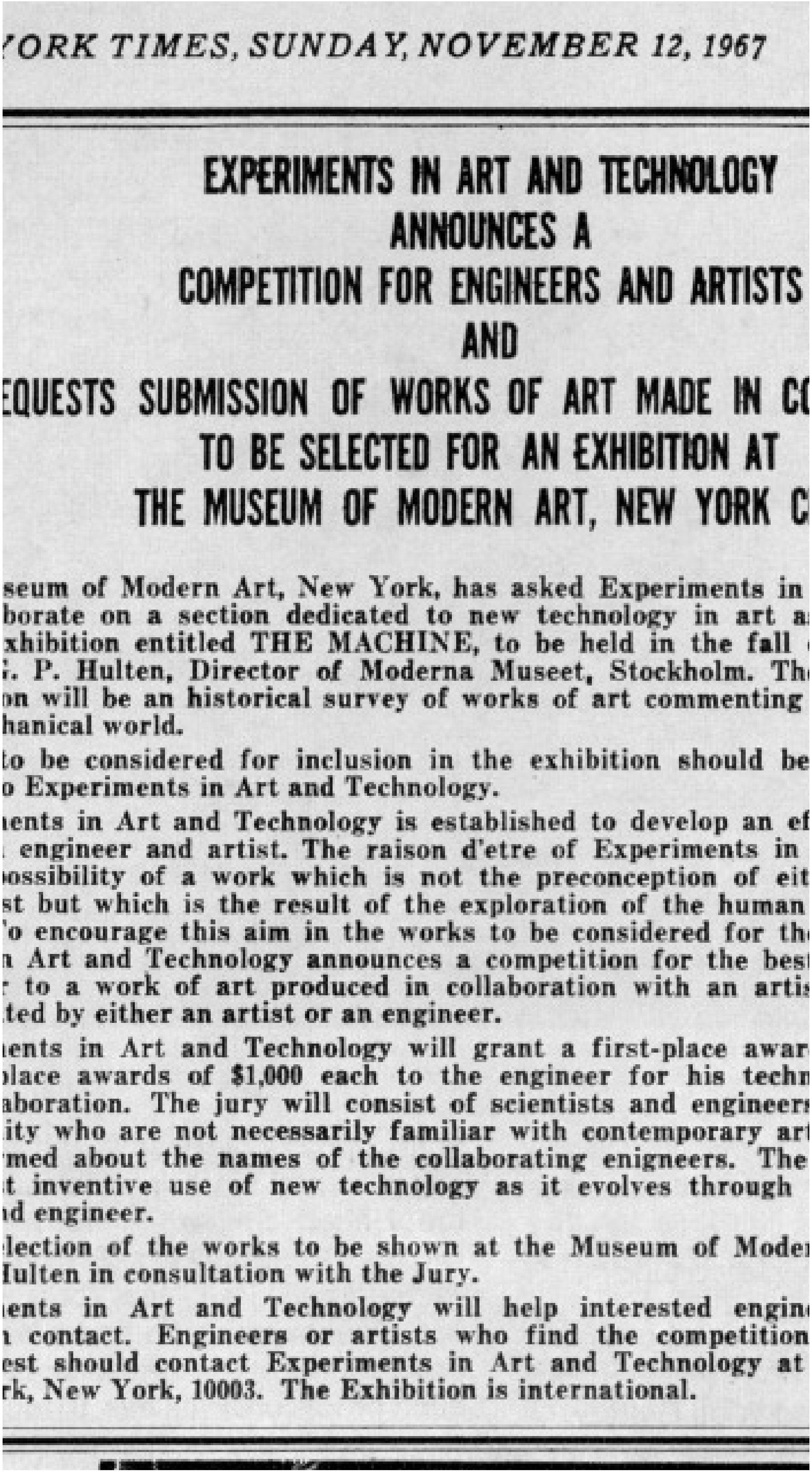
*   A collaboration with Golan Levin
** A group project within the MIT Media Laboratory's Aesthetics & Computation Group



ʼORK TIMES, SUNDAY, NOVEMBER 12, 1967

EXPERIMENTS IN ART AND TECHNOLOGY ANNOUNCES A COMPETITION FOR ENGINEERS AND ARTISTS AND ʼEQUESTS SUBMISSION OF WORKS OF ART MADE IN CO TO BE SELECTED FOR AN EXHIBITION AT THE MUSEUM OF MODERN ART, NEW YORK C

seum of Modern Art, New York, has asked Experiments in borate on a section dedicated to new technology in art a xhibition entitled THE MACHINE, to be held in the fall . P. Hulten, Director of Moderna Museet, Stockholm. Th on will be an historical survey of works of art commenting hanical world.

to be considered for inclusion in the exhibition should be o Experiments in Art and Technology.

ents in Art and Technology is established to develop an ef engineer and artist. The raison d'etre of Experiments in ossibility of a work which is not the preconception of eit st but which is the result of the exploration of the human o encourage this aim in the works to be considered for th Art and Technology announces a competition for the best to a work of art produced in collaboration with an artis ted by either an artist or an engineer.

ents in Art and Technology will grant a first-place awar lace awards of $1,000 each to the engineer for his techn aboration. The jury will consist of scientists and engineer ity who are not necessarily familiar with contemporary art med about the names of the collaborating enigneers. The t inventive use of new technology as it evolves through d engineer.

lection of the works to be shown at the Museum of Mode Iulten in consultation with the Jury.

ents in Art and Technology will help interested engin contact. Engineers or artists who find the competition est should contact Experiments in Art and Technology at rk, New York, 10003. The Exhibition is international.

1 Open request for submissions for the Experiments in Art and Technology (E.A.T.) portion of Pontus Hulten's *The Machine* exhibit. Printed in the Sunday New York Times on 12 November 1967

Introduction

During the 1960s a new kind of sculpture originated from the popular cybernetics theories of the time. Cybernetics, a synthesis of control theory, information theory, and biology, was defined by its pioneer Norbert Weiner, as "control and communication in the animal and machine [Wiener 1948]." A cybernetic sculpture is one which processes information from its environment and uses this information to control physical events. The 1968 *Cybernetic Serendipity* show at the Institute of Contemporary Arts in London and *The Machine* at the Museum of Modern Art in New York were two of the first exhibitions to widely reveal this work to the public. In his book *Beyond Modern Sculpture*, artist and critic Jack Burnam explains the relationship of this new interactive sculpture to the sculpture of the past:

> In the past such an interaction was impossible — or at best a very one-sided affair. It was, to place it within a cybernetic context, a relationship between a complex, self-stabilizing, goal seeking system (man) and an inert object (a stone statue perhaps) — or man and a work of art designed as a mechanical system seeking stability through pseudo-random motion (a Calder mobile) — or man and an aesthetic system with a determinate but very complex program (motion pictures, symphonic music, Kinetic Art, etc.). Still, the result in every case was not communication but one-way stimulation for the human party involved [Burnam p.36].

Despite initial excitement and promise, comparatively few sculptors assumed the daunting challenge of creating cybernetic sculpture. Due to a number of social, economic, and technical factors, the production of this work quickly stagnated, but despite its quick end, cybernetic art opened a new territory for exploration — one that has still not fulfilled its initial promise. As we enter the 21st century our culture has been significantly changed by the arrival of the internet and the proliferation of personal computing and digital communications. As the decades progress, we will shortly find ourselves interacting with machines more and more frequently, but what will be the qualities of these interactions? The future of cybernetic art has the potential to be a powerful force in shaping our future relations with our machines.

1.1 Motivation

The concepts and experiments presented in this thesis as *behavioral kinetic sculpture* are the intellectual progeny of cybernetic art as evolved over the last thirty years through the development of modern automata, behavioral robotics, artificial life, and kinetic sculpture. During this time, when our machines were more limited in their ability to process information and we were more limited in our ability to assist them, we developed a standard set of tools for human-computer interaction that impoverished our natural communication channels. The legacy of the mouse, keyboard, CRT screen, and the windows metaphor continues to dominate the way we interact with our machines, while the original reasons for their development are beginning to disappear. We are now entering a time when our relationships with interactive physical objects are being defined. The development of behavioral kinetic sculpture may reveal innovative possibilities for the future of our interaction with machines.

1.1.1 Behavioral model of interaction

The principle idea behind a behavioral model of interaction is to develop a method of interaction that is more similar to engaging with plants, insects, animals, and people than engaging with stones, books, furniture, and buildings. The goal of creating sculpture with behavior is not to mimic biological organisms, but to utilize their characteristics to develop a visceral engagement with three-dimensional works of art. Qualities of a behavioral mode of interaction include perception of control, responsiveness, unpredictability, engagement with the body, and nuance of communication. These qualities may be manipulated by the creator of a behavioral kinetic sculpture to either facilitate communication or to challenge expectations.

1.1.2.1 *Perception of control*

The experience of playing with a stuffed animal is much different than playing with a real animal. When a child interacts with a cloth animal, she/he is in total control of the situation, but interacting with a real animal requires mutual interest. To engage in a positive interaction the human must be aware of the animal's emotions through its physical cues and provide the appropriate feedback so that the animal knows how to respond. In this scenario, there is continuous information being passed back and forth between the animal and human. The human is not in control of the animal and the animal is not in control of the human, but there is reciprocal communication. The perception of control in a behavioral interaction may range from strong control to total lack of control, but there must be information communicated between both parties for a behavioral interaction to exist.

1.1.2.2 *Responsiveness*

The need for a response to every action is necessary to maintain communication. If speaking with other people, for example, we notice the changes in their facial expression as a response to what we say. We know that eye contact implies engagement, the nod of the head is a confirmation, and wandering eyes may mean a lack of attention. In speaking on the phone we often give feedback through verbal confirmations and tone of voice. If there is no response or feedback in a given situation, the people interacting are not able to build a model of the state of the other party and communication becomes confused and impossible.

1.1.2.3 *Unpredictability*

The idea of unpredictably is related to control but differs in expectation. If we are able to predict every response, interaction is boring. In growing a plant, for example, we should see a positive correlation between watering it and watching it grow, but if a plant grew exactly one millimeter every week and sprouted a new bud on exactly the first day of every month, we would not have the joy of seeing a new and unexpected flowering or new growth. A balance must be met, though, between the disinterest of unchanging reactions and pure chaos. If the plant grows a different amount each week regardless of the care it receives, there would be no noticeable correlation between the caregiver and the organism and the connection would be lost. Although random systems may provide appealing results, they do not allow humans to speculate the future of the system and therefore do not engage the imagination like a behavioral system.

1.1.2.4 *Engagement with the body*

Our natural modes of communication and behavior engage the entire body. We communicate through our movement, speak with our hands, and understand the world in relation to our physical presence. Total engagement of our body requires a physical kinetic presence. Through creating physical behavior in the medium of sculpture we are able to engage on a visceral level not possible in flat representation.

1.1.2.5 Nuance of communication

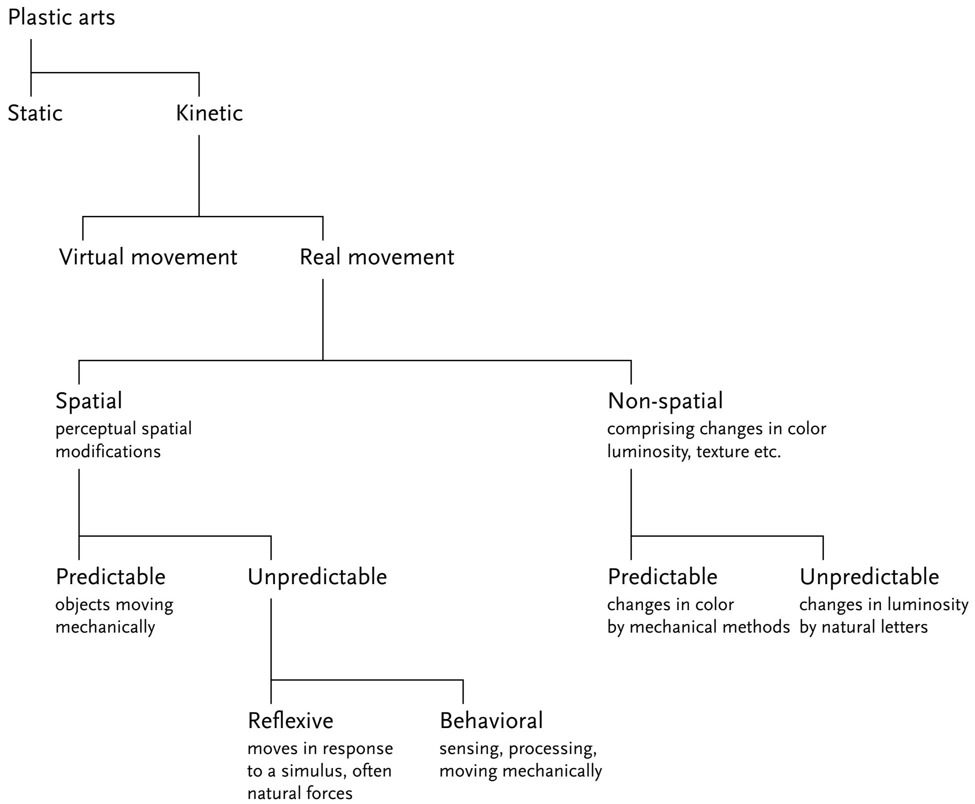
The amount of information we convey to other people while communicating with them is theoretically infinite, but filtered through our senses to make it manageable. In contrast, the information we convey to our machines through a mouse and keyboard is extremely small and quantized. A behavioral interaction would ideally provide a channel for communication where the minute details of human communication would affect the system.

1.1.2 The potential of new technologies

Integrating information processing technologies into kinetic sculpture enables artists to create sculpture that can receive, store, modify, and transmit information and make possible a new type of work: computational abstractions of biological systems. These abstractions can be imbued with reflex, affect, and the ability to communicate through combining electrical sensors, digital logic, and communications technology. By using a behavior-based software architecture to control a sculpture's movement, complex series of coordinated motion can be performed in response to the sculpture's environment and in relation to its internal state. In the 1960s when artists began working with these concepts, massive amounts of money and engineering skill were necessary to create the work. For the 1966 *Nine Evenings* event in New York at least 8,500 engineering hours were spent and there were still many technical breakdowns [Burnam p. 363]. Corporate sponsorship became necessary for many artists to realize their vision and artist organizations such at E.A.T., The Centre for Advanced Study of Science in Art, and the Center for Advanced Visual Studies were developed for supporting artist collaborations with interested engineers. Over the last thirty years, however, the development and subsequent advances in microprocessor technology, computer software, and sensor technologies have created a climate where raw materials are readily available and the knowledge required for executing such work is within the reach of the dedicated artist so she/he may create, explore, and innovate in a personal and liberated manner.

1.2 Defining the problem

Through further defining the concept of a behavioral kinetic sculpture, a foundation is constructed for discussion and evaluation in respect to other forms of sculpture and related disciplines. This definition is focused, but



2 Augmentation of Frank Popper's classification of kinetic art to include behavioral sculpture

comprehensive of historical work and general enough to allow for expansion and innovation in the future.

1.2.1 Refining the terminology

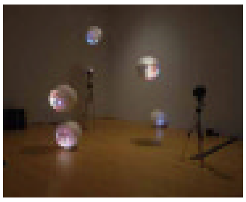
For the purposes of clarity, attention is given to the usage of the key words *behavior* and *kinetic* and as a result of its recently modified meaning, the elimination of the prefix *cyber-*.

1.2.1.1 Behavior

While the simplest definition of *behavior* is action and response to a stimulus, the use of the word behavior in this document refers to a more complex idea that is distinct from the phenomena of reflex. In his book *Design for a Brain*, W. Ross Ashby describes two distinct types of behavior:

> The first type is reflex behaviour. It is inborn, it is genetically determined in detail, it is a product, in the vertebrates, chiefly of centres in the spinal cord and in the base of the brain, and it is not appreciably modified by individual experience. The second type is learned behaviour. It is not inborn, it is not genetically determined in detail, it is a product chiefly of the cerebral cortex, and it is modified markedly by the organism's individual experiences. [Ashby p.2]

3 Alexander Calder. *Untitled,* 1976



4 Tony Oursler. *Glimmer,* 1999

5 Nam June Paik. *Passage,* 1986

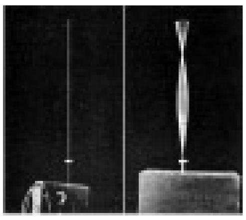
These statements are supported by ethological research such as Tinbergen's studies with three-spined sticklebacks. In studying these fish, he found that complex behaviors such as schooling are built from primitive reflex behaviors like obstacle avoidance [Tu p.21]. Within the context of behavioral kinetic sculpture, behavior refers to complex behaviors rooted in reflex, but modified over time through the sculpture's interaction with the environment.

1.2.1.2 Kinetic

The word *kinetic* is only understood in reference to the word *kinematic*. As originally defined by Andre Ampere in 1830, *kinematics* is the study of motion unattached to forces or objects and is therefore only considers ideal situations. *Kinetics*, on the other hand, is concerned with motions resulting from forces directly connected with physical systems. Alexander Calder's *Untitled* mobile (fig. 3) built in 1976 is an example of kinetic motion. Kinematics can only be studied in the mind, on paper, or in a digital environment, while kinetics can only be studied in the real world using physical matter acted on by external forces. Kinetics is therefore inherently associated with physical sculpture and a work of sculpture completely realized inside a computer is therefore a kinematic sculpture. If this kinematic sculpture has simulated forces, it is a simulated kinetic sculpture. According to this definition, video artworks combining moving images with dimensional elements such as those by the artists Tony Oursler (fig. 4), Bill Viola, Nam June Paik (fig. 5) are not included as kinetic works because their movement is confined to a surface.

1.2.1.3 Cyber-

During the origins of behavioral kinetic sculpture it was called cyborg or cybernetic sculpture, but as a result of the changing meaning of these words, they will not be used as descriptive terms in this document. Over the last thirty years these terms have assumed an extremely different cultural meaning primarily through the adoption of the recent term cyberspace, referring to a virtual world created within a computer network, and a shift in the meaning of cyborg. At one time, the term cyborg made reference to a machine with the properties of a biological organism but it currently refers strictly to a biological organism enhanced with electronic or electromechanical devices.

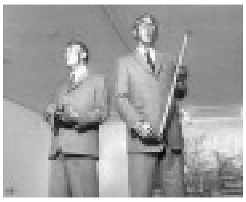


6 Naum Gabo. *Standing Wave*, 1920

1.2.2 Behavioral kinetic sculpture defined

Figure 2 presents a relational map of different categories of art. In this representation, behavioral kinetic sculpture is a subcategory of spatial movement that is not predictable. Artist Simon Penny explains, "Unlike previous mimetic art practices, in this work the *dynamics* of biological systems are modeled more than their appearance. These works exhibit a new order of mimesis in which 'nature' as a generative system, not an appearance, is being represented [Penny 1995]." The property that makes a sculpture behavioral is not visual, but is revealed in time as the sculpture interacts with its environment. It is the way it reacts to a loud noise, the way it responds when touched, or the sound it makes when there is no one around to hear it. In relation to other forms of art, behavioral art requires the work to react or adapt to the environment. As an explanation, consider the following hypothetical construction of four visually identical sculptures, each one a small box with a wire protruding from the top. These hypothetical constructions are similar in physical form to Naum Gabo's *Standing Wave* (fig. 6). The first sculpture is rigidly constructed and not able to move. It always remains in the same position and is therefore an example of a *static* sculpture. The second sculpture has a small motor inside its box which moves the wire back and forth in an unchanging rhythm. This sculpture is an example of an active sculpture. The third sculpture also has a small motor in its box, but also has a touch sensor and some simple electronics connecting the sensor to the motor. This sculpture senses if someone is touching it and reacts by turning on the motor, which moves the wire. There is no variation in the way it reacts, however, and is therefore an example of a *reflexive* sculpture. The fourth sculpture is physically identical to the third except it has more complex electronics for converting the sensor data into motion. This sculpture, like the fourth, is aware of whatever its sensors enable it to be aware of, but it may change the way it reacts to a stimulus depending on how it is programmed and is therefore called a *reactive* sculpture. For example, this sculpture could be programmed to move its motor once for every time it has been touched. On the fifth touch, then, it would move its motor five times. This sculpture remembers. As mentioned above, a *reactive* sculpture is a simple example of a behavioral kinetic sculpture. More complex behavioral kinetic sculptures may have hundreds of sensors and motors and have the ability to entirely change their programs, thus displaying the adaptability of a biological organism.

The behavioral sculptures that are included and discussed in this document are all human-made machines. It may easily be argued that many sculptures involving biological machines such as humans, animals, and plants may also be categorized as behavioral sculpture. Work such as Gilbert & George's *Singing Sculpture* (fig. 7) and the orchestrations of Vanessa Beecroft (fig. 8) are two examples which fit the above definition of behavioral kinetic sculpture. These works are usually categorized under the genre of performance and this categorization will be respected, but as eloquently examined in her essay "Mechanical Ballets: light, motion, theater," critic Rosalind Krauss points out the similarities between kinetic sculpture and performance including physical presence, choreography, and interaction with an audience. She writes, "certain sculpture was intended to theatricalize the space in which it was exhibited . . . by projecting, as its *raison d'être*, a sense of itself as an actor, as an agent of movement [Krauss p. 204]."



7 Gilbert & George. *Singing Sculpture,* 1969

8 Vanessa Beecroft. *VB 32*, 1997

1.2.3 Elements of a behavioral kinetic sculpture

A behavioral kinetic sculpture is a dynamic system, meaning it changes with time. This system is composed of a source of energy, inputs, outputs, and a control architecture which converts the information from the inputs into information which stimulates the outputs. These elements sum to form the complete sculpture, but other elements may be added to provide mass or form.

1.2.3.1 Energy

As in a biological organism, a behavioral kinetic sculpture requires a source of energy. Its energy may come from DC current from batteries, AC current from a wall outlet, or DC current from attached solar cells and other sources of renewable energy. This electrical energy may then be converted into light, heat, or motion. Only sculptures powered by renewable energy sources are able to obtain useful, sustained energy from their environment.

1.2.3.2 Input

The interface between the sculpture and the world is its sensors which convert physical stimuli into electrical signals. For example, a sound wave moving through the air may vibrate a tiny diaphragm within a microphone and this vibration will modulate an electrical signal which accurately reflects the sound in the environment. This analog electrical signal must then be sampled into a digital signal so that it is valuable to the control system. This process is known as an analog to digital conversion or ADC. There are many different sensing mechanisms that may be employed for creating an aware sculpture including light detection, motion detection, sonar, a video camera, touch sensors, gyroscopes, etc.

1.2.3.3 Output

The output of a behavioral kinetic sculpture allows it to communicate and to achieve its goals. For example, through moving its motors in a purposeful and synchronized manner a sculpture may project the emotion of anger or may attract the attention of a passerby if it needs attention. A sculpture may use actuators such as standard motors, servos, solenoids, or hydraulics to create movement.

1.2.3.4 Control

The control system for a behavioral kinetic sculpture is a set of rules that creates behavior through mapping the input and the output. To achieve this task it must store the information about the current state of the environment and possibly information about the previous state of the environment. W. Ross Ashby explains how the body of an organism may be defined as variable information:

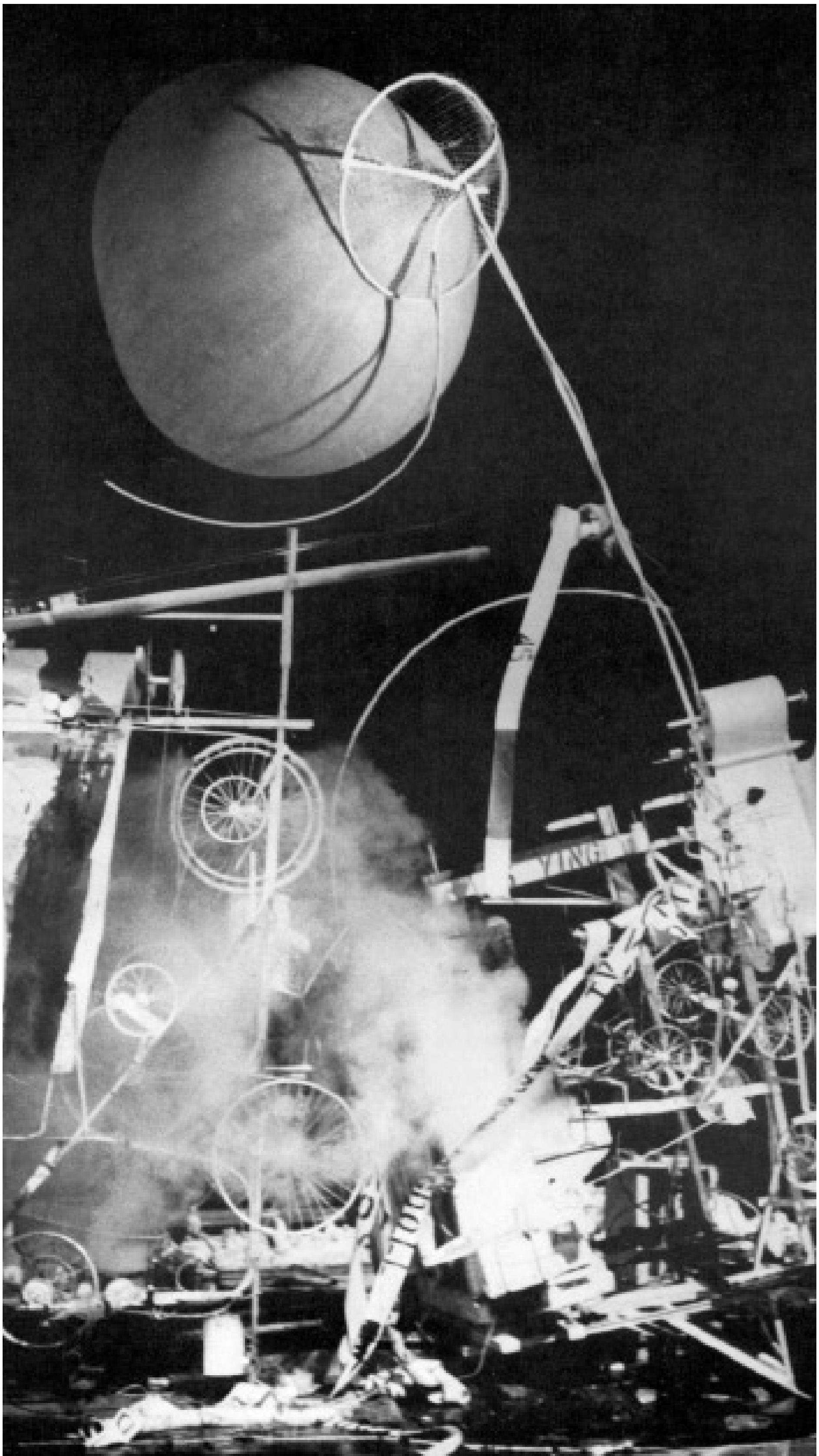
> All bodily movements can be specified by co-ordinates. All joint movements can be specified by angles. Muscle tensions can be specified by their pull in dynes.

> Muscle movements can be specified by co-ordinates based on the bony structure or on some fixed external point, and can therefore be recorded numerically. A gland can be specified in its activity by its rate of secretion. Pulse-rate, blood-pressure, temperature, rate of blood-flow, tension of smooth muscle, and a host of other variables can be similarly recorded [Ashby p. 30].

The amount of information that is stored in variables may vary from minimal to extremely complex and likewise, the control system may facilitate behavior that ranges from the relative simplicity of an insect to the complexity of a mammal. The control system for a sculpture is typically written in Assembler or C code and implemented on microcontrollers. An advanced sculpture has an adaptable set of controller rules so that it may change its behavior to better adapt to its environment.

1.3 Thesis structure

Beyond the introduction, this thesis is divided into four primary sections: background, experiments, analysis and discussion, and conclusion. The purpose of the background section is to reveal a history for behavioral kinetic sculpture that emanates from the diverse practices of automata, behavioral robotics and software, and most importantly the 20th century endeavor of kinetic sculpture. Key examples from these areas are briefly discussed to provide a general context in which to evaluate and describe the experiments presented in the following section. The experiments section reviews the path of the author's work from its origins in interactive software to more contemporary work in behavioral kinetic sculpture. This work is discussed and explained in relation to its concepts and implementation. Images of the work are used to support the text description. In the discussion and analysis section, themes found in the diverse experiments are presented in relation to both the background and the concept of behavioral kinetic sculpture. A dual approach to analyzing a work of behavioral kinetic sculpture is presented that is both a system and perceptual critique of the work, and the concept of interaction in regard to a behavioral kinetic sculpture is discussed. In addition, the concept of the artist as the generator of the work and the issues surrounding the tools involved in the production of this work are analyzed. The conclusion to this thesis reviews the document and poses a question for the future.



9 Jean Tinguely. *Homage to New York*, 1960. This self-destroying work of art performed on 17 March 1960 in the Sculpture Garden of the Museum of Modern Art, New York

Background

The concepts and technologies used in creating behavioral kinetic sculpture build upon many histories and disciplines. From mechanical automata we learn about simulated behavior, elegant and refined movement, and the fundamental human desire to create artificial life. From behavioral robotics we learn about building behavioral systems which sense their environment and use this information as the basis for their movement. From behavioral software development, we learn about advanced methods for creating behavior in a computational environment and about behavior as a model for human-computer interaction. From kinetic sculpture, we understand the history of this endeavor and give a direct context in which to place the work presented in this thesis. These four areas utilize the same materials and technologies, and are an extension of the ideas of mimesis and anthropomorphism that run deep in western civilization [Penny 1995]. Through discussing representative examples across all disciplines, conceptual threads are revealed and the objectives of each discipline are clarified.

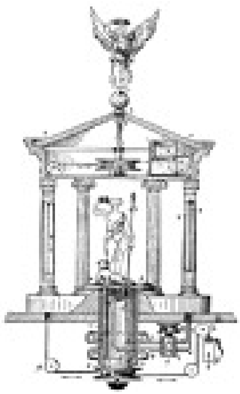
This background information is presented in a highly condensed format. The information is briefly discussed and many important references and ideas are not included. For more information on automata, consult the book *Automata* written by Chapius and Drotz. Good sources of information on behavioral robotics are *Behavior-Based Robotics* by Ronald

Arkin and *Cambrian Intelligence*, a collection of essays by Rodney Brooks. Information on behavior-based software can be found in the *Artificial Life* series published by MIT Press. The most provocative book written about kinetic sculpture is Jack Burnam's *Beyond Modern Sculpture*, and a detailed timeline of kinetic art is available in the exhibition catalog for the Force Fields exhibit and in Frank Popper's *Origins and Development of Kinetic Art*.

2.1 Automata

In the broadest sense, an automaton is a machine designed to automatically follow a predetermined sequence of operations or respond to a set of encoded instructions. Automata are described by Jack Burnam in his influential book *Beyond Modern Sculpture* as "seemingly self-propelled or self-animated images of animals or men [Burnam p. 67]." Automata are primarily concerned with the recreation of realistic and natural movement through anthropomorphism, animorphism, choreography, and coordination. Jean-Paul Sartre explains, "the automaton's charm is precisely the fact that it waves a fan or plays the guitar like a man and that nevertheless the movement of its hand has the pitiless and blank rigor of purely mechanical transmissions." The history of automata runs very close to the history of technology and many automata were technical wonders of their age and examples of the highest levels of craft and mechanical innovation.

2.1.1 Prehistory & Antiquity



10 Cross section of Hero of Alexandria's *Mobile Theatre* showing the cisterns and hydraulics

The idea of creating automata was present in the minds of humans well before technology was advanced enough to begin to create them. The story of the Titan Promethius who molded the first humans from clay and of Pygmalian carving an ideal female figure out of ivory which then comes to life are a few early myths about the creation of life from inanimate substances. Among the earliest forms of automata were those of the Egyptian civilization such as the articulated proto-automata found in tombs. They were used as proxies for a deceased master's valued servants and favorite concubines and were intended to provide company and assistance in the next world. They were originally crudely made from terra-cotta and later from painted wood which was pegged at the joints so they could be placed in alternative positions. Automata were also actively used by the ruling priests as a method of asserting their power. In Thebes "there were statues that spoke and made gestures. The priests made the hands and arms move by devices not as yet clearly explained [Chapius p. 15]." Similarly, a stature of Ammon in Napata chose the next sovereign by stretching out its arm and seizing one of the royal males as they passed in front of it.

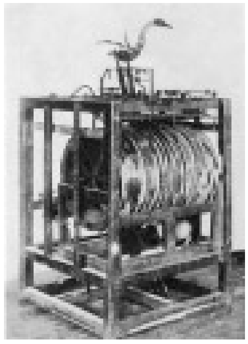
The most celebrated early builder of automata is Hero of Alexandria, whom we know from his twelve recovered texts. In his treatise on Automata, he describes his *Mobile Theatre* (fig. 10):

> The theatre begins to move towards a certain point, where it stops. Then the altar, placed in front of Bacchus, lights up, and, at the same time, milk or water flows from his thyrsus, while his cup runs wine on his panther. The four sides of the base are wreathed in crowns, and to the sound of drums and cymbals, Bacchantes dance in a circle around the little building. Soon, the noise has ceased, Bacchus, and a figure of Victory standing on top of the pediment, turn about. The altar, placed behind the god, now comes round in front of him and lights up in its turn. Wine and milk flow again from thyrsus and cup and the Bacchantes come round to the sound of cymbals and drums. When the dance is finished, the theatre returns to its original position, and the scene is over [Chapius p. 33].

Hero proceeds to explain the mechanisms for the piece—the cisterns, pipes, counter-weights, and valves all hidden within the capital, columns, and pedestal.

2.1.2 The Age of Reason

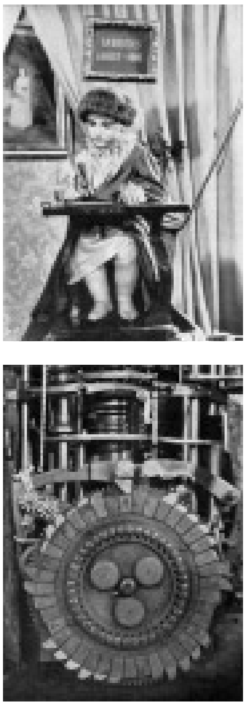
The 18th Century, under heavy influence from the 17th Century philosopher Rene Descartes and physicist Sir Isaac Newton, was the Golden Age of automata. Descartes believed that all material bodies, including the human body, are machines operated by mechanical principles. In his physiological studies, he dissected animal bodies to show how their parts move. He hypothesized that if a machine could be constructed perfectly enough, it could duplicate any of the lower mammals. Authority was given to the mechanized view of the universe in Newton's *Principia* of 1687, which explained the orbits of planets, the regularity of tides, eclipses, and movement of pendulums as a part of the great machine of the universe. Inspired by these ideas, works of 18th Century automata were at that time among the most technically advanced and precise objects ever produced by man.



11 A, B
Jacques Vaucanson.
The Duck, 1709

2.1.2.1 Jacques Vaucanson

Born in 1709, Vaucanson moved to Paris as a young man to study anatomy, art, music, and mechanics. His initial aspiration of creating moving anatomical figures for surgical demonstrations was thwarted by a lack of funding, and he instead began creating public curiosities. Vaucanson's major innovations to automata were increasing their smoothness and coordination through his advances in cam systems, miniature drive trains, and small flexible spring mechanisms. In 1738 he presented three automata before the French Academy of Sciences, a flute player capable of moving its fingers, a drummer, and his famous *Duck* (figs. 11 A, B). Vaucanson began working on the *Duck* in 1733 as an attempt to reproduce more than the outward features of an organism. Descriptions of the duck claim that it quacked, ate grain, drank water, and excreted the results. Each wing is claimed to have over 400 articulated pieces with several thousand pieces in the entire construction. An account written by a person who saw the duck performing explains, "we see the duck raise its head, look round in all directions, shake its tail, stretch itself, open its wings and flap them, while making a perfectly natural noise as if it were about to fly away. The effect is even more startling when the bird bends over its plate and begins to swallow grain with incredibly lifelike movements [Chapius p. 236]".



12 A, B
Pierre Jaquet-Droz. *Young Writer*, 1770

2.1.2.2 Pierre Jaquet-Droz

When the *Young Writer* (figs. 12 A, B) was built by Pierre Jaquet-Droz in 1770 it was the most advanced writing android built up to that time and it toured to every court in Europe to delight the wealthy. Chapius gives a fine description of the boy:

> The automaton is seated on a Louis XV-style stool behind a little mahogany table. In his right hand he holds a goose quill, while his left is leaning on the writing table. His head is mobile, like his eyes, which he can turn in every direction. When the mechanism is started, the boy dips his pen in the inkwell, shakes it twice, places his hand at the top of the page, and pauses. As the level is pressed again, he begins to write, slowly and carefully, distinguishing in his characters between light and heavy strokes [Chapius p. 293] .

The most fascinating aspect of the writer is the ability to program its output. The programming is executed by removing the disk in the small of its back and adjusting the wedges around its perimeter (fig. 12 b). Multiple adjustments must be made before the *Young Writer* will function correctly. The wedges must be positioned exactly in relation to the corresponding levers so that they don't slip on the thin cams (.7mm). To reduce wear on the cams, the levers pressing into them are faced with rubies, a technique borrowed from watch construction. Unlike Vaucanson's duck, the *Young Writer* was never lost or damaged and was still writing in the 1950s.

13 Animals from the film *Babe*, created by the Jim Henson Creature Shop

2.1.3 Contemporary automata

The modern progeny of automata are found in theme parks, special effects films, and in research labs. The disciplines that support current advances in automata are animatronics and biomimetic robotic research. The advances in electronics and materials that have taken place over the last one hundred years have enabled the creation of creatures which are nearly indistinguishable from the real thing and robots that are in some ways functionally identical to their inspirations.

2.1.3.1 Jim Henson's Creature Shop

Beginning as a traditional studio for developing artificial creatures for film and television, Jim Henson's Creature Shop has been creating sophisticated programmable animatronics for the last ten years. For the film *Babe* (1995), the story of a talking pig and other animals, they created their most realistic creatures to date. Neal Scanlon, creature shop mechanic, explains:

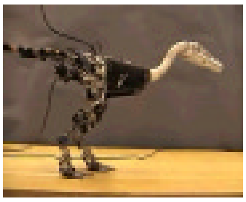
> Prior to *Babe*, an animatronic puppet had been made of thin foam latex skin over a hard fiberglass core that was articulated to provide movements. For this project, we built the creature in the same way their real-life counterparts were constructed — skin over muscles on a bony skeleton. And to bring the skin to life, we used a new material — silicone. The computer controls for *Babe's* creatures had several real-life behaviours built in, like blinking or, in the case of the pig, snuffling for food [Bacon p. 106].

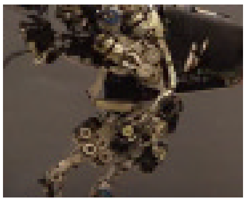
14 Animatronic dog for the film *101 Dalmations*, created by the Jim Henson Creature Shop

The film combined live action with animatronics so the automatons needed to be as perfect as possible. X-rays, paw and dental casts, and hundreds of caliper measurements were taken from the real animals and two people were hired to care for the dogs' coats, adding and removing each hair individually, to compensate for the real dogs' coats changing with the season. The Henson Performance Control System allows computers to be used as intermediaries between the performers and creatures. This software allows the puppeteer to build up a group of behaviors through layering their performance.

2.1.3.2 Troody, MIT Leg Laboratory

Peter Dillworth has spent the last four years working on *Troody* (figs. 15 A, B) at the MIT Leg Laboratory. Modelled roughly after the Late Cretaceous Troodon dinosaur, *Troody* is a prototype for an autonomous roaming dinosaur. The goal is for dinosaurs like *Troody* to be museum exhibits that roam through the hallways. *Troody* is currently a pair of robotic legs with a rigid tail and head for balance. In its current state it is very sophisticated hardware with a software control architecture no more complicated than a few IF/THEN statements. In working toward full autonomy *Troody* is very light and carries enough battery power to run for thirty minutes. It is interesting to compare the size of Dilworth's creation to that of Vaucanson. Although each automaton is relatively the same size, the *Duck* (figs. 11 a, b) required a podium over ten times the size of its body to store its control mechanisms, while the dinosaur carries everything within its structure.

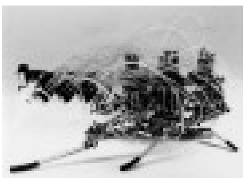




15 A, B
Peter Dilworth.
Troody, 1996 – 2001

2.1.3.3 Robot III, Case Western Reserve University

Developed at Case Western's Biologically Inspired Robotics Laboratory by roboticist Roger Quinn and biologist Roy Ritzmann, *Robot III* (fig. 16) is an artificial cockroach, an example of a living creature being used as the direct inspiration for the creation of an advanced machine. Different from the other automatons mentioned in this thesis, *Robot III* reproduces the actuators and nervous system of a cockroach, rather than its external appearance and behavior. Quinn explains:

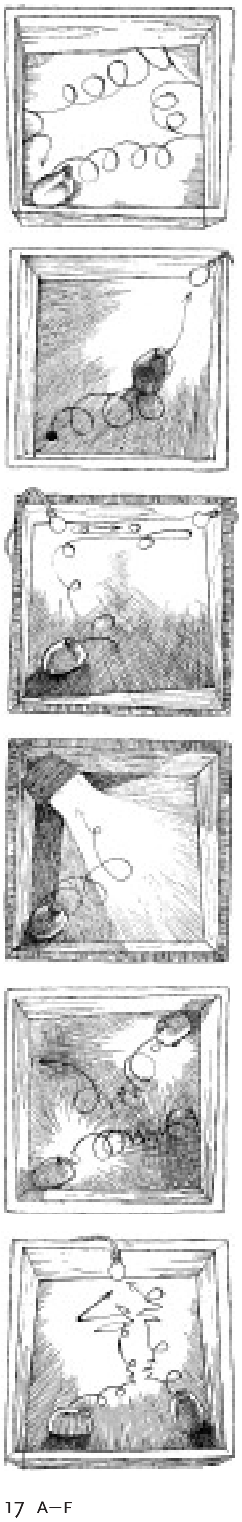


16 Roger Quinn and Roy Ritzmann. *Robot III*, 2000

> What we are trying to do is solve the problem of locomotion. We want to build a robot that is like the animal in as many ways as possible, so that we can

> actually make a robot that is as capable as the animal in terms of locomotion. That means walking, running, turning, climbing — all the things that the cockroach does really well. The way we are doing this, we call biology by default. If we know how the biology solves the problem, then that's how we solve the problem on this robot [Menzel p.103].

To understand the motion of real cockroaches they record signals from a cockroach's leg muscles while it is running and then try and replicate the muscle movements in the robot. *Robot III* is currently seventeen times the size of an actual cockroach due to the size of the cumbersome pneumatic actuators, but in the future Quinn and Ritzmann hope to incorporate synthetic muscles.



17 A–F
Illustrations from "An Imitation of Life," the 1952 Scientific American article written by W. Grey Walter

2.2 Behavioral robotics

Behavioral robots are built from the bottom up in a way that mimics the layered evolution of animal minds. Through adding capabilities a few at a time, behavior emerges as the artificial nervous systems of these robots become increasingly complex. In contrast to traditional robotics research, behavioral robots are built using artificial intelligence related more to the body than the intellect. These robots can, for example, quickly find their way through a cluttered room, but cannot prove theorems. Hans Moravec, the head of the Mobile Robot Lab at Carnegie Mellon University explains this difference well:

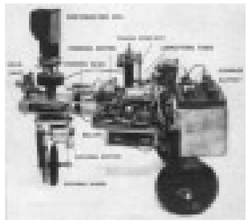
> While the pure reasoning programs did their jobs about as well and about as fast as a college freshman, the best robot control programs took hours to find and pick up a few blocks on a table. Often these robots failed completely, giving a performance much worse than a six-month-old child. We can make robots to play chess at a master level but we can't even make one that can find an appropriate piece and move it [Moravec 117].

The ability for robots to easily execute tasks such as picking up blocks has been made possible through innovative concepts largely originated at MIT by Professor Rodney Brooks and his students in the mid 1980s. In his 1991 essay "Intelligence Without Reason," he presents four key aspects of behavior-based robotics: situatedness, embodiment, intelligence, and emergence. Situatedness is interacting directly with reality rather than a representation of reality. It is a two-way coupling between the organism and the environment. Embodiment is experiencing the world directly through a physical body that provides constant feedback. Intelligence is a physical intelligence that uses the information in the world as a source of input into its computational engine. Emergence is the property of the many independent behaviors within the robot working together to create more complex behavior.

2.2.1 Foundation

Behavioral robotics has its conceptual origins in the discipline of cybernetics. Based in his ballistics research in the 1940s, pioneer Norbert Weiner developed the scope of cybernetics as an attempt to find the common elements between the functioning of automatic machines and animal nervous systems. The discipline of cybernetics alludes to the dream of the 18th century automaton creators — a fusing together of pure mathematics, electrical engineering, and neurophysiology into a science explaining the organization of systems which process information and show some degree of environmental adaptability. The behavioral robots of W. Grey Walter and the conceptual robots of Valentino Braitenberg emerged from these concepts.

2.2.1.1 Elmer and Elsie

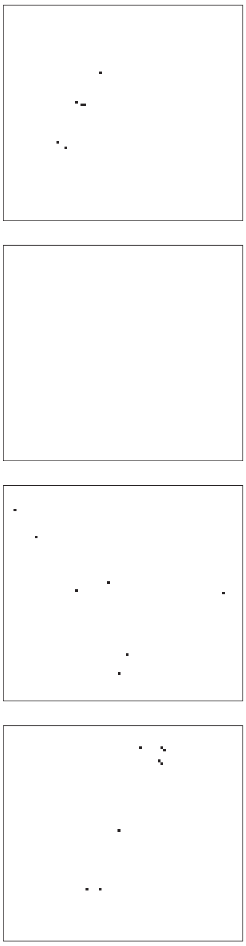


18 An annotated photograph of *Elsie*, the mechanical tortoise

In 1950 W. Grey Walter, the director of the physiology department at the Burden Neurological Institute in Bristol, England, created a precursor to modern robotics which he called *Machina speculatrix* because of their speculative nature. He originally created two machines and gave them the names *Elmer* and *Elsie* (fig. 18), originating from the descriptive terms ELectro MEchanical Robots, Light-Sensitive, with Internal and External stability. Their functional elements were two miniature radio tubes, one light sensor (a directional photocell), one bump sensor, a motor for steering, and a motor for forward motion. Their power was supplied by a miniature hearing-aid battery and a miniature six-volt storage battery. The light sensor was attached to the steering mechanism so that as it turned its wheel, it could look for light in different directions. The tortoises had five basic behaviors: seeking light through rotating its light sensor, moving toward a weak light, backing away from bright light, turning and backing up when its bump sensor is activated, and recharging its battery. The most interesting behavior is the way it would charge its battery. The tortoise's recharging station had a bright light above that would normally repel the robot, but when its battery was low it would see this light as dim and approach. Once it made contact with the charging station, the machine's nervous system and motors were disconnected until the battery voltage rose to the maximum capacity. Figures 17 A–F illustrates the behavior of the machines in different situations. Through building *Elmer* and *Elsie*, Grey expressed his interest in building machines that imitate life not through external appearance, but through performance and behavior. He describes his tortoises as "perhaps the simplest [machines] that can be said to resemble animals. Crude though they are, they give an eerie impression of purposefulness, independence, and spontaneity [Walter p. 45]."

2.2.1.3 Braitenberg vehicles

Thirty years after the creation of *Elmer* and *Elsie*, cybernetician and neuroanatomist Valentino Braitenberg published *Vehicles, Experiments in*



19 A–D Braitenberg's vehicles

A *Vehicle 1*

B *Vehicle 2a, 2b*

C *Vehicle 3a, 3b*

D Vehicle 4

Synthetic Psychology. In this small delightful book he presents conceptual schematics for fourteen unique synthetic creatures which he calls *Vehicles.* Braitenburg explores an evolutionary approach to robot design. *Vehicle 1* (fig. 19A) has one sensor and one actuator that are connected so that a strong sensor stimulus will make the motor turn quickly and vice versa. Therefore, if the sensor registers nothing the vehicle will not move. *Vehicle 2* (fig. 19B) has two sensors and two motors. If they are correlated the same way as Vehicle 1 they create Vehicle 2a and if they are crossed they create *Vehicle 2B*. If the sensor is attracted to light, for example, and there is a light in the room, Vehicle 2a will turn away from the light and Vehicle 2b will approach it. Braitenberg characterizes these machines as afraid and aggressive. *Vehicle 3a* and *3b* (fig. 19C) are identical to *Vehicle 2a* and *2b* but the correlation between the sensor and the motor is reversed — a weak sensor stimulus will cause the motor to turn quickly and a strong sensor stimulus causes the motors to stop. *Vehicle 3a* loves the light and will approach and stop when it gets too close, and *3b* is an explorer — it will approach the light but will turn and leave when it gets too close. The myriad varieties of *Vehicle 4* (fig. 19D) are physically identical to *Vehicles 2* and *3*, but they demonstrate instincts as a result of their nonlinear mappings between their motors and sensors. For example, it may "like one sort of stimulus when it is weak but not when it is too strong; it might like another stimulus better the stronger it becomes. It might turn away from a weak smell and destroy the source of a strong one [Braitenberg p. 17]." The simplest of Braitenberg's creatures are easily realized in software and physical form. The *Cells* project presented in Section 3.1.5 is a software implementation of Vehicles 1-4.

2.2.2 Behavioral robotic architecture

In his book *Behavior-based Robotics*, Ronald Arkin explains that robotics architecture is "The discipline devoted to the design of highly specific and individual robots from a collection of common software building blocks . . . An architecture describes a set of components and how they interact [Arkin p. 125]." While all architectures provide for sequential tasks, conditional branching, and iterative constructs, they are extremely varied in how they support the concept of behavior. Robotics research until the mid 1980s utilized concepts from traditional artificial intelligence research to build robots with centralized control. These robots scan the environment for information, model its possible actions by comparing the world data with its abstract internal representations, and then finally move — this process could often take several hours! A newer architecture that provides more dynamic response is characterized by the concept of reactive control. Reactive control is "a technique for tightly coupling perception and action, typically in the context of motor behaviors, to produce timely robotic response in dynamic and unstructured worlds [Arkin p.24]." The differences between these two approaches was clearly stated by Rodney Brooks through a collection of adjectives:

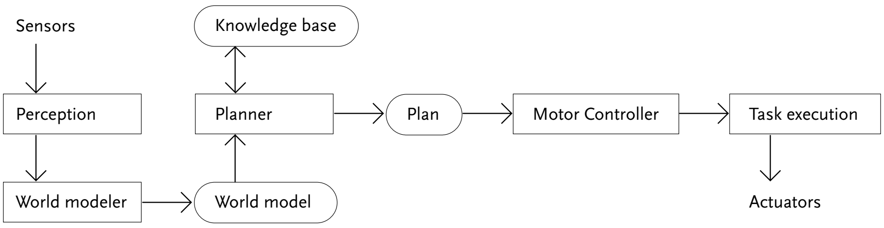
DELIBERATIVE ARCHITECTURE	*behavioral architecture*
centralized	*decentralized*
disembodied	*embodied*
contemplative	*situated*
environmental independent	*environmental dependent*
engineered	*evolved*

Comparing *Shakey* (one of the first mobile robots) with *Genghis* (one of the first robots built using reactive control) creates a better understanding of these disparate architectures.

20 *Shakey*, built at the Stanford Research Institute from 1966 – 1972

2.2.2.1 *Shakey*

Constructed in the late 1960s at the Stanford Research Institute, *Shakey* (fig. 20) inhabited a specially built world filled with custom designed objects to assist in its vision and navigation. The walls were uniformly lit, there were no distracting and changing shadows, and dark rubber baseboards clearly defined the wall from the floor. Researchers, communicating with *Shakey* through a command line interface, would ask it to move across the room or to move a shape from one place to another. *Shakey's* body had two independent stepper motors for movement, a television camera, bump sensors to detect collision, and it maintained a detailed model of its environment by comparing the information from its camera with its internal symbolic world model. Figure 21 shows a schematic of *Shakey's* linear sense-model-act approach to AI:

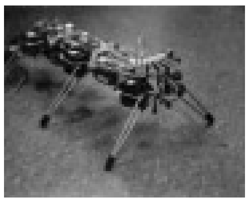


21 Diagram of *Shakey's* information flow

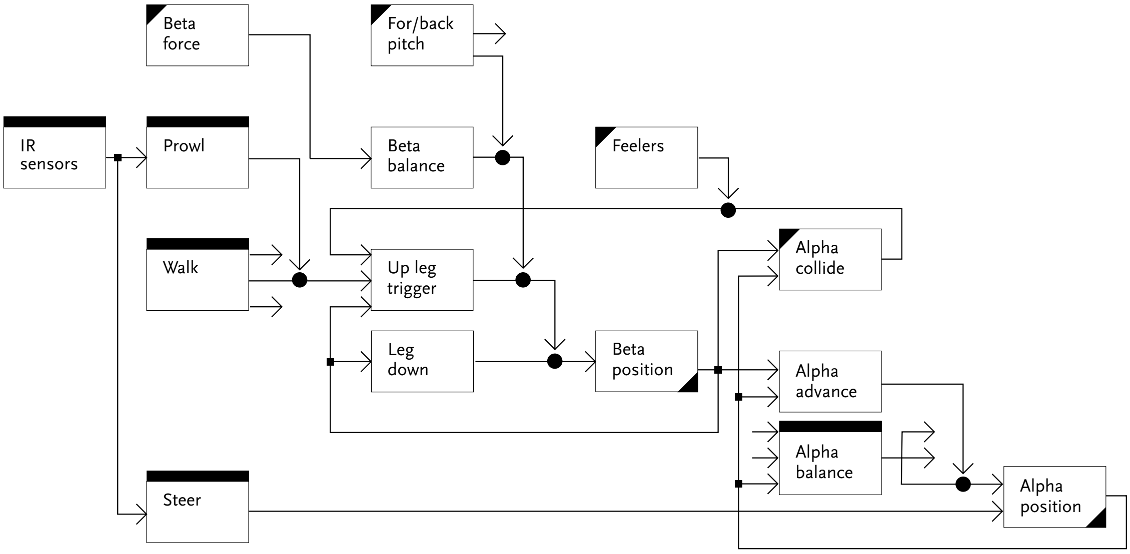
Shakey was considered to be a great success at the time. It worked, however, because it was situated in a carefully designed environment. Thirty years later, there is still no robot which can match all aspects of *Shakey's* performance in a general office environment.

2.2.2.2 *Genghis*

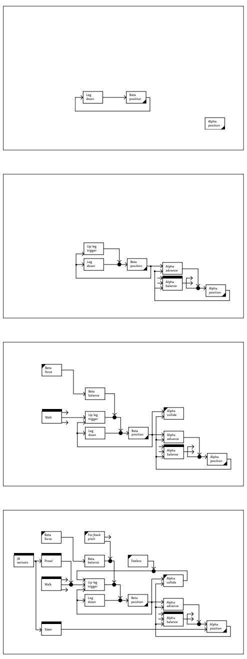
The challenge of building a robot that can navigate through the chaos of the real world was accepted by Rodney Brooks and his students in the mid 1980s. Many of the core principles of behavioral robotics architecture were first expressed in the insectile robot *Genghis* (fig. 22) which was built to walk over rough terrain and follow a human. The thirty-five centimeter long *Genghis* has six servo-controlled legs and senses the world through six passive pyroelectric sensors, two whiskers, and two inclinometers to detect orientation. In stark contrast to *Shakey*, *Genghis* maintains no model of the world and has



22 *Genghis*. Built at the MIT AI Lab in 1988 by Rodney Brooks et al.



23 Schematic of *Genghis's* subsumption architecture



24 A–D *Genghis's* architecture evolved from simple to complex

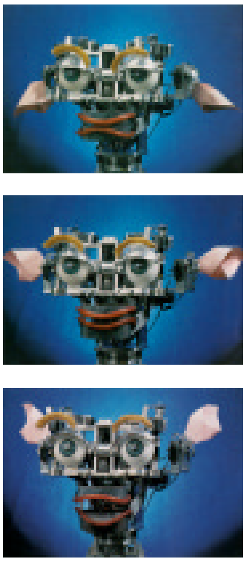
a completely decentralized control system known as subsumption architecture. *Genghis's* architecture (fig. 23) is built of fifty-seven independent finite state machines that are augmented with an awareness of time and the ability to read and write information to and from a group of data registers. These state machines mimic biology by running in a simulated parallel manner and mimic evolution by layering more complex behaviors on top of primitive ones. First *Genghis* learned to lift its body off of the ground, and then to swing and lift its legs. Next came issues of balance and learning to lift a leg higher when it cannot get over obstacles. More sensors were added and interfaced to facilitate obstacle avoidance and the ability to detect human movement. Figures 24 A–D shows how complexity was incrementally added to the architecture. Through adding complexity, high level behaviors such as following people emerged through the coordination of these micro behaviors. For example, each of the six legs operated in a manner largely independent from the others, each one having a localized sensory-motor unit. However, by building a thin central controller on top of each functioning leg, their movements can be coordinated. *Genghis* moves quickly through its environment and its perceived intelligence emerges out of a tight coupling between its body and the environment.

2.2.3 Contemporary behavioral robots

The initial innovations in behavioral robotics have led to an enormous amount of research and development. From their origins as radical experiments, these robots have since been used to travel to Mars and may be found in our homes as toys and synthetic pets. New innovations in this field have made possible a new category of behavioral robots that begin to mimic human communication and movement.

2.2.3.1 Kismet

Kismet is an autonomous robot head designed for intuitive social interactions with humans. It is specifically designed to respond to the emotional quality of the human voice, as well as patterns of movement and spatial proximity to external objects. *Kismet* is constantly monitoring its environment, looking for stimuli to trigger its emotions. The emotions experienced by *Kismet* are computationally modelled based on what is known about human emotion and its two methods of expression are tone of voice and facial expression (figs. 25 A–C). For example, if *Kismet* detects that it is being scolded it will lower its head and close it eyes. If it is having a stimulating exchange, its voice will become bright, its eyes will open wide, and its ears will turn upward. *Kismet's* small synthetic face is attached to 15 networked computers which control its vision, auditory, and motor control systems. Its system architecture consists of six subsystems: low-level feature extraction system, high-level perception system, attention system, motivation system, behavior system, and motor system. The behavior system (fig. 27) acts as an arbiter between a number of competing behaviors. There are three different branches, each for fulfilling a particular need: social interaction, fatigue, and stimulation. It is crucial that *Kismet* is able to convey its emotions properly so that the person interacting with it is able to give the correct stimulus to keep it in a positive state. One of *Kismet's* most interesting behaviors is Vocal play, a turn taking system by which the robot is able to have a proto-dialogue with a person by knowing when to speak and when it should react appropriately to the person speaking to it.



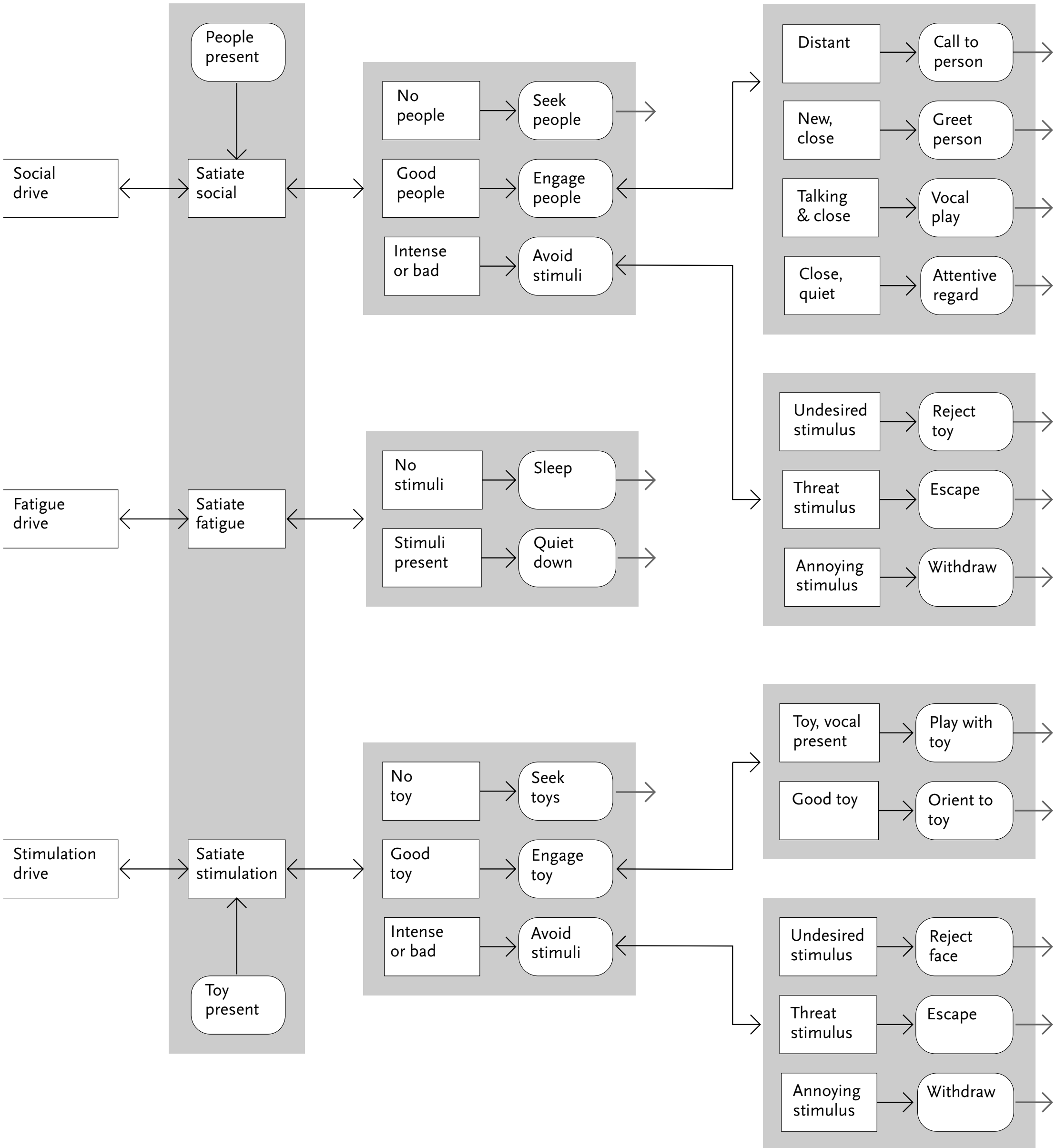
25 A–C
Kismet expressing a range of emotions

a Anger
b Happy
c Surprise

2.2.3.2 Aibo

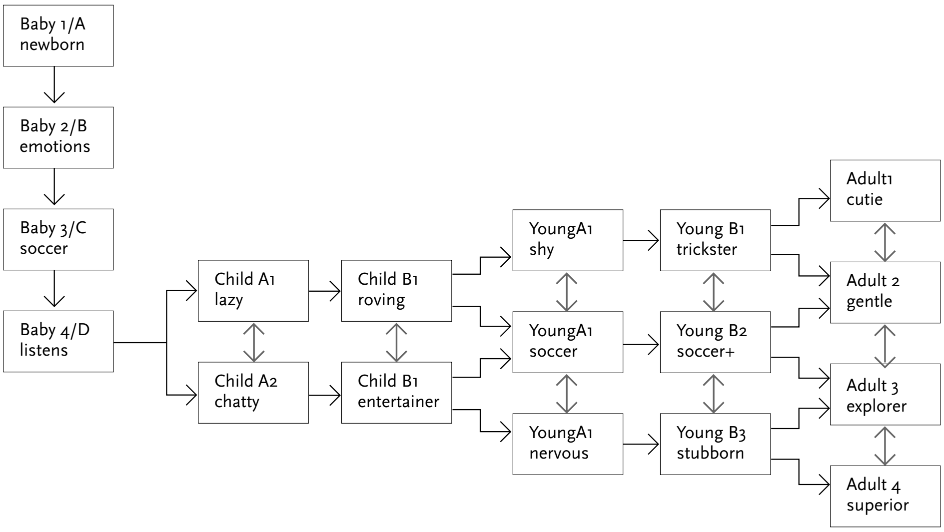
Sony's *Aibo* website explains, "In this age of twelve-hour workdays it becomes increasingly difficult to nurture a child, a pet, or even a houseplant! Imagine all the joys of having an intelligent, alert companion at your home without the toil, guilt and fretting that usually go along with emotional and physical maintenance [www.aibo.com]." Sony is hoping to profit from their perceived need for hassle-free companionship through developing *Aibo*, a small robotic dog. *Aibo* (fig. 26) experiences the world through many sensors located throughout its body. *Aibo* sees through a CMOS camera, has microphones for ears, an accelerometer for orientation, and three touch sensors. It communicates its mood through musical tones, body language, and through the color, pattern, and rhythm of the small lights that are its face. *Aibo* selects behaviors based on its current state, the combination of the current values for its ten different emotions: anger, affection, appetite, curiosity, disgust, exercise, fear, joy, sadness, and surprise. Stroking its head, for example, will make it happy and *Aibo* will flash its green lights and play a bright melody. More complex behaviors emerge over time. If *Aibo* has been ignored, it will beg for attention or if its movement is constrained, its desire to move will increase. New *Aibos* are young

26 Sony Corporation's *ERS-210* (*Aibo* version 2.0)



27 Schematic of *Kismet*'s behavior

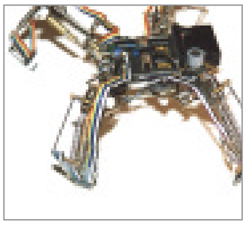
and have very few behaviors, but over time through the quality of interaction with their environment and owner, they develop into a "mature Entertainment Robot." The emotional development of the ERS-210 is shown in figure 28. The speed at which an *Aibo* develops, as well as the personality it has, are dependent on the frequency of attention it receives as well as the quality of interaction. *Aibo's* developmental state, memory, and personality are stored on a Memory Stick, a compact storage device, and software is available for changing its personality for special occasions or for reading your email aloud to you. The Party Mascot software, for example, gives *Aibo* "a song and dance repertoire that will liven up any gathering!"



28 Schematic of *Kismet's* behavior

2.2.3.3 B.E.A.M.

The acronym B.E.A.M. stands for Biology, Electronics, Aesthetics, Mechanics. It is a philosophy for building robots that has been adopted by a vibrant community of hobbyists who build simple machines from broken walkmans, salvaged cameras, and similar techno rubble. Los Alamos researcher Mark Tilden, the originator of the B.E.A.M. philosophy, has been creating small insectile robots for the last ten years. In contrast to more traditional robotics research which uses expensive and fragile digital machines, the B.E.A.M. robots are purely analog and are therefore extremely robust. Through clever electrical and mechanical design, seemingly complex behavior is achieved through a minimum of parts. The core of many B.E.A.M. robots is a solar engine, a two transistor circuit which uses a solar cell to charge a capacitor. The capacitor releases its energy when there is enough to give a quick burst of power to an attached motor. Most B.E.A.M. robots do nothing more than scuttle around the room or erratically navigate toward a light, but Tilden's patented research into what he calls Nervous Networks adds a level of sophistication that make possible robots like his four legged *Spyder* (fig. 29), which can navigate through a more complex environment.



29 Marc Tilden. *Spyder*

2.3 Behavioral software

The development of GUI software environments at Xerox PARC and their proliferation in the 1980s through success of Apple's Macintosh computer created a precedent for static screen representation where still objects on the screen symbolizing folders and documents sit motionless waiting to be moved by the user. In stark contrast, the development of the video game industry created an alternative screen environment full of life and movement. Research into behavioral software has emerged with and from the original spirit of video game innovation.

2.3.1 Artificial Creatures

Over the last twenty years there has been a tremendous growth in building artificial creatures. The results of this work are currently used heavily by the video game industry to build synthetic characters such as the Creature in *Black and White*, in the film industry for special effects such as the flocking bats in *Batman* based on Craig Reynold's *Boids*, and as effective simulations for robotics research. Additional pioneering research into this topic is being produced at research institutions and through private enterprise.

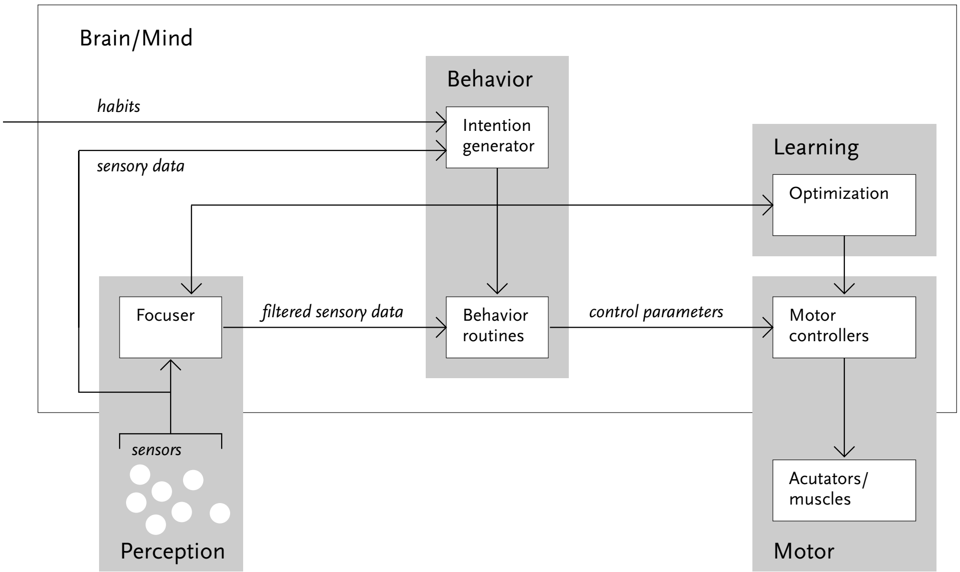
2.3.1.1 Bruce Blumberg & the Synthetic Characters Group

30 A–C
Silas, 1996.
Bruce Blumberg playing with his virtual dog within the ALIVE environment

The Synthetic Characters Group at the MIT Media Laboratory, led by Bruce Blumberg, has been making advanced artificial creatures since 1996. Prior to forming the group, Blumberg built an advanced simulated dog, *Silas*, as a part of his Ph.D. work. *Silas* was built as a project for the Media Lab's ALIVE environment (Artificial Life Interactive Video Environment), a video projection that allowed wireless full body interaction between a participant and autonomous graphic creatures in a 3D world (figs. 30 A–C). People interact with *Silas* through their gestures and *Silas* responds based on his current emotional state which is calculated based on the values representing his happiness, aggression, etc. *Silas* responds to over a dozen gestures and also instigates interaction to fulfill some of his own needs such as the desire to play. For example, if *Silas* wants to play he will drop a virtual ball at your feet. *Silas* has a total of 28 motivational variables, 90 unique behavior modes, 23 unique behavior groups and when finished in 1996, was one of the most sophisticated autonomous animated creatures created to date.

31 *Trial by Eire*. Created by the Sythetic Characters group at the MIT Media Lab in 2000

Recently the group has been working on a more advanced canine, *Duncan the Highland Terrier*. Using a new behavior architecture written by Marc Downie, research with *Duncan* focuses on behavioral adaptation in a goal-driven environment. *Duncan's* behavior architecture is based on the idea of an action-tuple which contains the animal's basic assumptions about the world. For example, a behavior such as eating will be selected through the tuple structure: if there is food | eat the food | until it is gone. The third part of this structure, "until it is gone," has a time associated with it and the entire tuple is associated with a value from 0–100 which states the likelihood that the event behavior will take place. Therefore if the animal is very hungry the value will be 100 and if the animal has recently eaten the value will be low. Through this architecture, Downie is interested in giving the creatures a knowledge of their own bodies, a concept of time, and the ability to learn and adapt. *Duncan* has been used in an installation called *Trial by Eire* (fig. 31) , where people control *Duncan* using voice

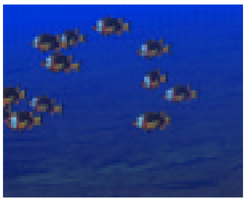


32 Control system for the artificial fish

commands such as "Down," "Away," and "Steady" to try and get him to herd a group of sheep through a course. Over time if the person is a good trainer, Duncan will be able to head the sheep on its own.

2.3.1.2 *Terzopoulos, Tu, Grzeszczuk*

In 1994 at the University of Toronto, Demetri Terzopoulos, Xiaoyuan Tu, and Radek Grzeszczuk built a virtual marine world inhabited by artificial fishes. As described in their paper, "Artificial Fishes: Autonomous Locomotion, Perception, Behavior, and Learning in a Simulated Physical World," they took great care in creating a physical simulation of a hydro mechanical environment and modelled the movements of the fish using biomechanical data. Each fish is made from 23 nodal point masses and 91 springs that allow the fish to locomote by contracting these virtual muscles. The fishes' sensors (including eyes), and brain (including motor, perception, behavior, and learning centers) are also simulated. In building the behavior of the fish, they borrowed concepts from the ethological work of Inbergen's study of three-spined sticklebacks. From this research, they implemented two types of behavior: primitive reflexive behaviors that directly couple perception to action, and higher level behaviors that combine these reflexes into motivational behaviors controlled by mental states such as hunger, fear, and libido. The behavior center of the fishes' artificial mind mediates between the perception systems and the motor system (fig. 33 A, B). The primary behaviors for the fish include avoiding-static-obstacles, avoiding-fish, eating-food, mating, leaving, wandering, and escaping. The fish also possess emergent group behaviors such as schooling.

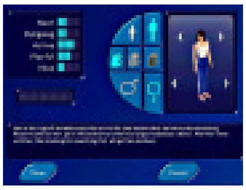


33 A, B
The artificial fish of Terzopoulos et al. navigating through their environment

34 A, B
Karl Sims.
Evolved Virtual
Creatures, 1994

2.3.1.3 Karl Sims

In his paper “Evolving 3D Morphology and Behavior by Competition” MIT trained computer scientist Karl Sims describes his environment for evolving virtual organisms by using competition as the fitness measure. In this simulated world, the organisms compete over the possession of a small green block — an activity similar to the face off in a basketball game or hockey match (figs. 34 A, B). Each organism is made up of a number of jointed blocks, sensors, and a brain. The creature behavior is determined by a virtual brain that accepts input sensor values and provides output values for the actuators. Outputs are applied as forces to the body’s degrees of freedom. The organisms experience their simulated world through the values of their joint sensors, a primitive visual system (that can detect orientation, the position of the ball, and the center of mass of the opponent), and contact sensors on the face of each part of their bodies. The way an organism moves is dependent on its size, shape, and morphology. These are determined by its genetic representation — a directed graph of nodes and connections. New organisms are created by mutating and merging these graphs. Although visually attractive, the most appealing aspect of this work is not the visual results, but the fascinating behaviors and methods of locomotion that develop through the simulated evolutionary process.



35 The Sims visual character editor

36 The habitat of The Sims

2.3.1.4 Will Wright and The Sims

As a follow up to his popular title *SimCity*, game designer Will Wright created *The Sims* in 2000, a simulation game where players create and control the environment of their simulated people. The game begins with a player creating a group of characters and determining each personality (fig. 35). From birth, their happiness and success are determined by how competently their lives are managed. The characters have careers, relationships, are able to bear children. The game encourages social and professional success which are the key factors in determining overall happiness. An interesting aspect of behavior related to *The Sims* is not found in the game, but the community of people who participate. Similar to the virtual world in the Bruce Sterling novel *Snowcrash*, people are obsessive about creating custom graphic skins for their characters and designing new furniture and wallpaper patterns. They painstakingly create skins emulating their favorite personalities such as Special Agent Dana Scully and Britney Spears and post the results on fan websites for others to download.

2.3.2 Abstract systems

In addition to research into the creation of artificial creatures, there has been development into using the concept of behavior to create abstract interfaces and systems. These range from the highly expressive works of John Maeda to basic research into the meaning of interaction as executed by Norwegian researcher Dag Svanæs.

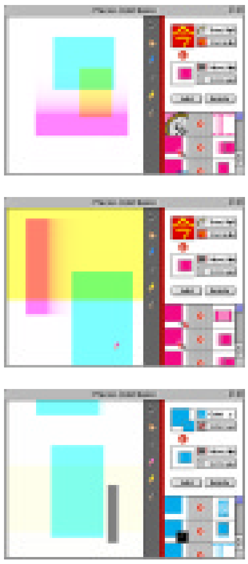
2.3.2.1 *John Maeda*

John Maeda is an MIT trained computer scientist who later received his Ph.D. in design from Tsukuba University in Japan. Since the mid 1990s he has been exploring computation as an expressive medium through the synthesis of the humanist values of design with the skills of an engineer. One of his first influential pieces, *The Reactive Square* (figs. 37 A, B), was inspired by the geometric work of Kasimir Malevich and the desire to create an alternative way for his children to interact with his computer. This work is made up of eight identical black static squares, each with its own reflexive behavior. When a square detects a sound, it visually changes based on the volume of the sound and in relation to its behavior so that your speech is transformed into a kinetic image. In *CMYK* (figs. 38 A–C), he explores the concept of programmable inks. Through a GUI interface people apply different behaviors to colored rectangles. A blue rectangle may, for example, be programmed to move north when it encounters a pink rectangle. As the rectangles move across the surface of the screen and intersect each other, complex patterns of movement originate from simple relational rules.

37 A, B
John Maeda.
Reactive Square,
1995

2.3.2.2 *Dag Svanæs*

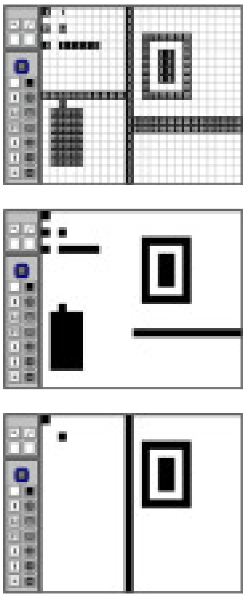
In 1996 Dag Svanæs began executing a series of experiments exploring the fundamental properties of interaction. In his paper “Kinesthetic Thinking: The Tacit Dimension of Interaction Design” he writes about the rigid thinking currently required for building interactive software and he imagines an alternative process that would remove programming from the domain of logical-mathematical intelligence and to open it up to people with musical and spatial intelligence. He thinks this could be done by thinking about programs as small behavior groupings called *interaction gestalts*. In his test application, *Painting with Interactive Pixels* (figs. 39 a–c), he constructed a simple design tool where the basic building blocks are enlarged pixels that have behavior. For example, some of the pixels respond to the movement of the mouse and others respond to mouse clicks. As people draw with these behavioral pixels and then interact with the result, their drawing responds to interaction according to the behavior of their composite elements.



38 A–C
John Maeda.
CMYK, 1994

2.4 Kinetic sculpture

Kinetic art gradually evolved throughout the 20th century as a nonrepresentational art using the parameters of real time and motion. Unlike static arts (traditional painting and sculpture) which are simultaneous and meant to be viewed at once, kinetic sculpture exists in both space and time. Its form and motion reveal themselves over time and are perceived within the context of the forms that came before the present and that will be revealed in the future. In opposition to automata and robotics, the value of kinetic art has not been found in its technical proficiency. As Jack Burnam clearly stated in 1969:



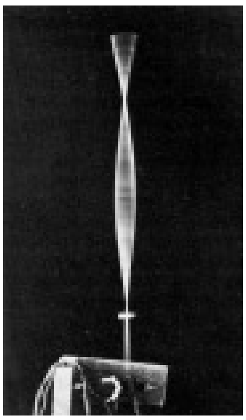
39 A–C
Dag Svanæs.
Painting with Interactive Pixels,
1998

> The short history of Kinetic Art has been marked by the comparative mechanical incompetence of its champions. What slight technical facility Kinetic Artists have demonstrated has usually been the result of technical assistance contributed by sympathetic technicians . . . The technician has consistently failed to make machinery conform to the older aesthetic precepts of our culture; instead, it has been the artist who was forced to try and make his art relevant to the prevailing technology. The Kinetic Artist, along with his enemies, has often sensed that he has united his art with forces inherently at odds with artistic endeavor. Even the engineer with his superior training has so far not produced superior Kinetic Art, usually the opposite. Successful Kinetic Art until now has either defied or trivialized the principles of mechanical invention [Burnam p. 218].

Although written over thirty years ago, these words still ring true today. The most successful kinetic art of the past three decades has not been rooted within the culture of technological advancement, but firmly within the tradition of the history of art.

2.4.1 Foundation

Amidst clash of the many "isms" during the early 20th century and in the aftermath of the first World War, the foundation for modern kinetic sculpture was built by four primary innovators. From 1920–1935 Naum Gabo, Marcel Duchamp, Laszlo Moholy-Nagy, and Alexander Calder set forth the course that nearly all kinetic sculpture would follow throughout the century. Interestingly only one of these artists, Calder, used kinetics as his primary medium.



40 Naum Gabo.
Standing Wave, 1920

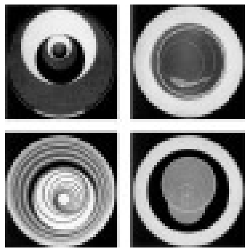
2.4.1.1 Naum Gabo

Born in Russia in 1890, Naum Gabo (originally Naum Pevsner) studied engineering, mathematics, physics, and medicine at a young age. This range of early experience enabled him to be one of the most articulate thinkers regarding the confluence of art and science. In 1920 he issued the "Realistic Manifesto" with his brother Antoine Pevsner, which clearly stated, "We renounce the thousand-year-old delusion in art that held the static rhythms as the only elements of the plastic and pictorial arts. We affirm in these arts a new element, the kinetic rhythms as the basic forms of our perception of real time [Borja-Villel p. 228]." In 1920, Gabo also completed his important *Standing Wave* [fig. 40], a 24.25" high thin metal rod attached to the vibrator from a doorbell. Developed as an example of the principles set forth in the "Realistic Manifesto" and as a demonstration for his students, the project opened many possibilities for exploration. Through the vibration of the rod, Gabo created a completely dematerialized volume—space defined by a moving wave. This influential work was the only experiment that he executed with real motion primarily because he felt encumbered by the use of motors. In his 1937 essay "Circle," Gabo explains, "Mechanics have not yet reached that stage of absolute perfection where it can produce motion in a sculptural work without killing, through the mechanical parts, the pure sculptural content; because the motion is of importance and not the mechanism that produces it. Thus the solution of this problem becomes a task of future generations [Burnam p. 231]." He instead chose to explore movement through static representation.

2.4.1.2 Marcel Duchamp

Marcel Duchamp, born in 1887 in France, created a number of paintings based on movement and mechanism before creating his first work using real movement. Most significant is his *Nude Descending Staircase* (1912) which he describes as "not a painting, but an organization of kinetic elements — an expression of time and space through the abstract presentation of movement [Popper p. 50]." With the creation of his ready-made *Bicycle Wheel* (1913) Duchamp created the first modern work to use actual movement to express meaning [Hulten 1968]. Between 1920 and 1935 Marcel Duchamp executed a series of experiments focusing on the optical properties of rotary movement. The first of these, *Rotary Glass Plate*, is a construction of five planes of glass, each containing one part of a spiral, attached to a rotating axle. When set into motion, the planar fragments of the spiral merge to create a completed spiral. Through the addition of a fourth dimension, he reduced space to a flat, intangible surface. *Rotary Demisphere* [fig. 41] was completed in 1925. It is five foot high apex with an attached motor which revolves a white demisphere painted with black eccentric circles and surrounded with black velvet. Rotation makes it appear to recede in space rather than protrude. In 1935 Duchamp created Rotorelief [fig. 42], a series of twelve centrifugal patterns which appear three-dimensional when placed on a rotating turntable. Like Gabo, Duchamp considered mechanical movement to be "unartistic," and he classified his work as not mechanical but metaphysical. He thought the future of art would be created through the manipulation of light, through a technology more sophisticated than mechanics.

41 Marcel Duchamp. *Rotary Demisphere,* 1925

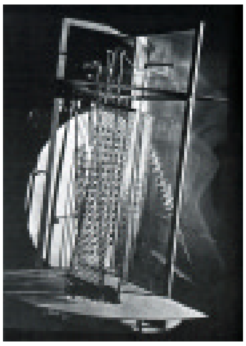


42 Four patterns from Marcel Duchamp's *Rotorelief,* 1935

2.4.1.3 Laszlo Moholy-Nagy

Born in Hungary in 1895 Laszlo Moholy-Nagy emigrated to the United States in 1937. His philosophy on modern art is stated in his Manifesto of 1922 written with Alfred Kemeny:

> We must replace the static principle of classical art with the dynamic principle of universal life. In practice: instead of static material-construction (relationships of material and form), we have to organize dynamic construction (vital constructivity, energy relationships), in which the material functions solely as a conveyor of energy. Carried further, the dynamic single-construction leads to the *dynamic-constructive energy-system*, with the beholder, hitherto receptive in his contemplation of art-works, undergoing a greater heightening of his powers than ever before and actually becoming an active factor in the play of forces [Borja-Villel p. 229].

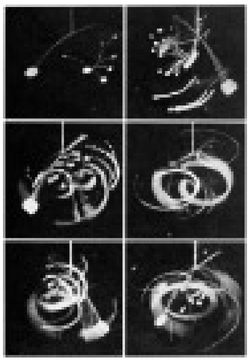


43 A, B
Laszlo Moholy-Nagy.
Light Prop,
1922–1930

His major work demonstrating these properties is the *Light Prop*, a.k.a. *Light-Space Modulator* (figs. 43 A, B), made between 1922-1930 during his tenure as the director of the metal shop at the Bauhaus and with the aid of an expert mechanic. As an object, it is five feet high and made from aluminum and chrome-plated surfaces driven by an electric motor, and was intended to act as a dynamic stage set. The art critic Rosalind Krauss sees it as a proxy for a human actor:

> The Light Prop has an internal structure that affects its outward appearance, and, more crucially, an internal source of energy that allows it to move. And, like a human agent, the work is meant to affect its space through the gestures which it makes over a period of time. The fact that these gestures — the patterns of projected light and the shifting patterns that relate throughout its internal structure — change in time, and have a complex program, gives the object an even more human, because seemingly volitional, quality. Thus, no matter how abstract its forms and its function, the *Light Prop* is a kind of robot; the place it was meant to take on stage is that of a mechanical actor [Krauss p. 208].

Regarding the future of kinetic art, Moholy-Nagy spoke of the concept of "extraordinary adaptability" and was interested in the ability of natural forms to adapt to their continually changing environment. He was inspired by the myriad forms of water; in rest, in motion, in gaseous form, in liquid and solid forms, a placid or rushing brook, a raging sea, a pattering rainfall, as a spraying fountain, or a drifting cloud of steam. He felt that once art dropped its representational role and space became real, the separation between the work and the spectator would dissolve. The dimension of time would make the work relative and it would no longer have an isolated permanent existence, but would merge with and be a part of the living environment.



44 Photographs of a moving Calder mobile by Herbert Matter

2.4.1.4 Alexander Calder

The American Alexander Calder (born 1898) became famous in the Parisian art community of the late 1920s through the performances of his *Circus*. After a visit to Mondrian's studio, he stopped making his representational wire constructions and made geometric constructions from wood, wire, and sheet metal. Throughout the 1930s he experimented with different types of kinetic movement that would later be developed further by the next generation of kinetic artists: unstable objects hung in front of a panel producing random shadows, sculpture propelled by pumped liquids, elements interchangeable by hand, and hand-driven cams and crank trains. He used motors to solve an aesthetic problem; instead of choosing a static position in which to place a visual element, he was able to put them in multiple positions in time. He explained:

> With a mechanical drive, you can control the thing like the choreography in a ballet and superimpose various movements: a great number, even, by means of cams and other mechanical devices. To combine one or two simple movements with different

periods, however, really gives the finest effect, because while simple, they are capable of infinite combinations [Hulten 1968, p.151].

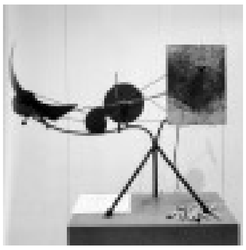
By 1935 he had rejected the use of motors and began creating art that was moved by the wind and by hands. At this time he pursued the forms and motions of his well known mobiles. These sculptures have *intermittent* motion rather than *mechanically continuous* motion, which gives them more of a relation to organisms than machines.

2.4.2 A maturing art

It was not until the 1950s and 1960s that many artists began to work exclusively with motion as their primary means of expression. The 1955 *Le Mouvement* show at the Gallerie Denise Rene in Paris was one of the first to feature this work. Including the pioneers Calder and Duchamp, the show also exposed the emerging talent of Yaacov Agam, Pol Bury, Robert Jacobson, Jesus-Raphael Soto, and Jean Tinguely. As pioneered by Calder, this period in kinetic sculpture is marked by a tendency to move away from motorized/regular movement and is characterized by an openness toward experimenting with natural/stochastic rhythms.

2.4.2.1 Jean Tinguely

The intellectual progeny of Dada, the Swiss sculptor Jean Tinguely (born 1925) succeeded by exploiting the underlying human hostility to mechanization [Burnam p. 244]. His creations move with feverish mechanical disorder, improvisation, and inefficiency, ignoring the established machine aesthetic of order, precision, and reliability. Tinguely stated, "For me, the machine is above all an instrument that permits me to be poetic. If you respect the machine, if you enter into a game with the machine, then perhaps you can make a truly joyous machine — by joyous, I mean free [Burnam p. 218]." His *Meta-matics* (fig. 45), vital and hectic drawing machines originating in 1958, are both a comment on art as a statement of individuality, and the cultural role of machines in commercial production. Through the Meta-matics, man and machine work together to create a wholly irrational product. A catalog for an exhibition of his work at the Jewish Museum in New York succinctly describes, "Tinguely's machines are really 'anti-machine,' … aligned on the side of animal energy and vitalism. The hectic and uncertain life of his mechanical equipment, always on the verge of breakdown or disintegration, releases finally something pure like an arabesque of movement, or gesture, and each of his machines carries its own distinctive face and personality [Schöffer p. 5]." In this frenetic spirit, Tinguely produced a group of auto-destructive machines — sculpture performances in which the work breaks apart following a loosely conceived plan of annihilation. His most famous auto-destructive work, *Homage to New York* (fig. 46) was performed on 17 March 1960 and built on site at the Museum of Modern Art during the three weeks



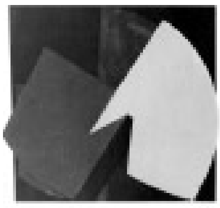
45 Jean Tinguely. *Meta-matic No.10*, 1959

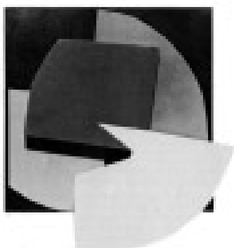
46 Jean Tinguely. *Homage to New York*, 1960

proceeding the performance. The materials, bought at dumps in New Jersey and second-hand stores in New York, included bicycle and baby carriage wheels, pulleys, a piano, fire extinguishers, two *Meta-matics*, a bassinet, pipes, flags, rusty oil cans, and stinking liquids. It was built in a spirit of total anarchy and freedom and when the time came, it performed accordingly. In his short essay "Garden Party," collaborator Billy Klüver explained:

> The piano was to begin playing slowly as the flame on the keyboard was lighted. But the step-up transformer had broken in transport, so the motor had to be started directly at full speed. The result was that the driving sling jumped the wheel on the piano as the motor started . . . A fuse had blown. It had been fixed. The piano began working again, but only three notes were playing — three sad notes . . . After three minutes, the first meta-matic went on. But Jean had reversed the sling so the paper was rolling up instead of down. It was a bizarre effect [Hulten 1987, p. 76].

Soon the fire spread and began to engulf the entire piano and the performance ended with a fireman extinguishing the flames.





47 A, B
Pol Bury.
Mobile Plane 4, 1954

48 Pol Bury.
1110 White Dots Leaving a Hole – Punctuation, 1964

2.4.2.2 Pol Bury

Stimulated by a visit to a Calder show, the work of Belgian Pol Bury (born 1922) changed radically in 1953 when he abandoned painting and began his first mobile structures. His *Mobile Planes* (figs. 47 A, B) of 1954 are masonite forms that rely on the viewer for movement. Each plane has freedom on its axis, permitting an infinite number of pictorial combinations. By 1957 he had incorporated electric motors into his work and had developed his characteristic form of kineticism. In his essay "Time Dilated" Bury explained:

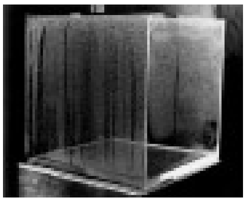
> Between the immobile and mobility, a certain quality of slowness reveals to us a field of 'actions' in which the eye is no longer able to trace an object's journeys . . . Journeys avoid "programmization" in the degree that they are endowed with a quality of slowness; they finally achieve a real or fictional liberty, a liberty acting on its own account and for its own pleasure . . . Speed limits space, slowness multiplies it [Bordier p. 20].

In his work after 1959, he created complex structures in wood, metal, and nylon that hinted at the movement of micro-organisms, sea urchins, or anemones. In his work, Bury felt that the mechanism should be hidden, there should be as much chance as possible, and the quality of movement should be anonymous, silent, and supernatural. Jack Burnam describes the experience of being in a room full of these constructions, "Through silence, one feels the creaking of cords, spools, and linked shapes from all directions. Out of the corners of the eyes hundreds of multisensual movements take place imperceptibly . . . Without the interference of other human visitors, a room of Bury sculptures rocks with subliminal activity."

2.4.2.3 Hans Haacke

The German born Hans Haacke (1936) isolated the kinetics of our natural environment through the construction of miniature ecosystems. He explained:

> Machines have a different temporal effect on human beings, that is, create a different effect on the nervous system, than nature's timing. Sunrise and sunset, the tides, running water, the patterns of time. Man is in tune with this timing: his breathing rhythm, his heartbeat, in short, the functioning of his whole body, and I would guess also the flow of his thoughts, are of a comparable nature. In contrast to this, artificial timing, as experienced daily in all highly industrialized societies, creates nervous tensions and probably contributes a great deal to the illnesses of these social organizations [Borja-Villel p. 296].

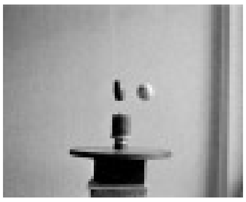


49 Hans Haacke. *Condensation Cube*, 1965

Toward his goal of creating sculpture that is continually changing and reacting to its environment he created the *Condensation Cube* (fig. 49) in 1965 and *Ice Stick* in 1966. The movement in *Condensation Cube* is created by the continual cycle of evaporation and condensation on its Plexiglas surface. *Ice Stick* is a 54" high artificial refrigeration unit which extracts moisture from the air to build a sculpture projecting the phenomenon cold. Haacke's kinetic work of this period can most easily be described as an exploration into natural systems philosophy through the study of feedback and equilibrium.

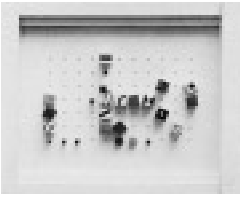
2.4.2.4 Takis

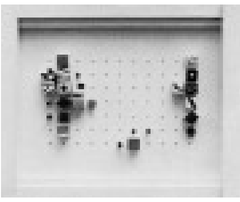
The Greek artist Takis Vassilakis (born 1925) is known for the extensive use of magnets in his work. His goal is to make the forces which dominate our world perceptible on a human level. Wayne Anderson explains Takis as "A romantic man, intensely in love with nature. He seems to be courting the whole phenomenological world, as if it were undifferentiated by size, distance, or significance [Anderson p. 7]." His *Magnetic Ballet* (figs. 50 a, b) of 1961 is characteristic of his work. In this piece an upright cylindrical electromagnet switches off and on at regular intervals. When the magnet is on, it attracts the nearby magnetic black spool and repels the magnetic white sphere. When the magnet is off the black and white spheres attract each other through their natural opposing forces. Some of his *Telemagnetic* constructions are lethargic and others are aggressive as a result of the number of objects and the strength of the magnetic field. Takis feels that Duchamp set artists free from the work of art in allowing natural forces to intervene between intention and art. When Duchamp dropped the one meter long string to the earth in the creation of his *Three Standard Stoppages* it was the first time that natural phenomenon had been allowed to enter into the creation of an artwork. Describing the formulation of one of his pieces, Takis said, "I follow the indications of the materials, I do not dominate them, I hardly ever create. You must understand that. When I use a found object, a piece of some machine, it is to get away from art and



50 a, b
Takis. *Magnetic Ballet*, 1961

nearer invisible forces [Burnam p. 270].” Although Takis’ work has been criticized as simple scientific demonstrations, it is poetic as opposed to explanatory and spiritual as opposed to pragmatic. It attempts to enrich our awareness of the world through enhancing perception.





51 A, B
Yaacov Agam.
Signs for a Language,
1953

2.2.2.5 Yaacov Agam

The Israeli born artist Yaacov Agam (born 1928) believes that, “nothing is fixed in nature nor in the cosmos, and the painting that attempts to attain the truth through congealed/fixed representations falls far short of touching this truth of nature. Everything in nature/reality/creation can be transformed with endless variety, while preserving a particular and defined character [Popper p. 110].” Following this philosophy, in his contrapuntal and polyphonic works, the structure is only revealed as the viewer’s presence produces motion, and in his transformables (figs. 51 A, B), the elements may be rearranged freely by the spectator-participant. Through the inclusion of movement and interaction the structure of the work unfolds in time and the artwork is in a state of continual evolution and a “permanent event” in which spectators participate.

52 Dennis Oppenheim, *Attempt to Raise Hell,* 1974

53 Dennis Oppenheim, products from the *Snowman Factory,* 1996

2.4.3 Contemporary work

After the initial boom in the 1960s, the amount of innovation and interest in kinetic art dwindled. In the opinion of art critic and curator Yve-Alain Bois, it was too hastily dismissed as a result of being “wrongly perceived as an art based almost entirely on easy optical tricks, it would soon be trashed as utter kitsch, on a par with such visible by-products as the Courregès dress and the lava lamp . . . kineticism came to be seen as an art of gadgetry [Bois p. 145].” Another large reason for its disappearance was the art world’s growing emphasis on body art, conceptual art, earthworks, and process as opposed to traditional art objects. Although today there are not many artists working exclusively as kinetic sculptors, many artists such as Dennis Oppenheim and Charles Ray are extending the scope of kinetic sculpture as an element of their diverse activities.

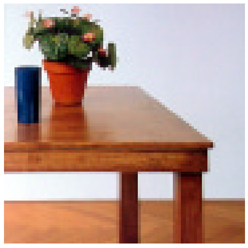
2.4.3.1 Dennis Oppenheim

Born in 1938 in Washington state, Dennis Oppenheim has been internationally recognized since the 1960s for his diverse work in conceptual art, earthworks, body art, and video. In the 1970s he began to build kinetic works involving motors. His sculpture *Attempt to Raise Hell* (fig. 52), created in 1974, is an early example of this direction in his work. In this piece a seated puppet acting as a surrogate for the artist smashes its head into the rim of a nearby hanging bell once every sixty seconds. Toward the end of the 1970s, Oppenheim began creating complex sculptural machines. Of these pieces he said, “Machines are a rather perfect device to use as a metaphor for thinking. [Through these] industrial and mechanical systems . . . I felt I could objectify the mechanics of thought. [Heiss p. 39]" His recent *Snowman Factory* (fig. 53) addresses issues of the mechanization of art and the idea of the object versus performance through manufacturing small representations of three-tiered snowmen out of hollow fiberglass. Through creating this "self-perpetuating, self-manufacturing" automaton, Oppenheim is commenting on the relationship between the individual and the machine, thus making reference to the works of Duchamp and Tinguely.

2.4.3.2 Charles Ray

The work of the American artist Charles Ray (born 1953) spans photography, sculpture, performance, and film. Much of his work is rooted in minimalism, but through his background in performance he is also concerned with the relations between people and things, bodies and objects. In his 1987 *Ink Line* (fig. 54), he focuses on the kinesthetic desire to touch by creating a stream of black printer's ink that runs like a string from the ceiling of his studio to the floor. His *Rotating Circle* (1988) is a rotating white disk installed flush with a white wall. As it rotates it creates an illusion of immobility. Ray's 1989 *Tabletop* (fig. 55) has a quality of movement similar to the work of Pol Bury. As described by curator Paul Schimmel:

54 Charles Ray. *Ink Line,* 1987



55 Charles Ray. *Tabletop,* 1989

> Tabletop consists of six objects arranged on a table. At first glance the objects seem stationary. But, in fact, they rotate so slowly that without patience — the very same patience that one needs to see Minimalist paintings — the viewer would not know that they are rotating at all . . . *Tabletop* permitted him [Ray] to explore the boundaries of peripheral vision and to create motions that readjusted the line where recognition begins [Ray p. 79].

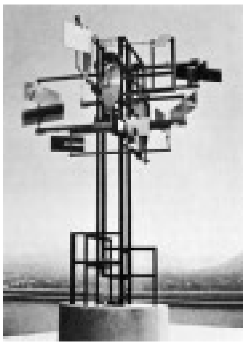
All of Charles Ray's kinetic work refers to a similar hidden instability which he feels leads to a potential anxiety and disruption of the expected course of events.

2.5 Behavioral kinetic sculpture

The term *behavioral kinetic sculpture* is both specific and broad in its scope — as a further categorization of kinetic sculpture narrows the possible, but as an art with a short history and little precedent it is open to a large amount of innovation and exploration. Like kinetic sculpture, behavioral kinetic sculpture emphasizes sculpture as a system, but the systems necessary for the creation of behavioral sculpture are more complex and require the shift from mechanical to electromechanical construction. Early pioneers include Nicolas Schöffer, Liliane Lijn, Piotr Kowalski, Wen-Ying Tsai, Stephen Antonakos, James Seawright, and Nicolas Schöffer [Popper 1993]. In addition to the works described here, the conceptual origins of behavioral sculpture are also found in the performance-based sculpture of Vito Acconci, Mark Morris, and Charles Ray, but their reliance on choreographed human participation makes these works distinctly different.

2.5.1 Origins

Two public exhibitions, one in New York and the other in London, were the world's first widely publicized introduction to behavioral sculpture. *Nine Evenings* was organized by Bell Labs physicist Billy Klüver in 1966. It was the first major modern event planned as a collaboration between artists, engineers, and dancers and was attended by over 10,000 people, but was received by the press as an avant-garde catastrophe. An outgrowth of this event was the organization E.A.T. (Experiments in Art and Technology, Inc.), a brokerage between artists and engineers meant to bridge the "substantial blocks, both psychological and intellectual, among the engineering professions and industry against supporting the seemingly frivolous and illogical ideas of artists [Burnam p. 362]." In 1969 E.A.T. had 300 artist members and 75 engineers. The *Cybernetic Serendipity* program organized by Jasia Reichhart at the Institute of Contemporary Arts (ICA) in London was another major event combining work in computer graphics and sculpture within the larger context of explaining recent advances in computer technology to the public. Participating artists included Nam June Paik, Nicolas Schöffer, James Seawright, Yaacov Agam, Edward Ihnatowicz, Jean Tinguely, and Wen-Ying Tsai.



56 Nicolas Schöffer. *CYSP I*, 1956

57 Wen-Ying Tsai & Frank Turner. *Cybernetic Sculpture*, 1960

2.5.1.1 Nicolas Schöffer

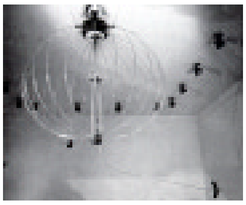
Nicolas Schöffer (born 1912) had an engineer's optimistic view of the possibilities of a technological society and his sculpture worked toward defining a more perfect, rational future through their calculated and meticulous engineering. His *CYSP I* (fig. 56) sculpture was created with the financial backing of the Philips corporation and was produced with the assistance of engineer Francois Terny. As the first fully realized cybernetic sculpture, *CYSP I* "Utilizes control devices to allow the sculptural array to respond to changes in ambient sound and light. Different colors make its blades turn rapidly or lie stationary, move the sculpture about the floor, turn sharp right angles or stay still. Darkness and silence animate the sculpture, while brightness and noise make it still. Ambiguous stimuli . . . produce the unpredictability of the organism [Krauss p. 213]." A more opinionated account of the sculpture is given by Sam Hunter, Director of the Jewish Museum in 1966. He explained, "It is a robot work-of-art, an ingenious dual structure that stimulates and also chills the imagination, for like all purely mechanical spectacles—fireworks, moving colored lights, the play of illuminated fountains—it risks a certain inhumanity, no matter how ingenious or magical its mix of visual effects [Schöffer p. 11]."

2.5.1.2 Wen-Ying Tsai

The work of artist and engineer Wen-Ying Tsai (born 1928) was among the first to electronically respond to its environment. He presented *Cybernetic Sculpture* (fig. 56), a collaboration with engineer Frank T. Turner, at the MOMA in 1968. Using the principle of a standing wave, originally utilized by Naum

Gabo, the *Cybernetic Sculpture* consisted of many 9'4" high steel rods whose vibratory movement was modulated by a strobe light which reacts to sound. It was engineered extremely well so that "the response of the trembling rods seems a direct translation of his [your] voice [Hulten 1969 p. 201]."

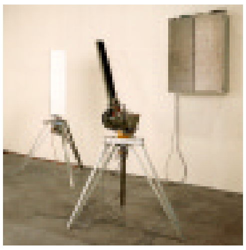
2.5.1.2 James Seawright



58 James Seawright. *Scanner,* 1966

Jack Burnam compliments American James Seawright (born 1922) as the most technically accomplished practitioner of cyborg art, but his work is not focused on the technology, but on fusing behavior with visual form. Seawright states, "I generally think of motors, lamps, circuits, etc, as they are used in my sculptures as having little interest in themselves; it is the way they are integrated into a functioning system that strikes me as the essential application of contemporary technology [Crosby]." Seawright's goal was not to *program* the sculpture, but to produce a personality through the conversion of sensors' data to the actuators. In his 1966 work, *Scanner* (fig. 58), he uses the condition of the sculpture's previous states to determine the course of future states.

2.5.2 Contemporary work



59 Alan Rath. *Friends and Aquantances,* 1998

60 Alan Rath. *Rover,* 1998

After a period of twenty years when very little work of behavioral sculpture was made, the last ten years have seen a resurgence. Simon Penny explains, "In the nineties we have seen a flowering of quasi-intelligent sculpture and sentient installation work which combines the spatiality of sculpture and installation with the reactive, timebased nature of electronic media [Penny 1999]." Contemporary work in behavioral kinetic sculpture interacts with its environment in a similar way to its predecessors from the 1960s, but many practitioners of contemporary behavioral sculpture have a very different philosophy than their immediate predecessors. The work of artists Simon Penny and Perry Hoberman embodies the spirit of Jean Tinguely through its sense of social parody and criticism. Other work, like that of Alan Rath, reflects an engineer's appreciation of technical mastery and a joy of creating playful, graceful objects.

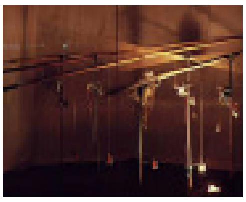
2.5.2.1 Alan Rath

Alan Rath (born 1959) studied electrical engineering at MIT and while there, worked with Otto Piene at the Center for Advanced Visual Studies. His work has the stark visual aesthetic of industrial robots, but their movements and behaviors are designed to elicit response from humans. In speaking about Rath's work, David Ebony of *Art in America* said, "His machines are not aggressive monsters, nor are they passive or subservient beasts. While their movements hint at human behavior and social interactions, they are not anthropomorphic [Rath p. 43]." This quality is revealed in *Friends and Acquaintances* (fig. 59):

> [It] is an intricate and wildly exuberant work in which Rath perhaps most convincingly conflates the human, organic, and mechanical. The five elements in the

piece — three freestanding tripods and two wall-mounted metal boxes — interact with each other in a way that hints at sexual activity and verbal communication. Revealing brightly lit, warm-red interiors, the boxes open and close in response to other elements in the sculpture. Long, rolled-up metal tongues unfurl and protrude in a comic, though rather lurid way to penetrate the open boxes attached to the wall [Rath p. 46].

His *Rover* (fig. 60) is a short, wheeled vehicle similar in concept to W. Grey Walter's tortoises (section 2.2.1.1) but its construction is far more elaborate. As viewers enter the gallery, it moves out of its recharging station and moves toward them to inspect the environment with its video eye. In addition to his work in robotic sculpture, Rath has also built a series of sound sculptures and more conceptual work utilizing large LED displays.



61 Simon Penny.
Lo Yo Yo, 1988

62 Simon Penny.
Petite Mal, 1993

2.5.2.2 Simon Penny

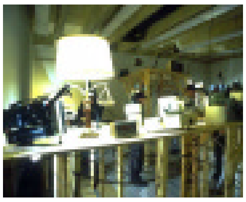
Australian theorist and artist Simon Penny has been making robotic works since 1987. His goal is to create interactive art that explores kinesthetic intelligences, rather than the "literary-imagistic" intelligence supported by screen interactivity. His Lo Yo Yo (fig. 61) is a piece which visualizes the electromagnetic information that permeates our environment. The motion of five rods rhythmically move up and down scanning the broadcast frequency of an attached radio to produce a live sound mix. At any one time, some of the rods will be stopped, some will be moving quickly, and some will be moving slowly, thus creating a constantly shifting audio environment. A more anthropomorphic piece is his *Petit Mal*. Penny collaborated with several engineering assistants to create this autonomous robot that follows people around the gallery space. He said, "It is important that *Petit Mal* is just a little out of control, it is a reaction to oppressive theories of control so ubiquitous in computer science. It is an engineer's nightmare, although the mechanical structure is inherently stable it has a chaotic motion generator at its heart, the double pendulum, an emblem of unpredictability." Through the creation of this robot, Penny is exploring the aesthetics of machine behavior and interaction.

2.5.2.3 Perry Hoberman

Perry Hoberman is an American installation artist who works with technology ranging from obsolete to state-of-the-art. Timothy Druckrey describes his work:

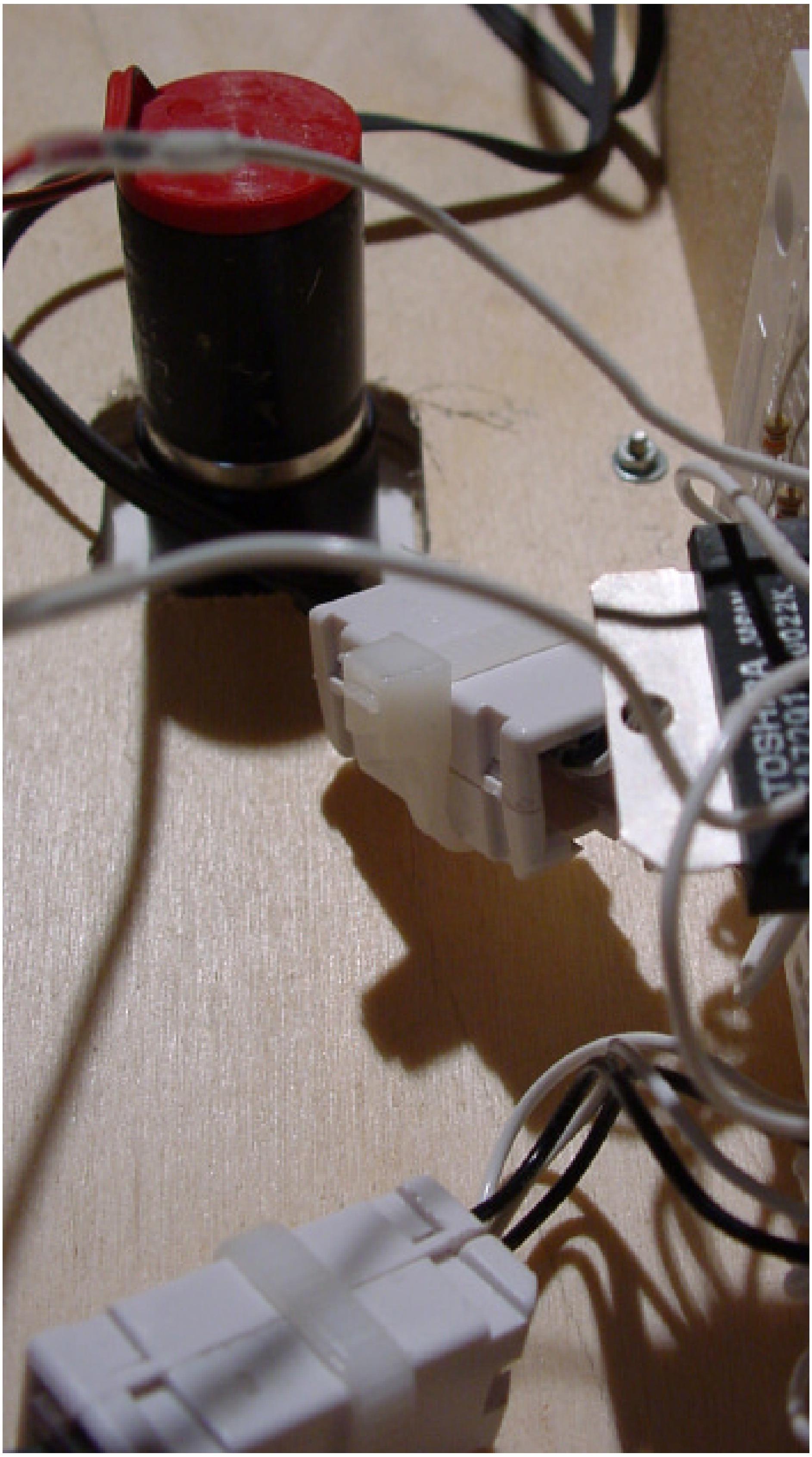
> Perry Hoberman's work aims at assimilating its technologies, devouring its images, betraying its illusions, and creating a kind of raucous discourse. Less outright subversion than ingenious sabotage, the satiric constructions, parodic objects, mocked images, pseudo-virtual environments, iterated banalities, and efficient surfaces betray their own artifice as they signify just how deeply the expectations of artificiality have embedded themselves in the imagination [Duckrey].

His *Faraday's Garden* is a collection of hundreds of household and office appliances such as power tools, radios, lights, and phonographs organized on tables in a room. As people walk through the space, their footsteps turn on and off the machines, creating a stochastic cacophony of noise and motion. Because the interface is transparent, the machines seem aware of human presence, responding to every movement. In *ZOMBIAC*, Zone Of Monitor-Based Inter-Amnesiac Contact, Hoberman lobotomized old computers, converting their raster displays into glowing green binary lights. The machines track people as they enter the room as stepper motors swivel the monitors to follow them. In response to movement, each machine communicates with its nearest neighbors through bursts of light and sound.



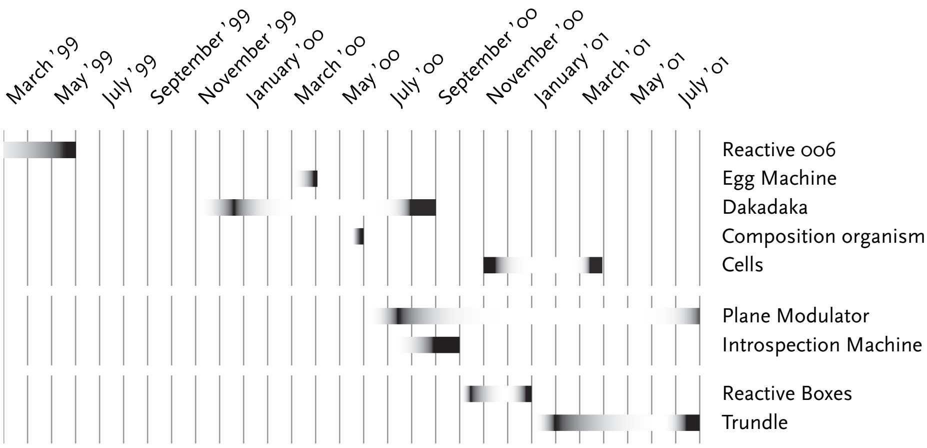
63 Perry Hoberman. *Faraday's Garden,* 1990-99

64 Perry Hoberman. *ZOMBIAC*, 2000



65 The interior of the *Physical Box*

Experiments



66 Diagram of the author's work executed over the past two years. Experiments range from two-dimensional reactive screen-based work to three-dimensional kinetic sculpture

The following works discussed range from experiments in reactive screen-based interface design to experiments in behavioral kinetic sculpture. Although the subject of this thesis is specifically behavioral kinetic sculpture, non-sculptural work is discussed to provide context and comparison as well as to facilitate a richer understanding of the nature of interaction. These experiments progress almost linearly from purely reactive two-dimensional compositions to three-dimensional physical sculptures (fig. 66). The desire to create behavioral kinetic sculpture emerged naturally from the process of imagining continually complex experiments and a frustration with screen-based form and interaction. The common thread is the study of dynamic reactive systems that receive and process input as a means of generating and altering visual compositions.

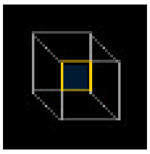
3.1 Screen

In January 1999, after eight years of using the computer as a tool, I began to think more about it as a medium. In an effort to imagine new forms and interactions I felt that I needed to develop a deeper understanding of the medium of computation and began programming as a method of working with the material more directly. Through writing programs, I was able to think about form as a dynamic system. The first experiments I created were curious cousins of my previous work, but over time they gradually evolved into a new aesthetic.

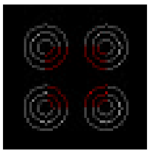
3.1.1 Reactive 006

Reactive 006 is a set of 32 individual studies. Each study is a text machine, a grouping of words which according to set specifications, describes an image, the way an image changes with time, or the way an image may be modified through interaction. The text machines are written in the C language and use augmented vocabulary from the OpenGL graphics libraries. The machines are divided into four groups: Static, Active, Reflexive, and Reactive. Each grouping defines progressively more complex machines, so that while some of the first machines were described in a few phrases, the last machines created required more advanced vocabulary and often more detailed descriptions. As an example of a text machine, a pseudocode description for simple Machine 1_1 (figs. 67 a) follows:

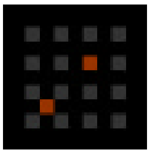
```
// Machine 1_1, draws an isometric cube
setColor(gray)
drawLine(20, 40, 40, 20)
drawLine(20, 80, 40, 60)
drawLine(60, 80, 80, 60)
drawLine(60, 40, 80, 20)
drawLine(20, 80, 60, 80)
drawLine(60, 60, 80, 60)
drawLine(20, 40, 40, 40)
drawLine(40, 20, 80, 20)
drawLine(20, 80 20, 40)
drawLine(40, 20, 40, 40)
drawLine(60, 80, 60, 60)
drawLine(80, 20, 80, 60)
setColor(darkBlue)
drawRectangle(41, 41, 59, 59)
setColor(yellow);
drawLine(40, 40, 40, 60)
drawLine(40, 60, 60, 60)
drawLine(60, 60, 60, 40)
drawLine(60, 40, 40, 40)
```



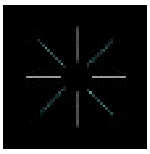
Machine 1_1



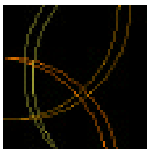
Machine 1_2



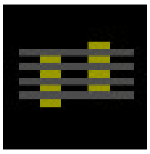
Machine 1_3



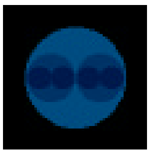
Machine 1_4



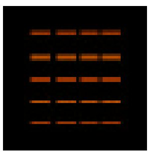
Machine 1_5



Machine 1_6

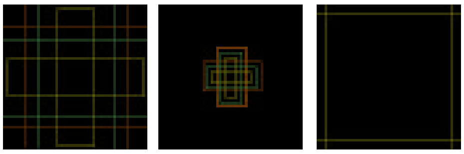


Machine 1_7

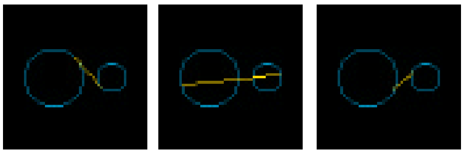


Machine 1_8

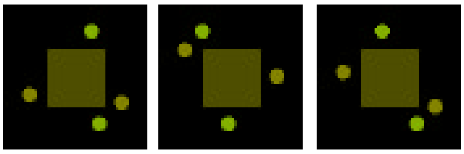
67 A-H. *Reactive 006*, Static Group



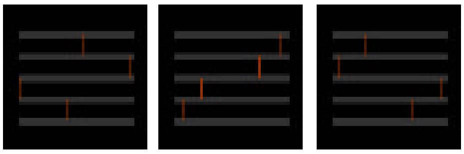
Machine 2_1



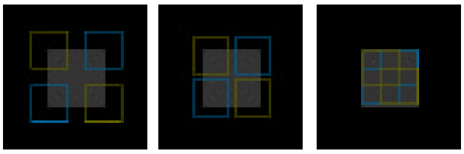
Machine 2_2



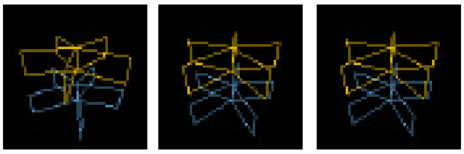
Machine 2_3



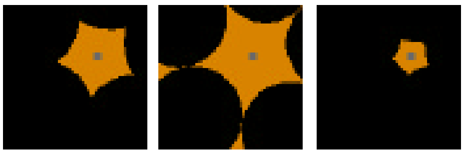
Machine 2_4



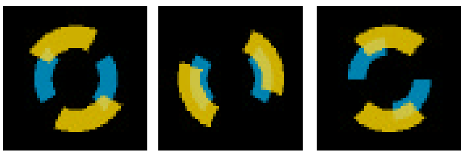
Machine 2_5



Machine 2_6

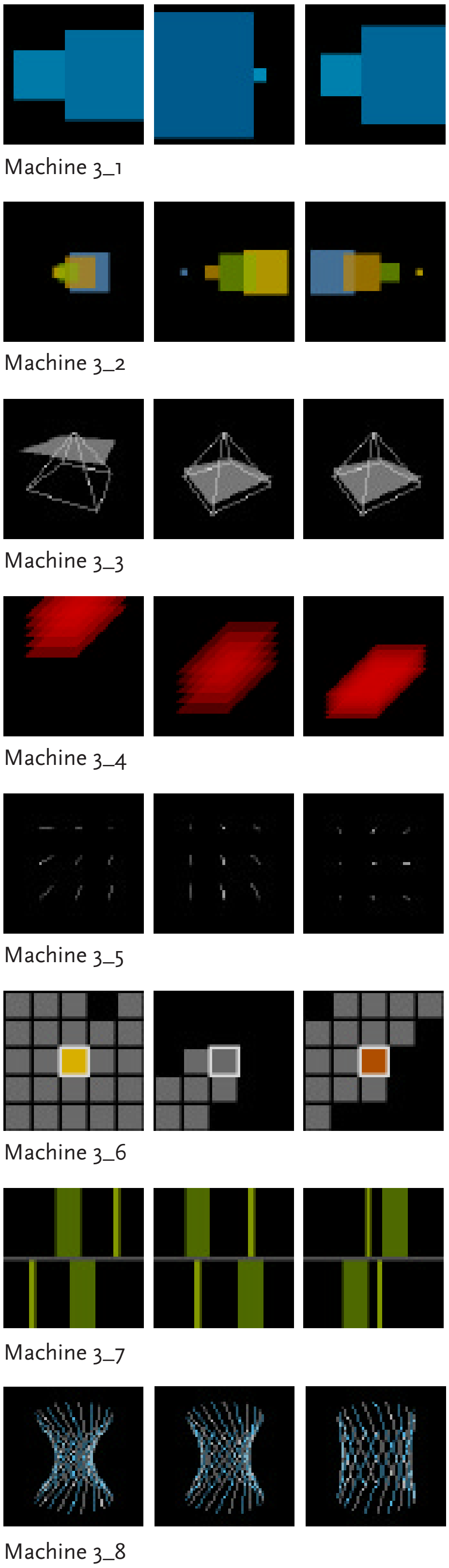


Machine 2_7

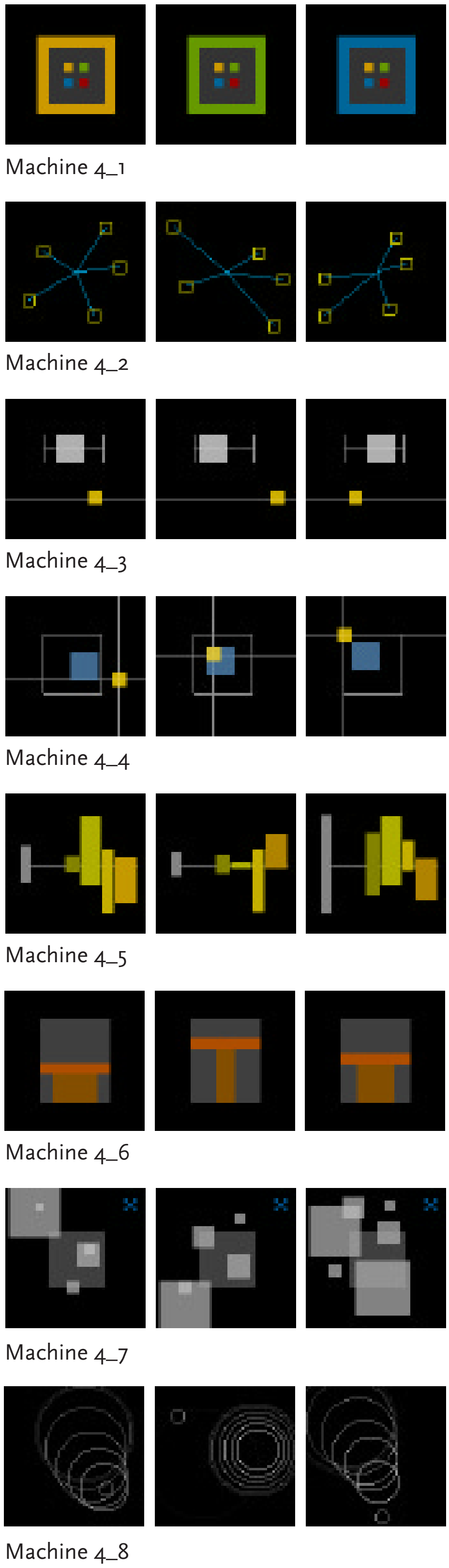


Machine 2_8

68 A–X. *Reactive 006*, Active Group



69 A–X. *Reactive 006*, Reflexive Group



70 A–X. *Reactive 006*, Reactive Group

3.1.1.1 *Static Machines*

The machines in the static group are characterized by not changing with time. Similar to a painting or drawing, these machines remain immutable and stable despite existing within a dynamic environment. The machines that comprise the static group use text to describe geometric primitives and utilize the concepts of iteration and recursion in the service of producing graphic images. For example, Machine 1_3 (fig. 67 c) draws its matrix of rectangles by embedding the rectangle drawing command inside an embedded loop:

```
// Partial code from Machine 1_3
// Embedding a drawing command within an embedded loop
set x = 15
set y = 15
repeat(4)
    repeat(4)
        drawRectangle(x, y, x+10, y+10);
        x = x + 20
    y = y + 20
    x = 15
```

3.1.1.2 *Active Machines*

The machines in the active group are characterized by changing with time, but changing in a way that is entirely specified and unchanging. Similar to a film or animation, these machines present pre-determined images one after another in an unchanging sequence. The machines that comprise the Static group use text to describe geometric primitives and their locations in reference to a quantized position in time. They utilize the concepts of trigonometry to modulate movement and the concept of phase shifting to construct patterns in time. For example, each of the red vertical lines in Machine 2_4 (figs. 68 j–l) move from left to right based on the cosine of an imaginary point moving around the circumference of a circle. To create an interesting rhythm each of these lines is slightly offset from the others so that as some are changing direction, others are stopped, and others are moving very quickly.

3.1.1.3 *Reflexive Machines*

The machines in the reflexive group are characterized by their ability to dynamically change in relation to their environment, but the way they react is entirely specified and unchanging. Their major innovation is capturing mouse movement and using it to alter their position, direction, and the speed of movement. In Machine 3_1 (figs. 69 a–c), for example, the horizontal position of the mouse determines the size relationship of the blue rectangles. If the cursor is at the far left of the image, the left square is small and the right large, but as the cursor moves to the right this ratio reverses. The rectangles in Machine 3_6 (figs. 69 P–R) move in relation to the mouse's distance from the center point of the image. As the mouse moves away from the center of the image, the rate at which the rectangles pan across screen increases. The angle of the mouse in relation to the center point of the image is used to determine the direction of movement.

3.1.1.4 *Reactive Machines*

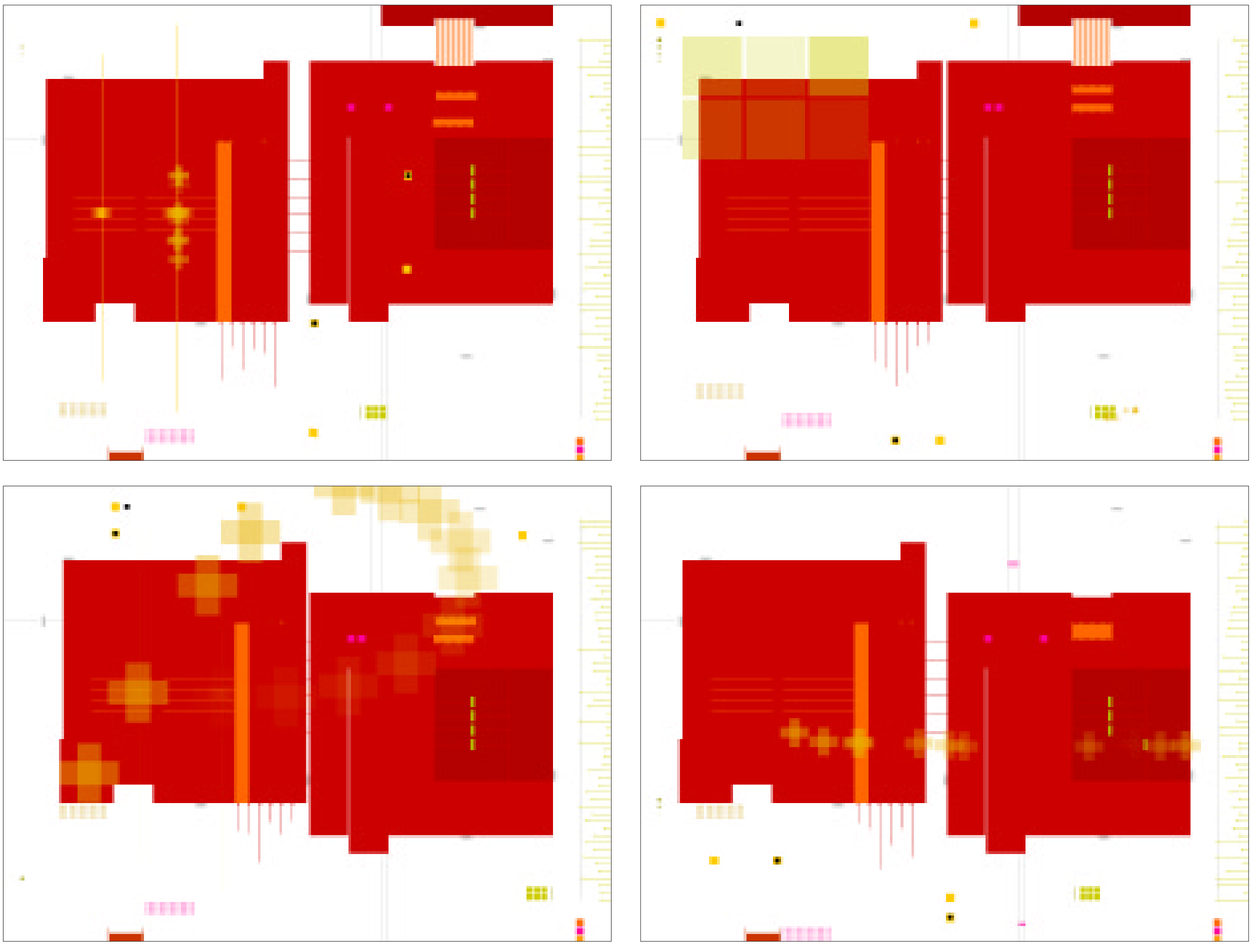
The machines in the reactive group are characterized by their ability to remember and to switch between modes. They do this through using logical statements. The simplest of these machines, Machine 4_1 (figs. 70 A–C), remembers the most recent color that has been selected and displays it on its outside band. By clicking on one of the four small colored rectangles, it is possible to select a new color. This machine utilizes the IF/ELSE syntax to know which color to display:

```
// Partial code from Machine 4_1, selecting different modes with IF/ELSE syntax
if (yellowSelected)
    setColor(yellow)
else if (greenSelected)
    setColor(green)
else if (blueSelected)
    setColor(blue)
else (redSelected)
    setColor(red)
draw
```

Machine 4_7 (figs. 70 S–U) also uses the IF/ELSE syntax and additionally adds the syntax element of ARRAY to store a large sequence of numbers in a conceptually powerful construct. This allows Machine 4_7 to efficiently define and draw thirty separate rectangles, each with a dynamically modifiable size, speed, and position.

3.1.2 Egg Machine

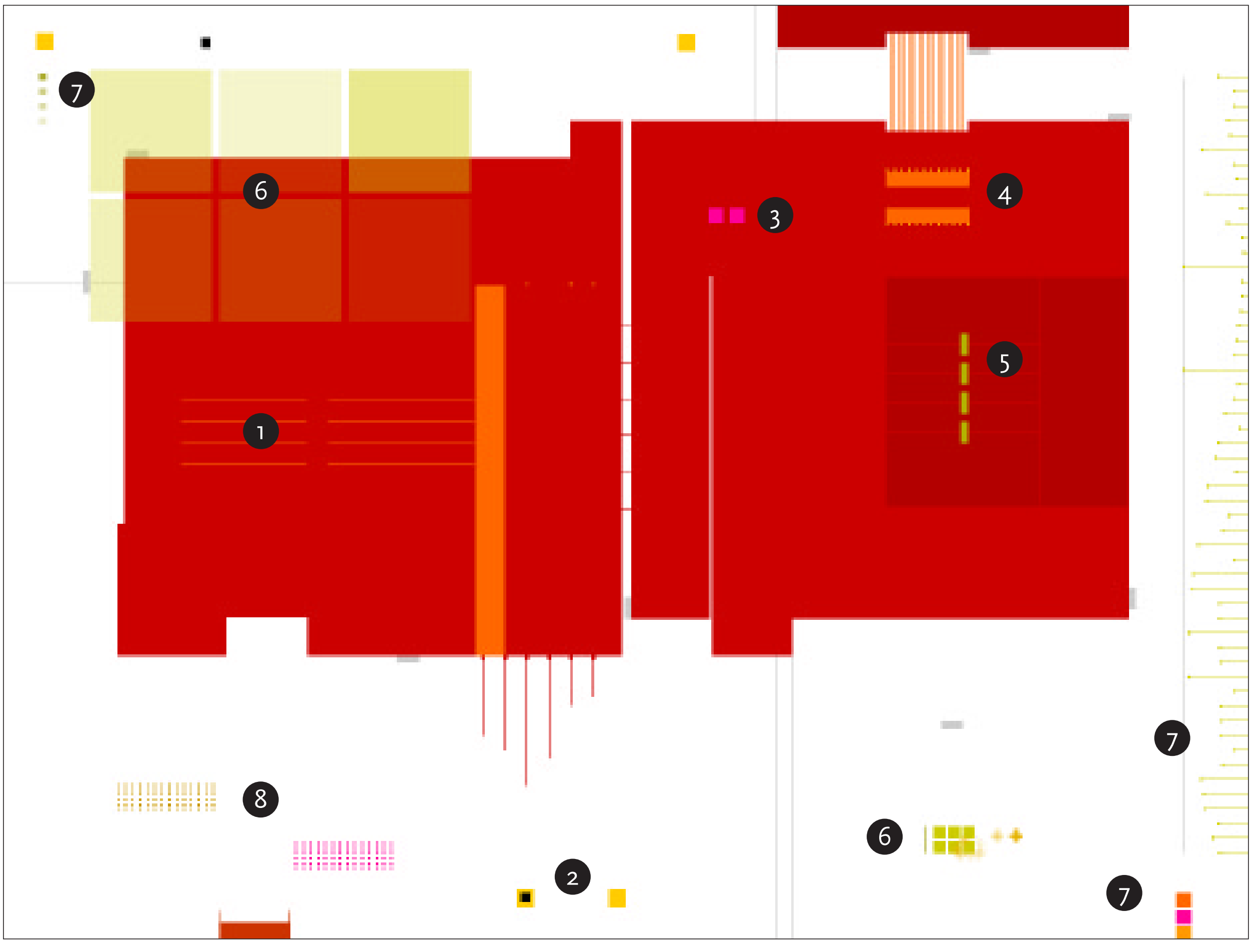
Egg Machine is an extension of the text machines explored in the *Reactive 006* experiment. When integrating many of these machines into a unified composition, issues of dynamic structure, temporal modulation, and hierarchy become dominant. *Egg Machine* uses its manipulable screen-based interface as a method of additive audio synthesis. As people transform the screen interface through interaction with a mouse, they alter internal parameters that change the frequency and volume of the wave forms that are converted into sound. The focus of interaction with *Egg Machine* is on exploration. Its composition is comprised of eight separate visual systems, each with its own rules and unique grammar. Intentional operation of *Egg Machine* requires



71 a–d
Egg Machine
Four different states of the image as captured during interaction

decoding these grammars and manipulating the graphics to alter the synthesized sounds. For example, through noticing that two elements on the screen have a similar size and color and thereby determining they are a part of the same system, the participant may change the spatial relations between these elements to change their movement or the sound they control.

Visual system 1, noted in fig. 72, is defined by two rectangles implied by two arrays of horizontal lines. When the cursor enters one of these areas, its presence is marked by two vertical lines (fig. 71 A) and a tone of 550Hz is produced. While visual system 1 is active, the horizontal position of the mouse modulates the frequency of the 550Hz tone. Visual system 2 is two pairs of matched yellow rectangles. Each of these pairs maintains visual orientation so they are always facing each other. A small black rectangle is constantly being passed between them, as if the rectangles were playing catch. When the black rectangle is caught by a yellow rectangle, a short tone of 500Hz is produced. The two pink rectangles that create visual system 3 are constrained to horizontal

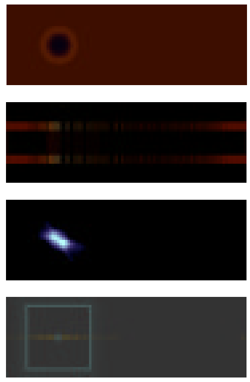


72 Still image from *Egg Machine*

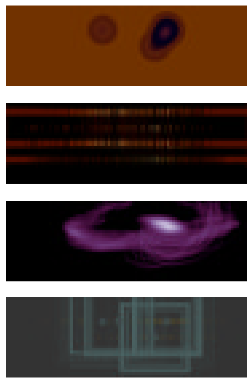
movement. If they are positioned so they are straddling the gray vertical lines in their vicinity, a fluttering high pitched tone escapes as previously hidden pink bars move up the gray lines with an effect similar to a Jacob's Ladder. Visual system 4 is two spiked, orange horizontal bars that are continually oscillating left and right. The movement of these bars is constrained to the vertical axis. As they are moved closer together by the cursor, their oscillating frequency and the tone they produce increases. As they are moved farther apart they decrease their oscillating frequency and their tone. The four small green rectangles that make up system 5 are each models of a spring. As they are pulled left and right and released, their distance from the origin point increases the amplitude of a 300Hz tone. Therefore as the springs oscillate, they modulate the volume of the tone. Visual system 6 is triggered by the cursor rolling over the moving small green grid in the lower right area of the screen. While the cursor is on top of one of the green squares a buzzing noise is created and the rectangle is duplicated, magnified, and displayed in the upper left area of the screen. The array of green lines on the right edge of the screen is the core of visual system 7. Changing the lengths of each of these lines programs a temporal sequence that is displayed along the left edge of the screen. Long lines correspond to large pauses and short lines correspond to small pauses. The orange, pink, and yellow stacked squares in the lower right area of the composition are tokens for a separate stored temporal program. By selecting one of these squares, previously programmed rhythms can be loaded. Visual system 8 is the speed setting for the movement of the two large red shapes that dominate the image. Moving the two adjacent matrices into horizontal alignment triggers the motion of these shapes. There are six discrete speed settings, each corresponding to the degree of alignment.

A large effort was made to develop a fluid grammar of interaction and a refined quality of movement for the *Egg Machine* experiment. Transparency was used to create subtle fading effects for introducing and removing elements from the composition space. For example, when an interaction with system 6 triggers the appearance of a second, enlarged grid, it fades into view, thus making its presence known but without completely distracting attention from the initial area of focus. This technique is analogous to the way our eyes bring an object slowly into focus as we move our gaze across a room. Similarly, fading in a visual rollover feedback element makes the transition between "off" and "on" more natural. This is analogous to touching an object lightly before grasping it tightly. As the elements of *Egg Machine* move across the surface of the screen they are constantly modulating their rate of movement so they ease in and out of their stopping and starting points. This technique is an abstraction of natural physics and gives the graphic elements a quality of grace and mass.

Egg Machine is a wholly deterministic system. Every visual element and its modifiable parameters are the result of a conscious decision making process by the creator. It will not adapt its behavior depending on how people interact with it or as the result of any other external factor. It has no representation of time or energy, hence if someone were to leave it on for a week and not interact with it, *Egg Machine* would be in an identical state at the end of its isolation.



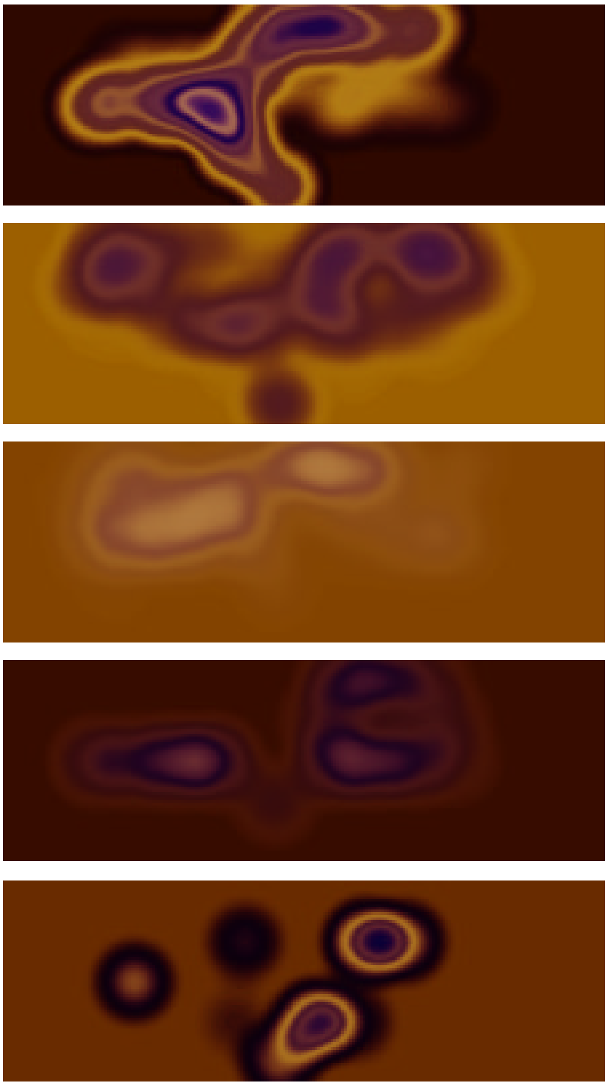
73 A–D
Dakadaka maps spatial coordinates from the keyboard to the screen. Pressing the letter "A" creates an image in the middle and left of the screen



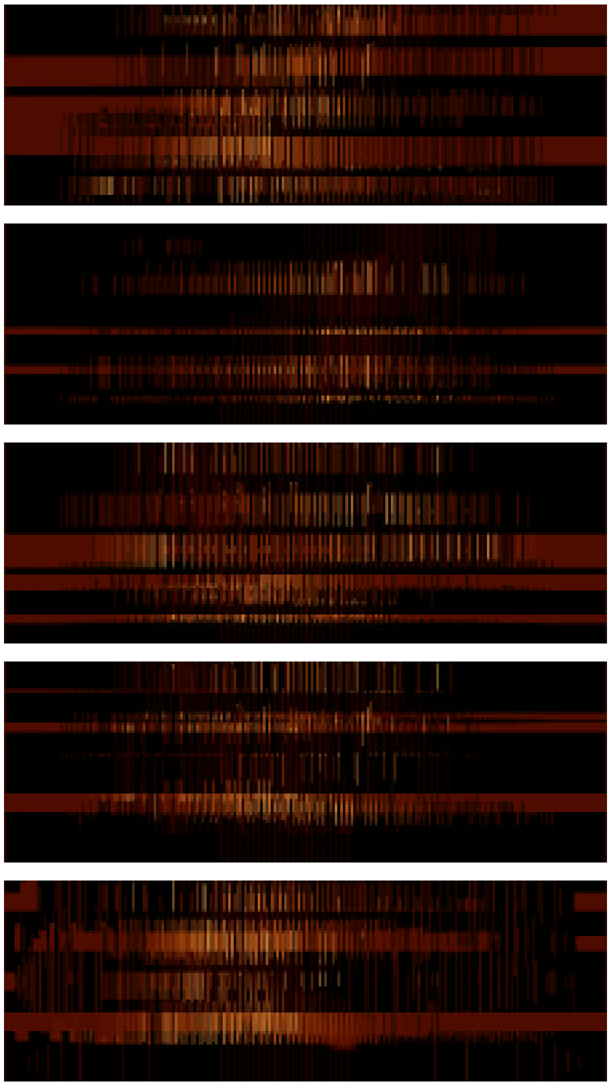
74 A–D
Each of *Dakadaka*'s graphic layers display similar keystrokes in different ways. These images emerge through typing "T-O-K-Y-O"

3.1.3 Dakadaka

Dakadaka is an interactive Java applet built in collaboration with Golan Levin to explore the fluid process of typing as both a positional typographic system and an abstract dynamic display. Typing can be thought of as a percussive spatial action — a play of tiny thoughts scattered onto a tightly organized grid, a kind of speech spoken through the fingers with flashing rhythms and continuous gestures. Alphabetic and pictographic writing systems commonly create meaning by permuting a large set of dissimilar symbols. There are, however, alternatives that achieve the same result by using a set of similar symbols which are differentiated not by their form but by their position in space. Some of these positional typographic systems use permutations of space to

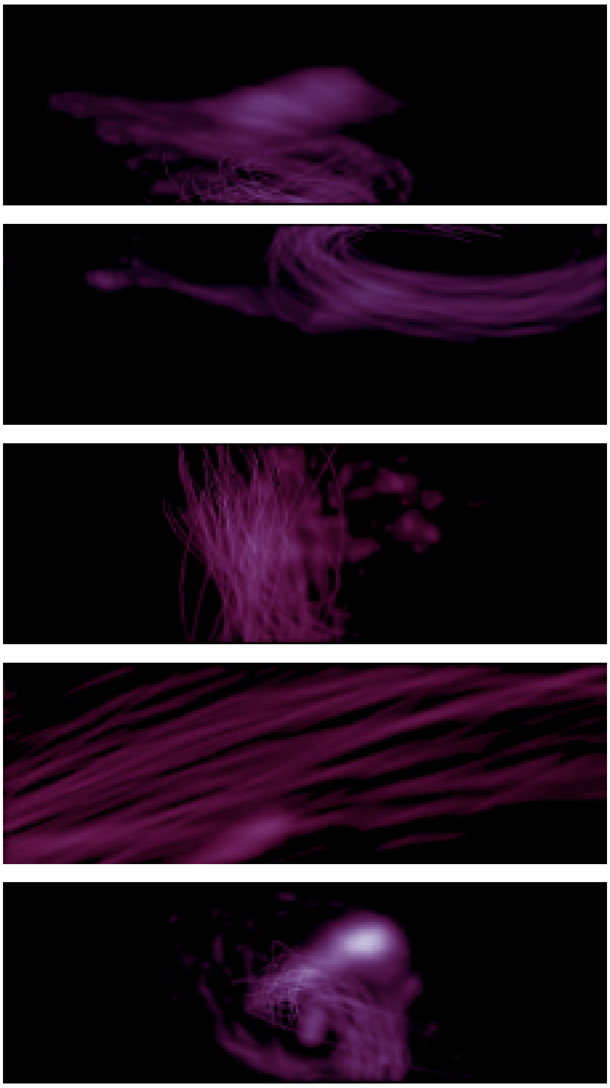


75 a–d. *Dakadaka*, *Blob_mode*

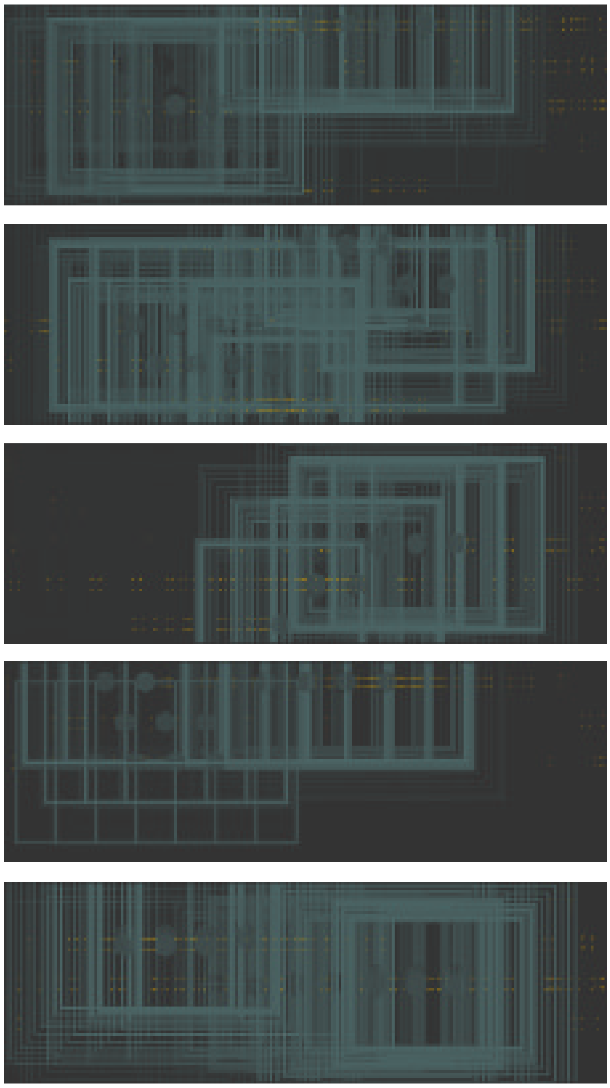


76 a–d. *Dakadaka*, *Line_mode*

create letters; others create words by varying the spatial patterns of similar elements. The design of *Dakadaka* was inspired by such systems because of their natural application to the gridded keyboard space and because of their ambiguous situation between writing and pure abstraction. By removing the symbolic language (letterforms) from the act of composing words, only the raw physical action of typing remains. The temporal qualities of this physical action are analogous to those of speech. By connecting the physical act of typing to a dynamic display instead of a static one, *Dakadaka* reflects these fleeting performances back to us, reminding us of their gestural and continuous qualities.



77 a–d. *Dakadaka*, *Worm_mode*



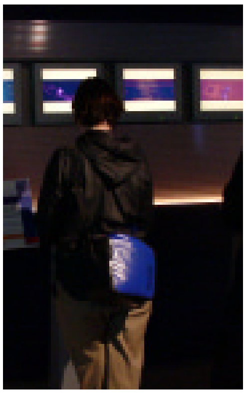
78 a–d. *Dakadaka*, *Daka_mode*

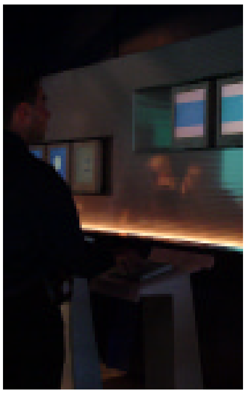
3.1.3.1 Foundation

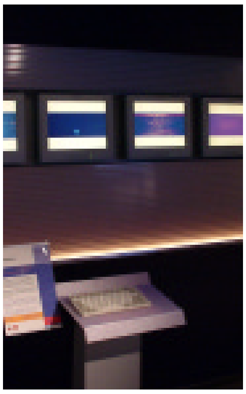
The technical foundation of *Dakadaka* is its ability to capture keyboard events and translate them into positional coordinates. The spatial position of the keys on the keyboard are mapped to their analogous position within the *Dakadaka* image plane. For example, on a standard English (US) keyboard layout, the letter "Q" is mapped to the upper left corner of the space and the "?" is mapped to the lower right area of the space. Figures 73 a–d show the result of typing the letter "A" and figures 74 a–d show the result of typing "T-O-K-Y-O."

3.1.3.2 Graphic layers

Four different graphic layers were built on top of this foundation, each using the keystroke information in a different way to create a unique visual and temporal image. In *blob_mode* (figs. 75 A–D), written by Golan, depressing a key creates an expanding pool of color on the still black field of the screen. As the pools grow in size they shift from orange to black and back again as the program cycles through a customized 8-bit color palette. When pools intersect they briefly merge to form glowing asymmetric shadows that mirror their composite words. In periods of high activity, the entire palette shifts so that orange shifts to yellow and black shifts to blue. *Blob_mode* connects individual letters through its bleeding images, thus creating a literal visual analogy to gestalt principles of proximity. The property of this layer to display a group of characters simultaneously on the screen for a short space of time is also analogous to the property of speech entering and then slowly fading from our consciousness. *Line_mode* (figs. 76 A–D) presents an analogy of typing that is more similar to editing. Once a mark is made in this layer, it remains until it is overwritten. For every key pressed, two thin vertical lines move from the point of contact to the opposite ends of the image. This is similar to a sound radiating from its origin until it fades from range. Color is added to the screen a keystroke at a time — the first time a line moves over the black background it leaves a dark red trail, but each time a line covers the same spot more than once, it begins to lighten that spot. Over time, a history of letter frequency is built up in the light and dark values on the screen. In *worm_mode* (figs. 77 A–D), also written by Golan, the space between the letters is emphasized. As a series of two keystrokes are made, this layer will connect them with a swirling purple swath. The frequency in which the letters are hit and their distance from one another determine the width and speed of this mark. For example, if typing is proceeding at a slow pace, the purple trace will maintain a narrow and uniform width, but if the speed of typing begins to increase, the purple trace will become fragmented, leaving a scratchy and diverse trail. The images created in *daka_mode* (figs. 78 A–D) are built up over time from the teal squares and yellow pixels that appear when a key is hit. The squares oscillate quickly and with force when a key is pressed, and then gradually damp themselves into a static state. Re-typing a key will once again initiate oscillation. The horizontal yellow lines that are created with each keystroke are continually being overridden by new marks, but a quick glance at the screen reveals the recent history of letters typed into the system. In all the graphic layers, movement is the direct action of someone using the system and while some layers maintain a history of the conversation and others do not. A common element between the four layers is allowing the act of typing to be seen as an expressive performance, not a mechanical process of converting thought into characters.



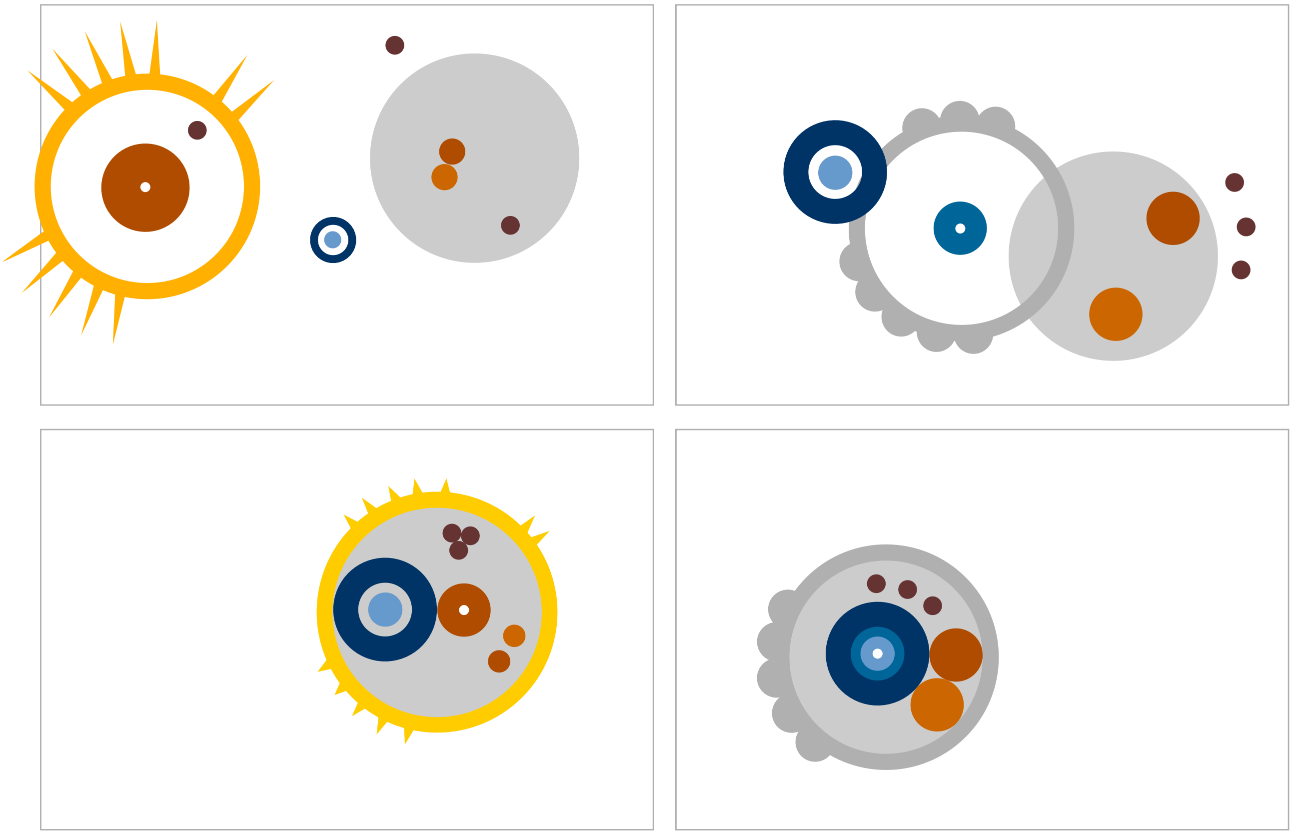




79 A–C
Networked *Dakadaka* at the Ars Electronica Center in Linz, Austria

3.1.3.3 Networked Dakadaka

For the exhibition *Print on Screen* (figs. 79 A–C) at the Ars Electronica Center in Linz, Austria, *Dakadaka* was extended to be a networked application. With the assistance of Ben Fry, the software was modified so that one *Dakadaka*

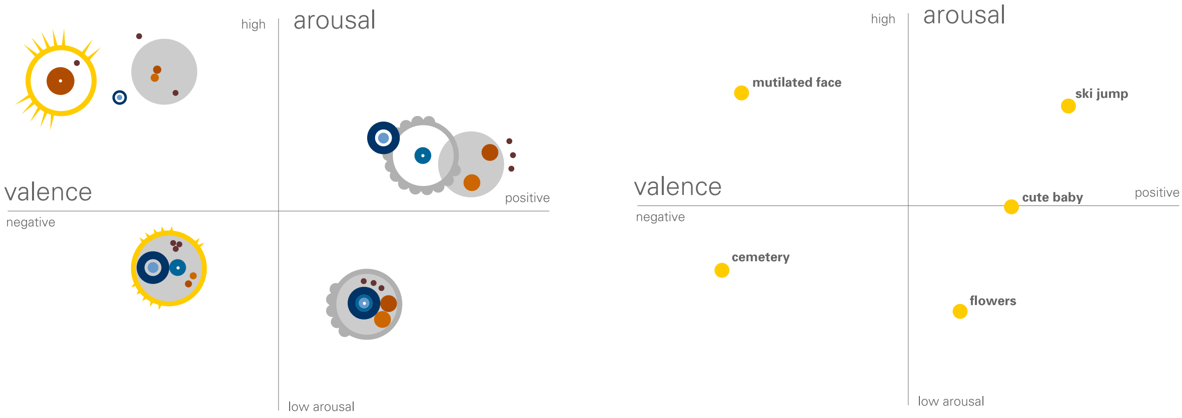


80 A–D
Four different emotional states of the *Composition Organism*

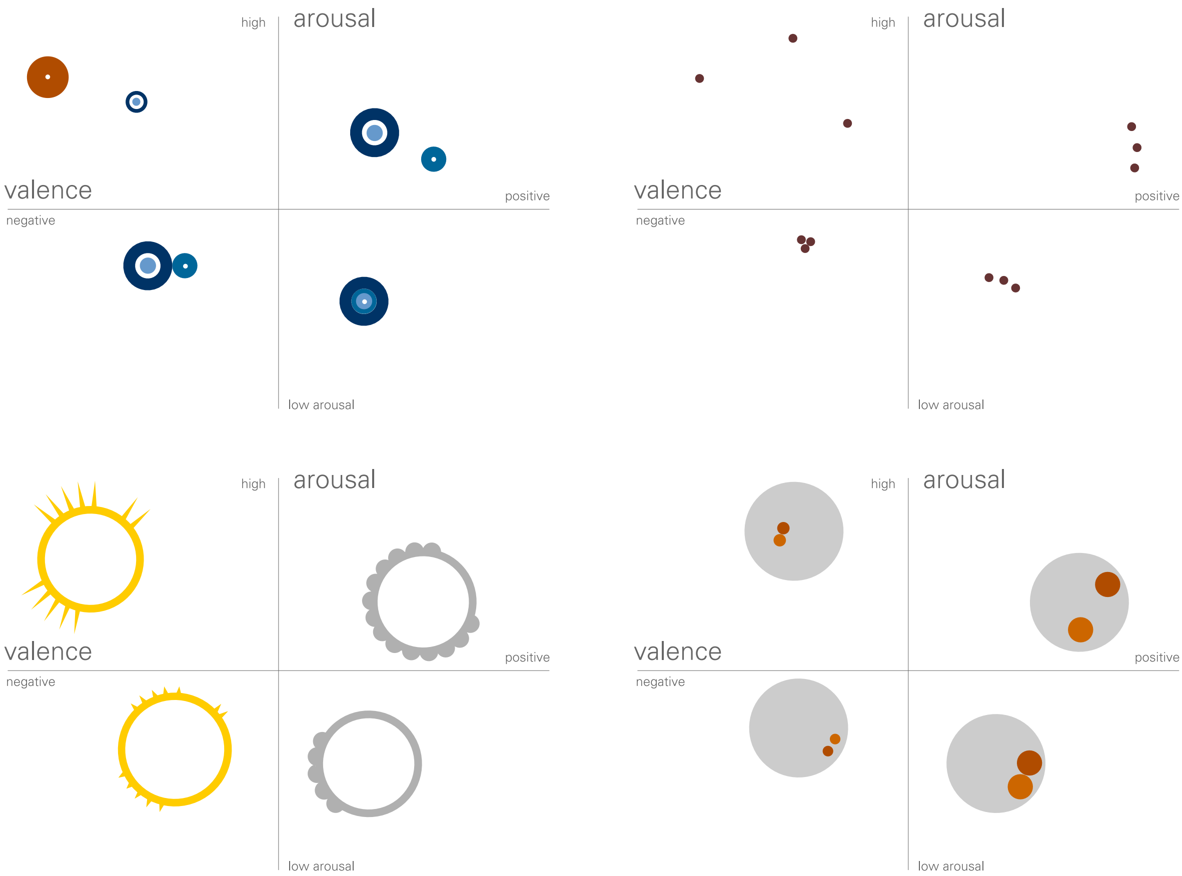
display could simultaneously receive multiple keystrokes from any networked computer anywhere in the world. This feature was utilized to allow one keyboard to control two applications at once. One of the applications acted as a server, broadcasting the keystrokes from its attached keyboard to the other machine which was continually listening for this information. A text file associated with each identical *Dakadaka* application specified whether it would broadcast or listen, which graphic layer it should apply, and if it is broadcasting, to which IP addresses it should broadcast. Through linking multiple displays to one keyboard, the typographic effect of *Dakadaka* was enhanced— each screen became a communication filter, translating the raw keystroke information into structurally identical but visually disparate translations.

3.1.4 Composition Organism

Based on readings in ethology and animal physiology, this design exercise was executed to create a better understanding of the behavior of living creatures by translating the concept of an organism into an abstract screen-based computational system. The *Composition Organism* was a conceptual exercise and was not implemented as a piece of software. Many of the ideas generated from this project provided the



81 A, B. Emotional states of the *Composition Organism*



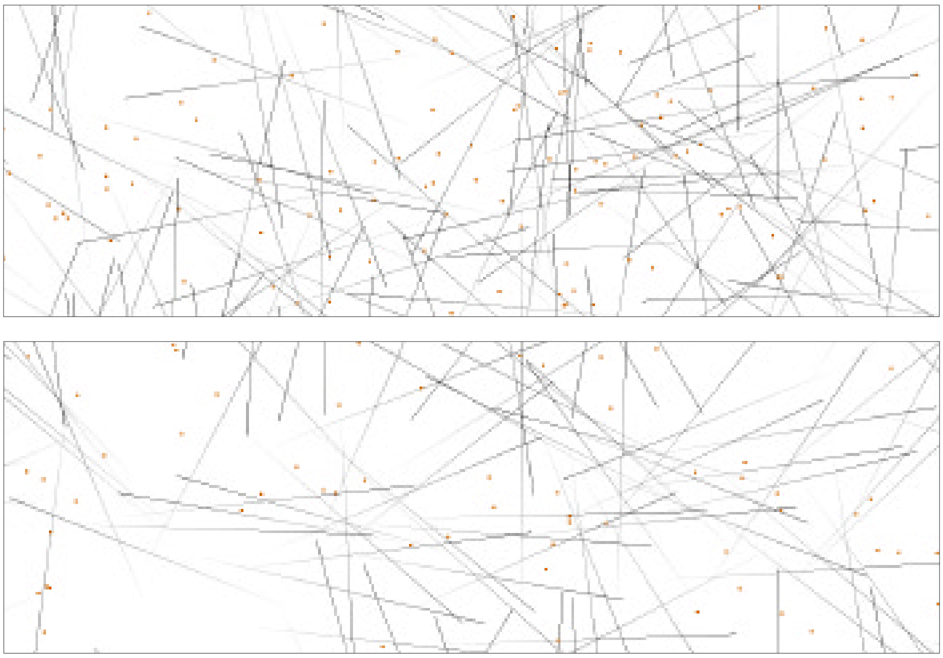
82 A–D. Each visual element of the *Composition Organism* reacts in a unique way

foundation for the behavioral kinetic sculpture, *Trundle* (section 3.3.2).

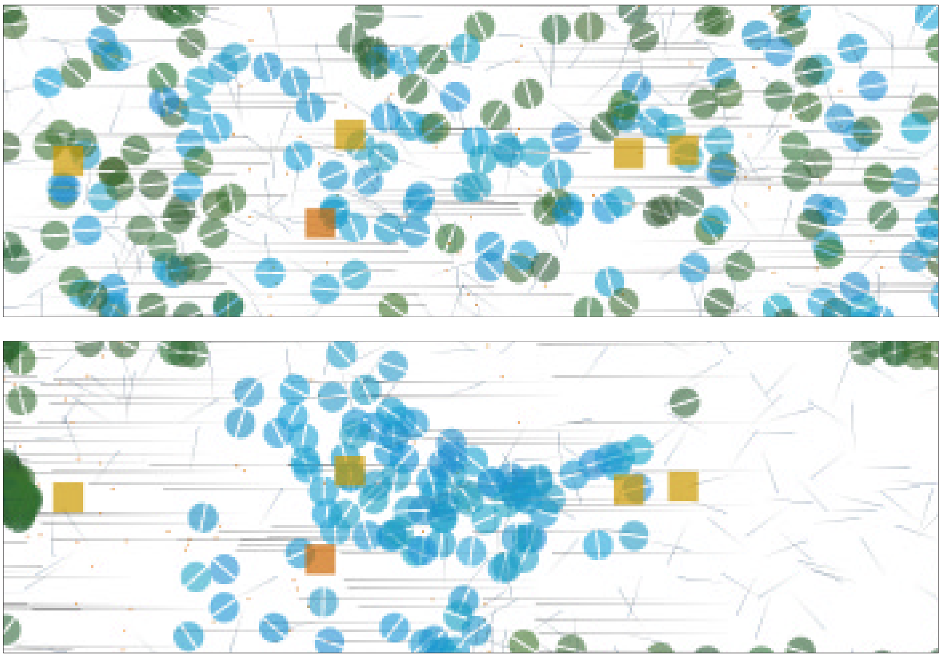
As defined by this exercise, there are five basic properties of a *Composition Organism*: filters and processes information from the environment, maintains a representation of the environment and its internal state, communicates to externalize its state and to reach its goals, develops as a result of interacting with its environment, and modifies behavior to maintain preferred state. The *Composition Organism* is further defined as having four parts: base state, input, representation, and output. The base state is equivalent to the knowledge an organism has when it enters the world. The base state includes a set of core actions and activities (reflexes and instincts) and physical constraints (the movements the physical body allows). Its input could mimic those of a human — sound, touch, sight, smell, and taste — but they could also extend beyond into remote parts of the electromagnetic spectrum or into conceptual space. The representation could be deliberate, hierarchical, and complex like that of *Shakey* (section 2.2.2.1) or it could be flexible, light, and modular like that of *Genghis* (section 2.2.2.2). The primary functions of the representation are to filter and interpret the data from the sensors, maintain a balanced state, and to control the output. Data coming into the organism is often noisy and first needs to be filtered by the representation to be usable. Depending on the complexity of the representation, the data is evaluated as useful or not useful and the organism alters itself to compensate for the perceived changes in its virtual environment. To communicate its current state and reach its goals the representation controls the movement of the composition. There are many methods available for the *Composition Organism* to use for communication — some within human perception and some beyond. The basic methods are auditory, visual, and kinetic. Auditory communication can be achieved through modulating pitch, timbre, volume, and tempo. Visual communication (fig. 81 A) can be achieved through modulating the color, form, scale, position, and orientation of the organism's geometric limbs. Figures 81 A and B presents each of the organism's visual elements as mapped into a two dimensional representation of the organism's current affect. The vertical arousal axis displays the stimulation of the organism and the horizontal valence axis displays the quality of its affect from the range of negative to positive. The organism may also communicate through its speed and qualities of movement. The communication channels open beyond the human senses include speaking to other machines through network protocols, producing audio tones outside the human auditory range, and changing at a rate that is undetectable by human vision, etc.

Through an extended period of interaction with a composition organism, its form and mannerisms change, building upon its base state and as the result of the quality of interaction it has experienced during its life. For example, an organism that receives very little stimulus may become lethargic, exhibiting very little energy.

83 A, B
Cells: Vehicle 1



84 A, B
Cells: Vehicle 2



3.1.5 Cells

Based on the work of Valentino Braitenberg (described in section 2.2.1.3), the *Cells* project explores variations in behavior made possible by a simple simulated neural system.

3.1.4.2 Cells 1

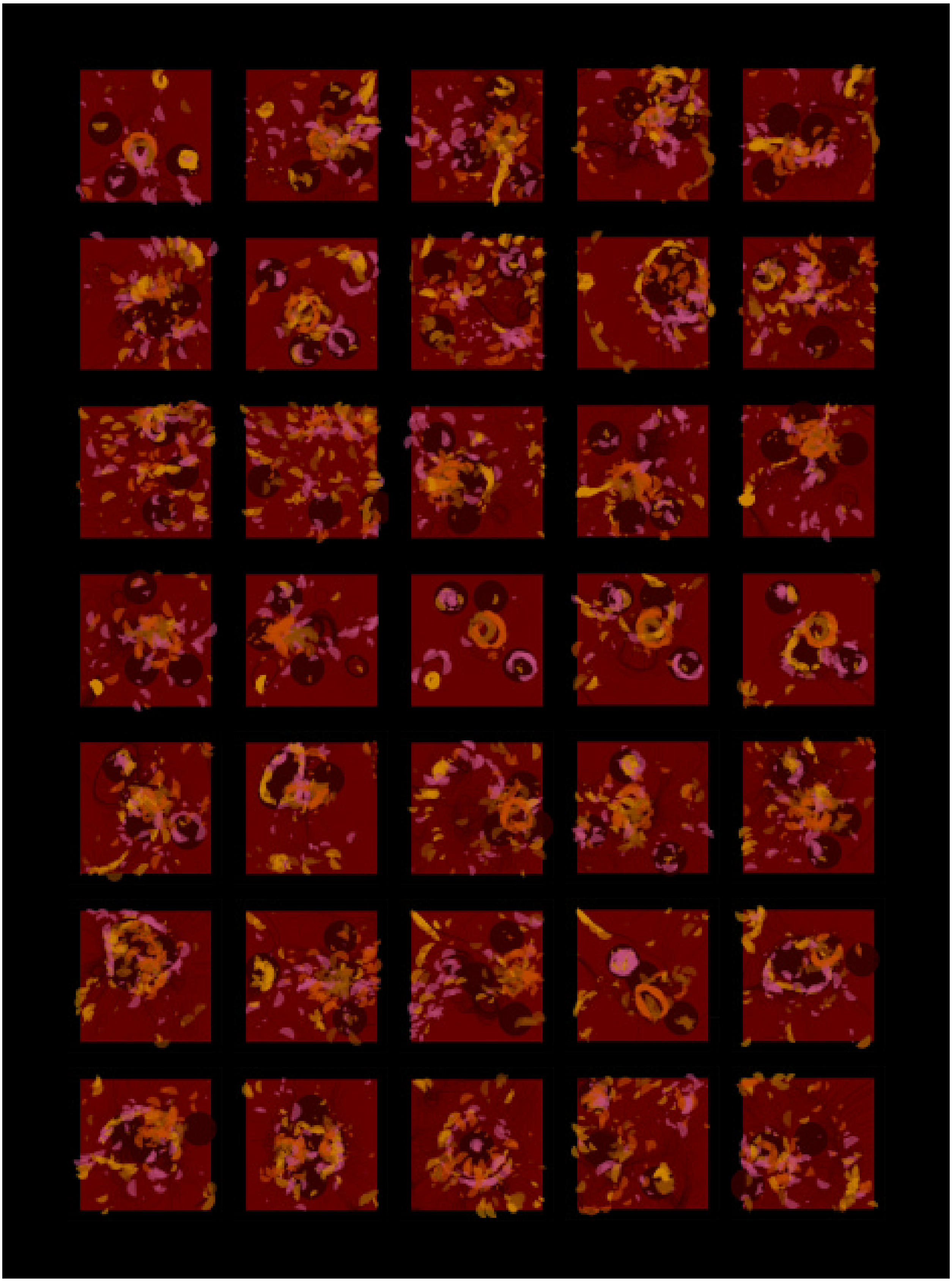
The simplest of Braitenberg's vehicles is one sensor attached to one motor. The lines in *Cells 1* (figs. 83 A, B) are virtual analogues to Braintenberg's Vehicle 2, the elements in *Cells 2* (figs. 84 A, B) have two to this simple vehicle. A simulated surface beneath the lines mimics patches of friction. As each line moves forward, its sensor (shown in the image as a dot) constantly monitors the surface. When the lines move over areas of high friction they slow down and when there is no friction, they speed up until reaching their terminal velocity.

3.1.4.3 Cells 2

As an analogue to Braintenberg's *Vehicle 2*, the elements in *Cells 2* (figs. 84 A, B) have two simulated sensors and two simulated motors. The blue hemispheres have crossed connections between their motors and sensors and the green hemispheres have straight connections so that their left sensor controls their left motor, etc. The yellow rectangles in these systems represent the locations of the sources of attraction. When the system begins, it is in a state of random chaos, but over time, it gradually moves to a state of kinematic order. All of the cells are constantly moving, pulled in many directions by the different forces acting upon them, but they slowly begin to find a comfortable pattern of movement and they repeat it constantly. When one of the attractors is moved, the system is taken out of its cycle, and once again slowly begins to find an equilibrium.

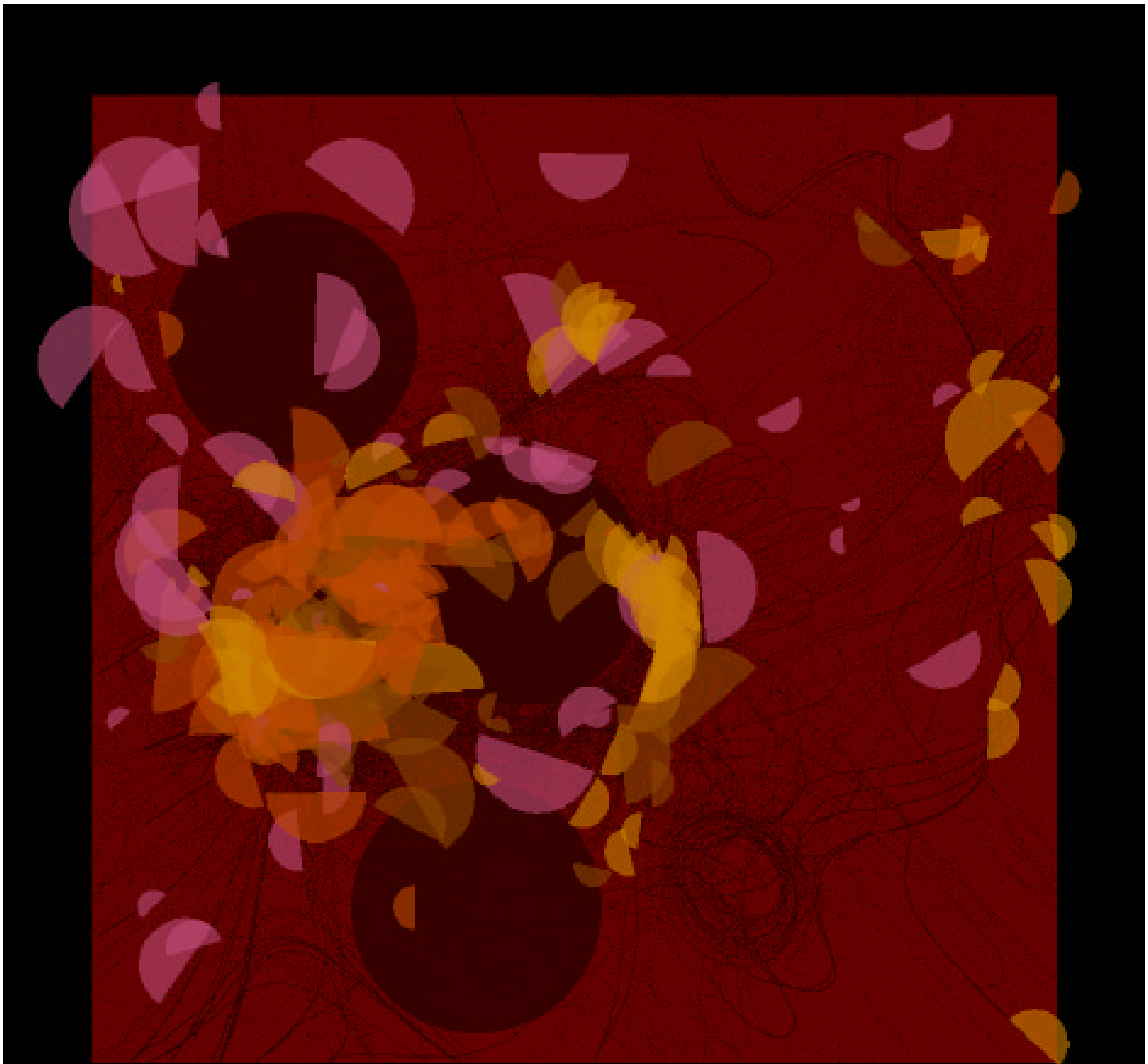
3.1.4.4 Cells 4

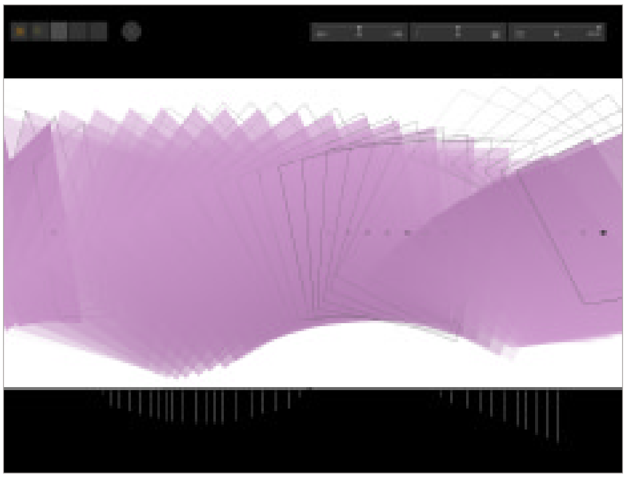
The final and most complete of the Cells studies includes four different types of Braitenberg's vehicle 4. The primary characteristic of the cells in *Cells 4* (figs. 85 A–II & fig. 86), represented by a single half circle, is the nonlinear mappings between their virtual sensors and motors. These mappings make it possible, for example, for a cell to move quickly when it is far away from an attractor, to move more slowly as it moves closer, and when it becomes too close, to speed up again. This property makes the behaviors of these cells far move interesting than those in the previous experiments. The recent history of the locations of these cells are shown through a black train of 1000 points that each cell leaves behind. These trails are a visual tool that enables us to see the complex movements of these simple cells over time. The attractors in this system are visually represented by large black circles which may be moved from location to location through an interface on the right edge of the image area.



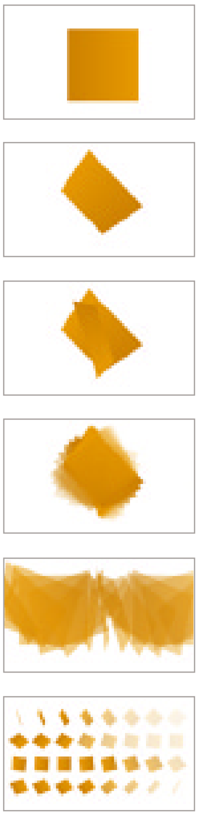
85 A–II
Cells: Vehicle 4

86 *Cells: Vehicle 4*





87 The digital interface to *Plane Modulator*



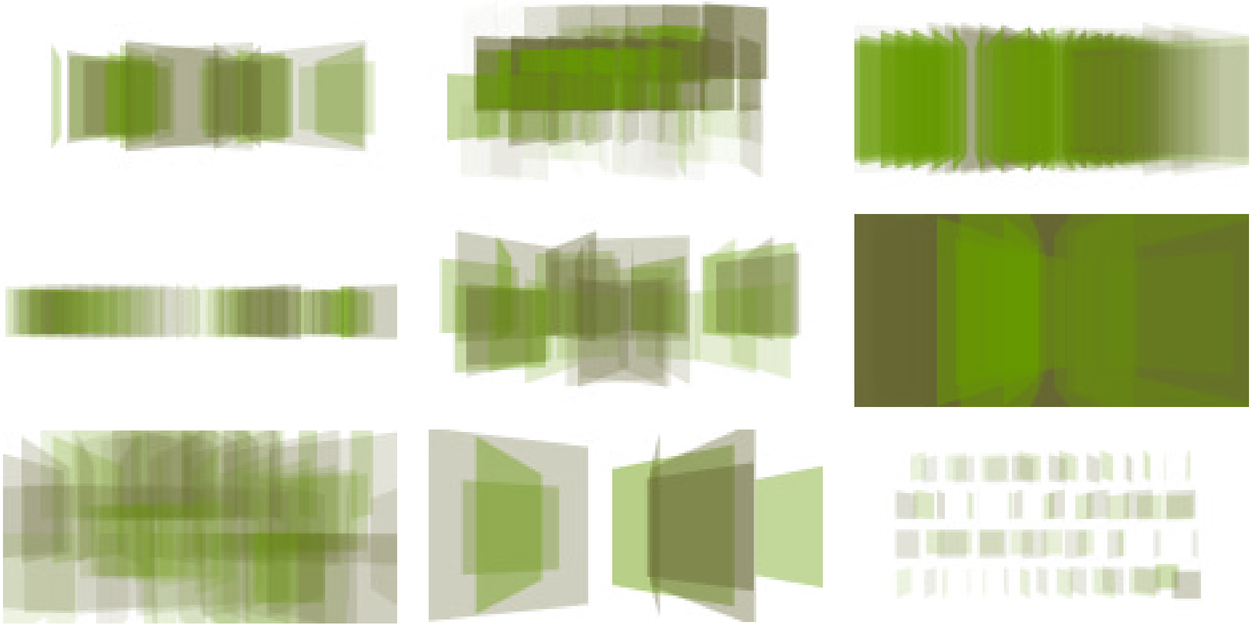
88 A–F
Example screens of the *Plane Modulator* as the image builds over time

3.2 Hybrid

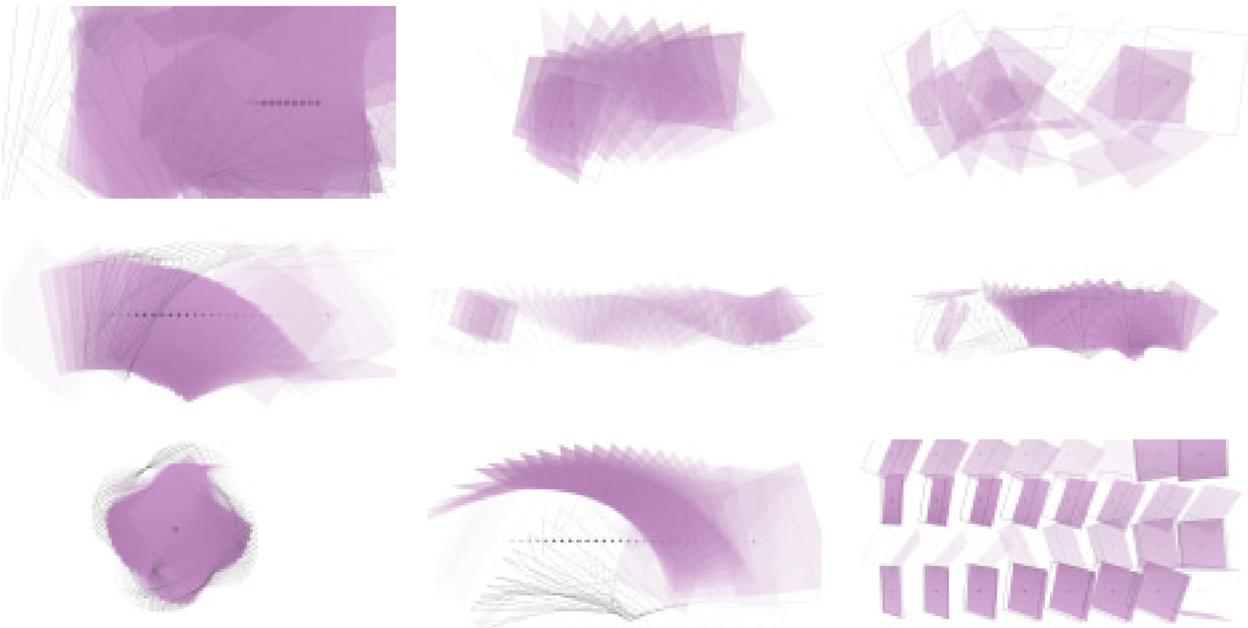
Every interaction with computational systems involves a physical component. Common physical devices for input such as the mouse and keyboard were once strange and awkward devices but are now so common they are almost transparent. Output devices are also by necessity physical. A monitor, for example, must convert digital color information into analog waves of light. In the context of this thesis, the word hybrid does not refer to these types of physical/digital integrations. Hybrid is used here to refer to projects in which a screen-based interaction has a unique physical interface that has been specially built to integrate with the function of the image.

3.2.1 Plane Modulator

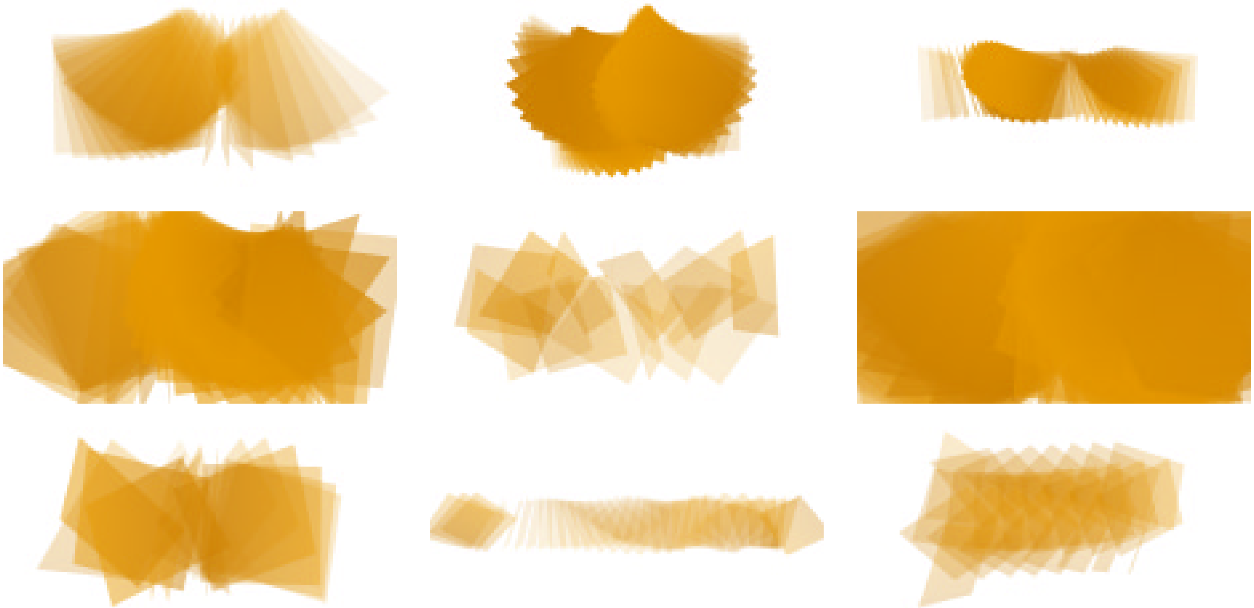
Plane Modulator is a dynamic system for analyzing and experiencing the relationships between time and space. Manipulating the location, phase, and transparency of multiple instances of the same moving object creates new kinematic forms. *Plane Modulator* is inspired by past technological developments used to augment vision. After the development of the camera in the mid 19th century, men such as Eadweard Muybridge and Etienne-Jules Marey began using its potential to stop time and analyze details of movement that had never before been visible to the human eye. In the 1930s, Harold Edgerton pioneered the process of stroboscopic photography which enabled capturing the successive movements of an object with a still camera. Utilizing this technique, the photographs of Herbert Matter (fig. 44) and L. Moholy-Nagy began to reveal a new vision, a sight unbound from time. The medium of computation has provided a medium for further extending our vision. Some of the experiments of John Maeda reveal this in an eloquent way. In his experimental *Parametervision*, every possible image constructed by a two dimensional parametric system can be viewed in a single image plane. *Plane Modulator* combines both innovations



89 A–I
Plane Modulator. 9 images created with 32 green primitives. The green primitive is two parallel green and a brown planes that are rotating around a common central Y axis



90 *a–i*
Plane Modulator. 9 images created with 32 purple primitives. The purple primitive is two parallel planes, one purple and the other a gray outline

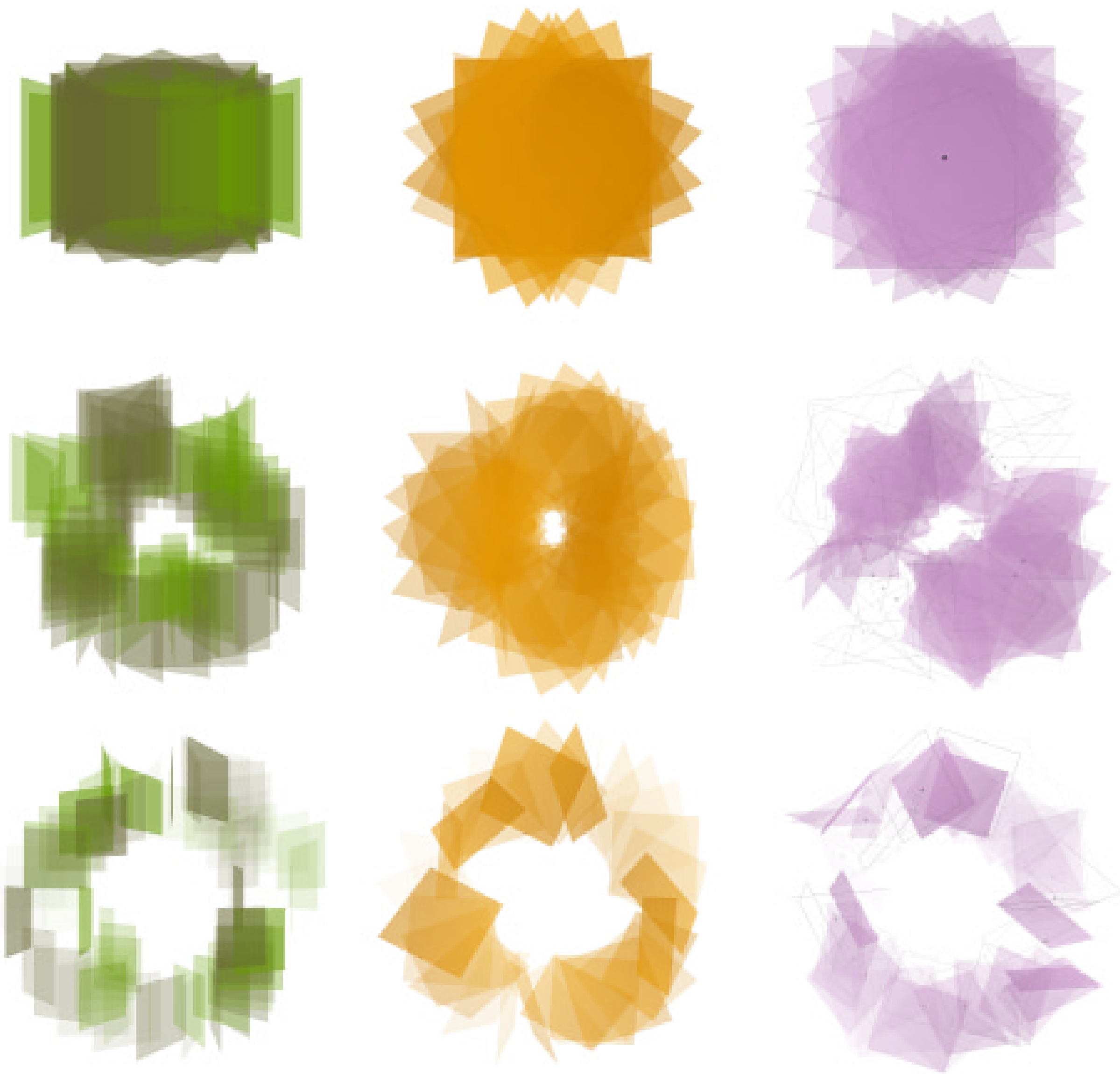


91 A–I
Plane Modulator. 9 images created with 32 yellow primitives. The yellow primitive is one yellow plane rotating around its X and Y axis

into a system for constructing a new vision. It augments the early experiments in time and motion by providing the tools for analysis made possible through computation.

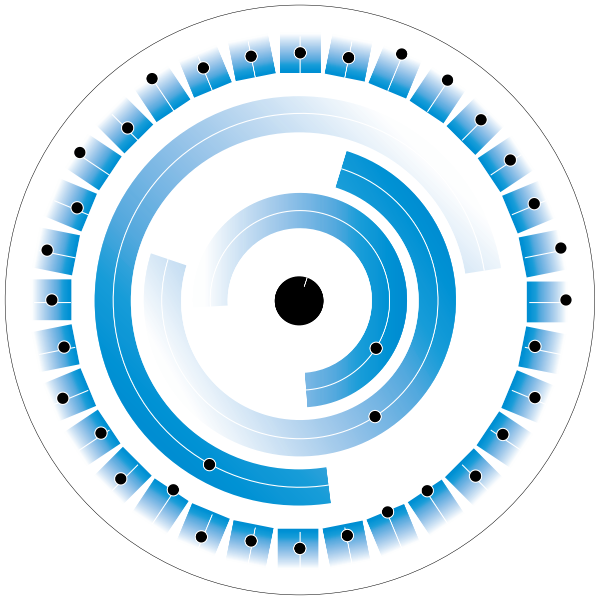
The *Plane Modulator* begins by rotating a simple plane about an arbitrary axis to produce a dynamic quadrilateral (fig. 88 A–F). The addition of a second instance of the plane at a different rotation begins to construct the movement of the object through space. Through adding more instances, the virtual volume of the rotation reveals itself, but the shapes of the individual planes become obscured. Increasing the horizontal and vertical spacing between the planes clarifies their individual movements.

In the screen interface for *Plane Modulator* (fig. 87), clicking the mouse in the black, bottom portion of the screen creates a new shape. Clicking and dragging the lines left and right changes the phase of these shapes. The length of each line corresponds to the degree of transparency—the longer the line the more transparent the shape. The upper right section of the screen contains controls for changing the display parameters. The first of the three boxes controls the speed of the shape, the middle controls its size, and the third controls its horizontal and vertical position. The buttons located in the upper left corner of the screen allow for a new graphic primitive to be selected. Clicking on the graphic "X" in the upper left clears the screen.



92 A–I

The *Radial Plane Modulator* uses the same geometric primitives as the *Plane Modulator*, but transforms the Cartesian coordinates of the objects to radial coordinates



93 Design for the *Radial Plane Modulator* physical interface. Interaction is through moving tokens around on the surface of the table

3.2.2.1 *Radial Plane Modulator*

One of the most important aspects of the *Plane Modulator* is its cyclical movement, but this is not revealed in its original Cartesian organization. Every element on the screen repeats its pattern of motion in the same cycle, but each one also has a unique offset (phase) so that they are cycling at different times. The *Radial Plane Modulator* (fig. 92) was built to demonstrate this property. By changing the core geometry from Cartesian to radial, there is no beginning and end to the pattern of elements. This modification also had the effect of making the images created by the program more similar to objects rather than landscapes. As an additional improvement for the *Radial Plane Modulator*, a physical interface was developed to allow the image to be easily modified by more than one person at a time, to give people who may not be familiar with computer interfaces and input devices an opportunity to easily modify the image, and to bring a level of physical enjoyment into a project that was previously entirely visual.

3.2.2.2 *Video Modulator: Memory Image*

As a further experiment with the *Plane Modulator* software, a live video signal was input into the system. This was inspired by Canadian animator Normal McLaren's beautiful 1968 film *Pas de Deux*, a multiple image of ballet dancers in motion created by artfully exposing multiple frames of film into one. The hopeful goal of adding video was to create a real-time video editing space that was not limited to displaying one frame at a time. The video input software architecture used in the *Introspection Machine* project (Section 3.2.2) was used to convert the video signal from a CMOS board camera into a 40 x 60 pixel

RGB image internally represented as a one dimensional array of numbers. The video modulator overlays five consecutive images of video and an interface provides control over the transparency of each layer of the composite. Using this functionality, it is possible to place the emphasis of the image on its recent past. Figures 94 A–J show the images of the *Reactive Boxes* experiment (section 3.3.1) created by the video modulator.

94 A–J
Still images from the *Video Modulator*

3.2.2 Introspection machine

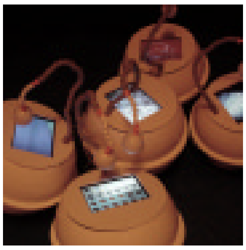
The *Introspection Machine* is an interactive visual feedback environment. The machine consists of multiple modules, each with a screen display and a flexible, manipulable eye. Each module transforms the video image from its eye into a dynamic display. By redirecting these eyestalks, users can explore an unbounded space of continuous light, complex forms, and surprising relationships. The reconfigurable eyes comprise the principal interface by which participants interact with the installation. Light is transferred from computer to computer, making it possible for the video output from one reactive display to be used as the input for another. An *Introspection Machine* module may also be turned to face itself, creating a tight loop of visual recursion. As visual material from each display is reinterpreted by the others, visual patterns shift and mutate based on the connections, configuration, and movement of the eyes. As a complex feedback system, the *Introspection Machine* has analogies to a visual network. The *Introspection Machine* was created by the Aesthetics and Computation Group at the MIT Media Laboratory.

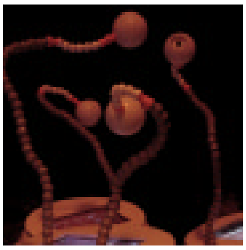
3.2.3.1 Physical design

The *Introspection Machine* consists of five physically similar modules, each consisting of a monitor, a CMOS board camera, and computer. Each camera is mounted at the end of a flexible pipe which runs the video signal into a video capture card installed in a computer. The flexibility of the pipes allow the cameras to be moved and pointed in different directions which allows for the input into the system to be highly variable. The software running on each machine uses the continuously refreshing video information to update the visual form which is displayed on the monitor. Each monitor is embedded within two twenty-four inch plastic hemispheres and the computers are housed under a nearby bench. The monitors are supported in the spheres with a 0.5" Plexiglas support brace.

3.2.3.2 Software

Multiple software modules, each utilizing the video information in a different way, were written for the *Introspection Machine* hardware platform by the different members of the Aesthetics and Computation Group (figs. 98 A–E). In *Flurry*, written by Golan Levin, particles move towards areas of high or low

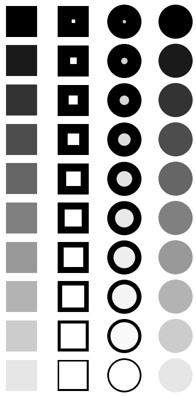




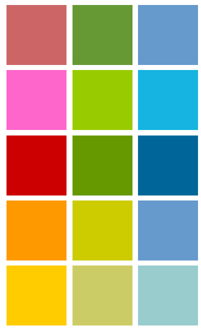
95 A–D
The *Introspection Machine* as installed at SIGGRAPH 2000

change in the video image. When directed to look at itself, *Flurry's* moving particles themselves become the agents of change. Tom White's *Springfield* is a dynamic vector field drawn using the color information in the video signal. The underlying image is constantly redrawing itself, slowly replacing old information with the continually updated motion data. In *Disgrand*, by Ben Fry, the video image is deconstructed, sorted, and then redisplayed according to the numeric color values of each pixel in the original image. The *Booba* application, by Elise Co, is a matrix of abstract flower modules expressing a range of motion from inert to manic depending on the averaged localized signal corresponding to each module. In Jared Schiffman's *Tri-way* software, hundreds of circular nodes travel in one of three directions based on the amount of red, green, and blue components in the background color video.

The Console software that I developed for the *Introspection Machine* is based on the concept of dynamic apertures (fig. 96). There are three types of apertures used in the project: size, transparency, and openings. The size apertures display changing data by growing and shrinking, the transparency apertures fade in and out, and the opening aperture increases and decreases the width of its border. Each of these elements changes its transparency in relation to the value of the data extracted from video input signal. For example, a size aperture will shrink to a dot when the video element associated with it is white and it will grow to fill its cell when its element is black. The color of each element is determined through a relational mapping to the original RGB color signal. A color table was built to provide a set of key points for the elements to cycle through (fig. 97). For example, if the video cell associated with each element has a higher red value than green or blue value, it will choose its color from the red column. Each element is assigned to one column of the chart.



96 The aperture system of the Console software for the *Introspection Machine*



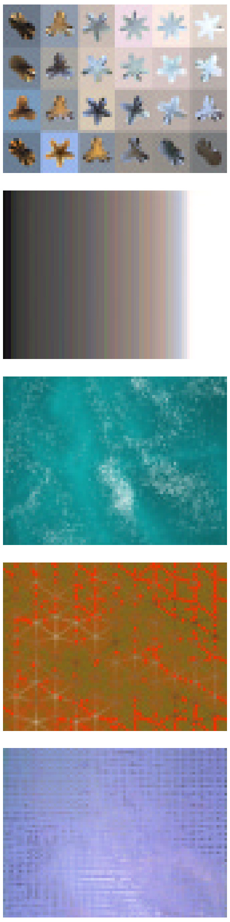
97 Color table used for transitions in the *Introspection Machine*

3.3 Physical

When I began building physical interactive objects in the summer of 2000, I saw my task in gaining competence to include four primary areas: physical construction and mechanical design, actuator technology and interfacing, knowledge of how to sense the world, and understanding software mappings between the sensors and the actuators. I began the process of learning by creating three simple studies and then began working on *Trundle*, a more complex behavioral kinetic sculpture.

3.3.1 Reactive Boxes

The *Reactive Boxes* were built to explore various ways of interacting with sculptural systems and to test different types of sensors and motors. The first study is physically reactive — its motion is triggered by touching one of two sensors mounted on its surface. The second study has a remote interaction via a



98 A–E
Multiple software modules were written for the *Introspection Machine*

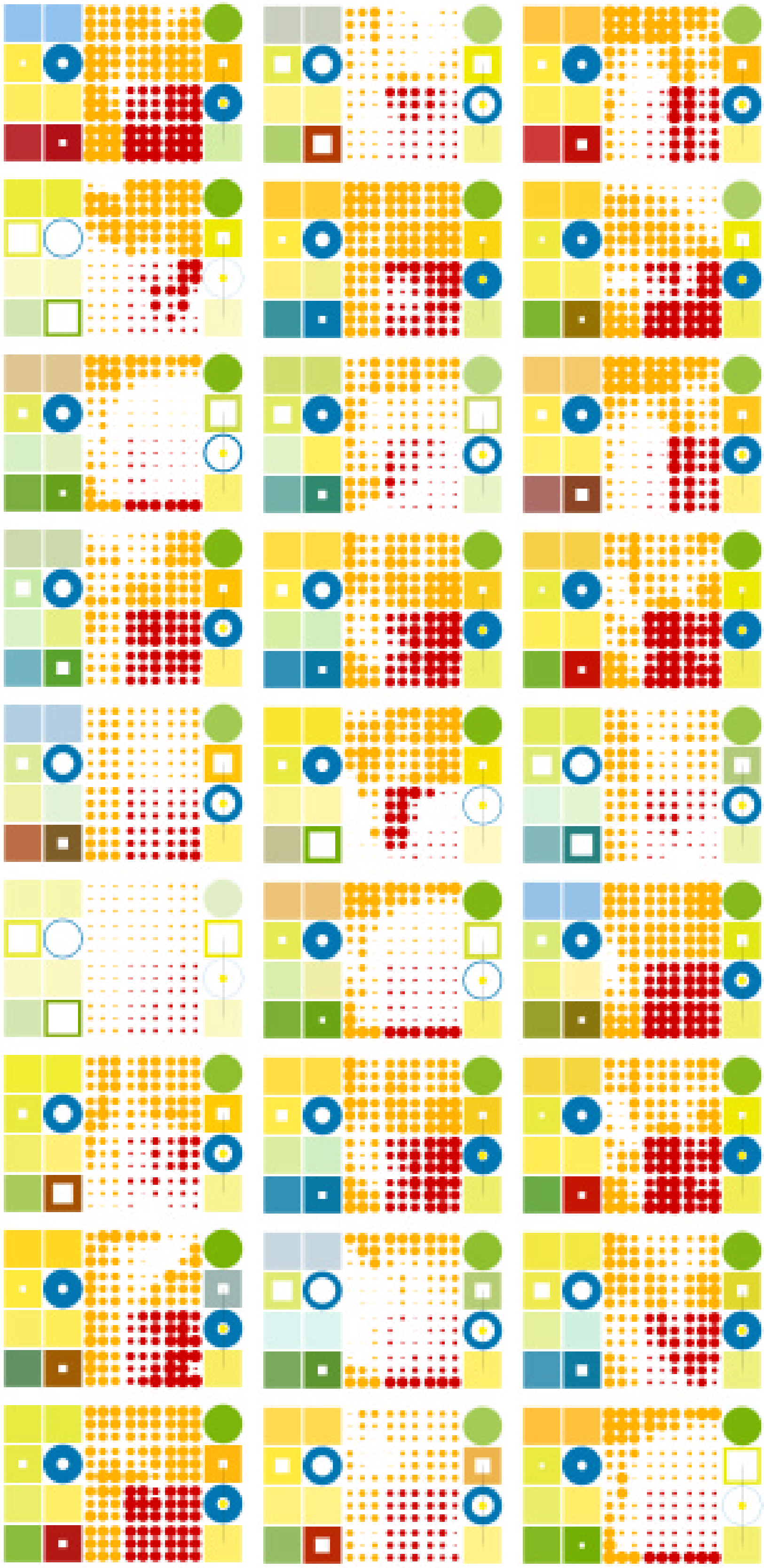
A *Booba*, Elise Co

B *Disgrand*, Ben Fry

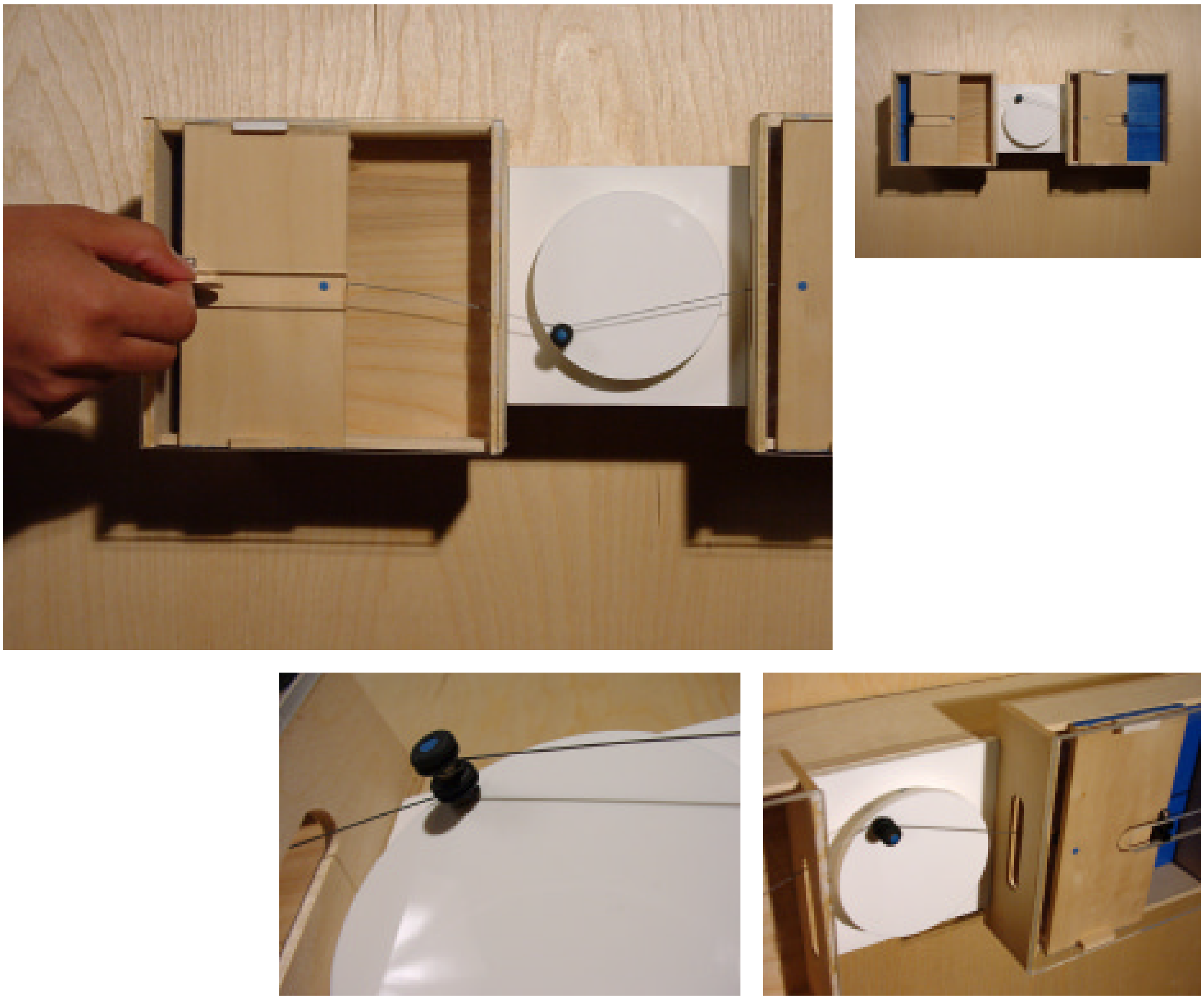
C *Flurry*, Golan Levin

D *Tri-way*, Jared Schiffman

E *Springfield*, Tom White



99 A–AA
Individual images from the Console software written for *Introspection Machine*

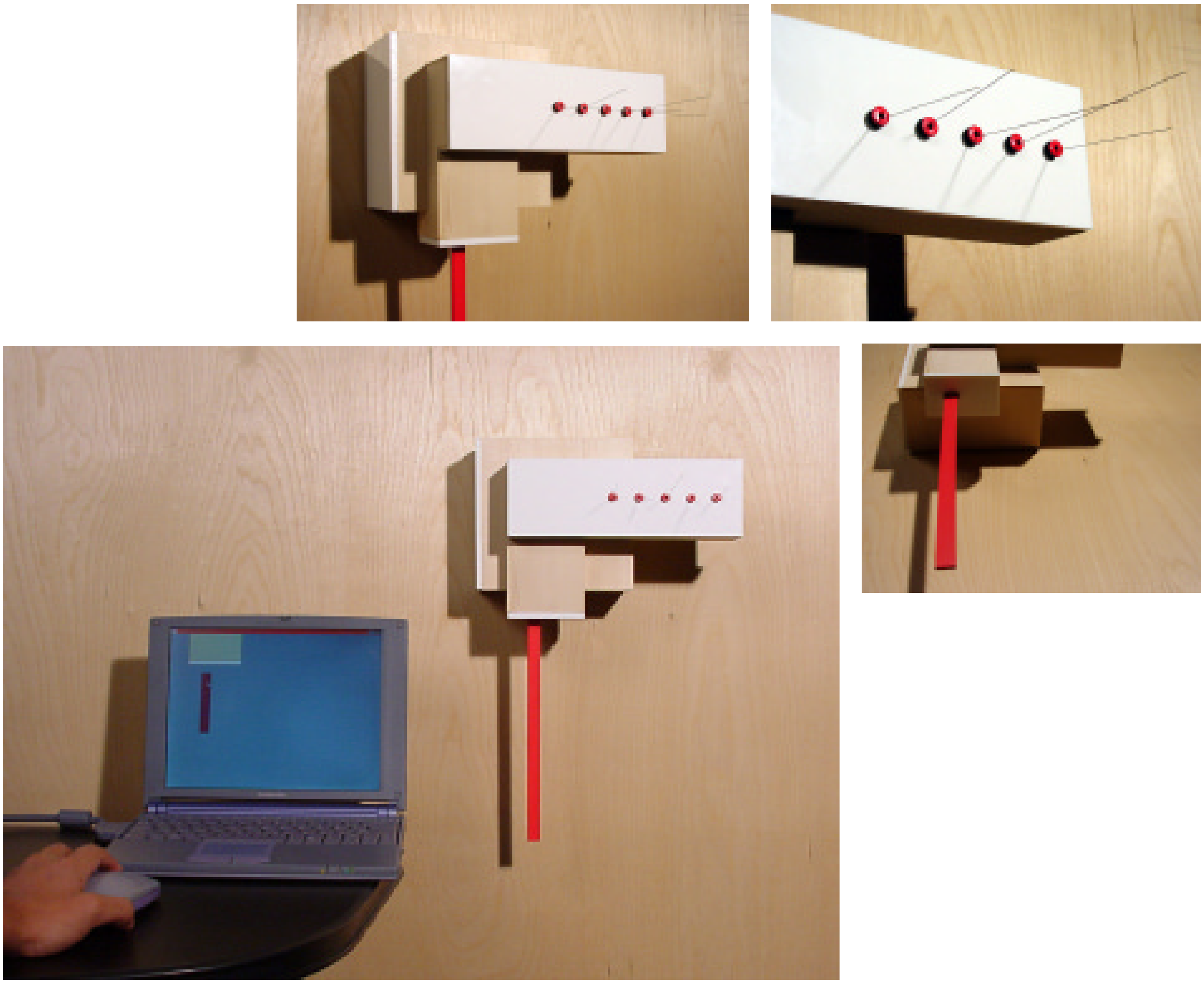


100 A–D
Physical Box.
By triggering the sensor with a small solid object (such as a coin) the motor is activated

screen-based interface. Sending a stimulus from the interface triggers a solenoid and the temporal difference between stimuli is calculated to modulate the speed of a DC motor which turns a series of wires. The third study reacts to ambient stimuli in the environment by using the sound and light levels in the room to generate motion.

3.3.1.1 Physical Box

Shown in figures 100 A–D, the *Physical Box* is made of three sections, a white plastic circle in the center and two wood squares on either side. Two thin plates on each of the wood sections are connected to a pivot point in the center circle with a thin steel wire. The circle is directly attached to a DC motor. Interacting with the *Physical Box* involves triggering one of two Toshiba TLP507A sensors mounted to the surface of the object. As these sensors change their output from 0 volts to 5 volts when their IR beam is interrupted by an object

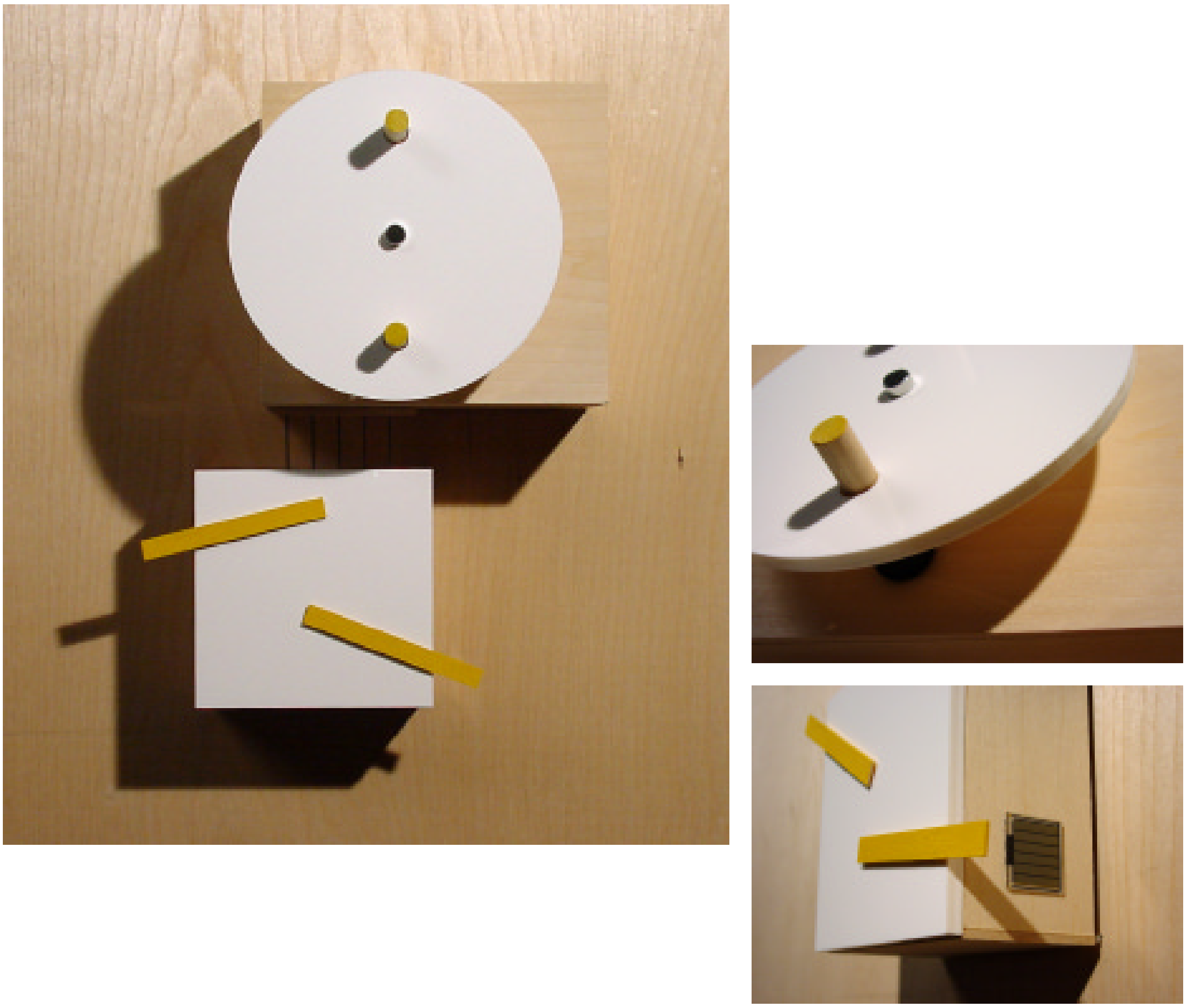


101 A–D
Remote Box.
The interior of the box houses two motors and a small circuit board which receives and processes input and drives the motors

such as a coin, they provide current to the motor. Triggering the right sensor causes the motor to turn clockwise while triggering the left sensor causes the motor to turn counterclockwise. Triggering both sensors at the same time causes the motion to stop. As the motor turns the center wheel, the panels with the sensors attached also move. Therefore to keep the box in motion, the movement of the person's hand must be in synch with the rhythm of the motor. The electronics used for this box are entirely analog and in addition to the sensors, a Toshiba TA729AP is used to drive the motor.

3.3.1.2 Remote Box

The *Remote Box* (figs. 101 A–D) is made from two interlocking plastic and wood boxes, a solenoid motor, a DC motor, and an array of five thin wire whiskers. The movement of the *Remote Box* is controlled by a microcontroller and the interaction is through a networked java application. A person can



send a stimulus to the box by manipulating an abstract digital interface on a computer screen which sends a signal to the box through a serial connection. This stimulus triggers the solenoid motor inside the box which causes it to contract the red pole partially back into the box, creating a sharp noise. The time difference between signals determines the speed and rhythm of the DC motor which turns the wires on the face of the box. For example, triggering the solenoid frequently will cause the box to move its wire whiskers very slowly. Triggering the solenoid quickly twice in a row is interpreted by the box as a positive gesture, and it modulates the wires into a short dance. The electronics built for the *Remote Box* include digital components. The logic for the *Remote Box* was programmed on a PIC16F84 microcontroller and a MAX233 chip is used as the PIC's interface to the attached PC's serial line. Once again, a Toshiba TA729AP is used to drive the motors and protect them from strong bursts of current.

102 A–C
Ambient Box.
There are two independent sections, the top responds to sound and the bottom responds to light

3.3.1.3 *Ambient Box*

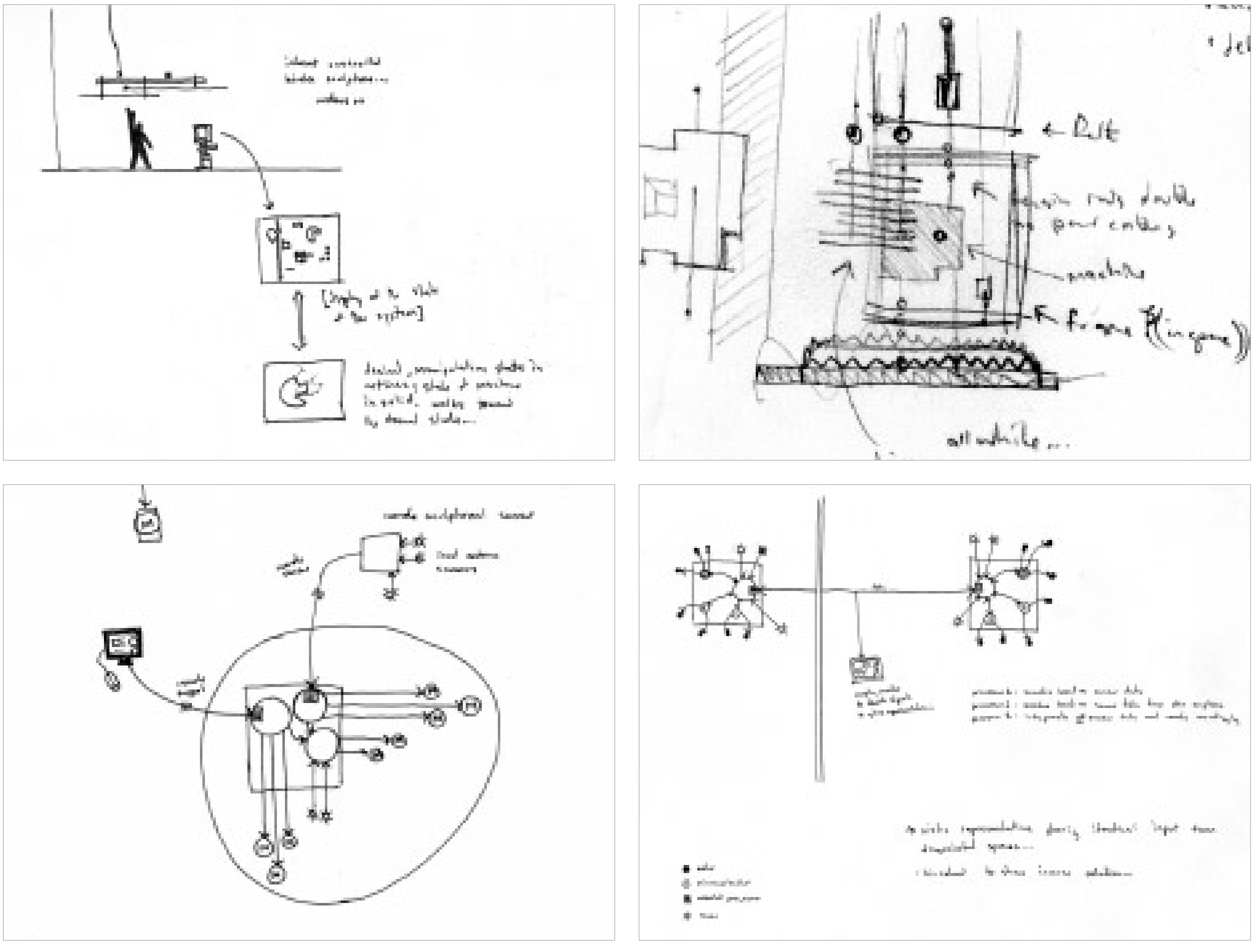
Shown in figures 102 A–C, the *Ambient Box* is composed of a top piece which responds to sound and a bottom piece which responds to light. A microphone attached to the front of the circular panel constantly monitors the sound level in the room and moves a motor attached to this panel quickly if there is a significant change in the sound level and slowly if the change is slight. The signal from the microphone must pass through three stages before it is usable as the stimulus for the motor. First the weak signal from the microphone is amplified through an LM386 so that it has a dynamic range of between 0 and 5 volts. This signal is then input into one pin of an ADC08331 chip. As this analog to digital converter is triggered by the microcontroller, the original analog signal is converted to a string of numbers ranging from 0 to 255. These 8-bit values are then cleaned and refined through a software implementation of a low-pass filter. The original microphone signal is now ready to be used as input for the top motor. The bottom part of this box operates in a simplified manner. The yellow rectangles on the bottom box are each attached to tiny motors which cause them to turn. These small motors are attached to a small group of electronics knows as a solar motor. This configuration is made from a solar panel, two transistors, a diode, and a small resistor, and works by storing energy from the solar cell in the capacitor and then releasing it when there is enough to move the motor. The result is long pauses of no movement and then a sudden burst of motion as one of the rectangles spins and then quickly returns to a dormant position.

3.3.2 *Trundle*, a behavioral kinetic sculpture

After the completion of the *Reactive Boxes*, *Trundle* was developed as a platform for experimenting with more sophisticated sensing capabilities and more interesting mappings between the sculpture's environment and its movement. *Trundle* began as a series of system sketches (figs. 103 A–D). How could a distributed sculpture be built that would communicate with itself over a network? What type of sensors would it have? How would it move? What would the interaction model be? Over time, these questions were answered through a series of drawings, models, and iterative changes to the sculpture.

3.3.2.1 *Structure*

The primary structural framework of *Trundle* is made from 3/16" aluminum panels and 1/8" stainless steel rods. Steel counterweights are used for balancing the asymmetric joints. Connections are made with shaft collars (fig. 112 A). Each of the three sections are attached by a single 0.25" steel rod, thus making the structure prone to oscillation and vibration. When the sections are not connected with gears, the sculpture is a smooth, continuously moving mobile. Extremely fluid Abec-5 bearings and the high mass of the counterweights give the sculpture a high inertia which keeps it in motion for a long duration. As



103 A–D
Initial sketches for *Trundle*

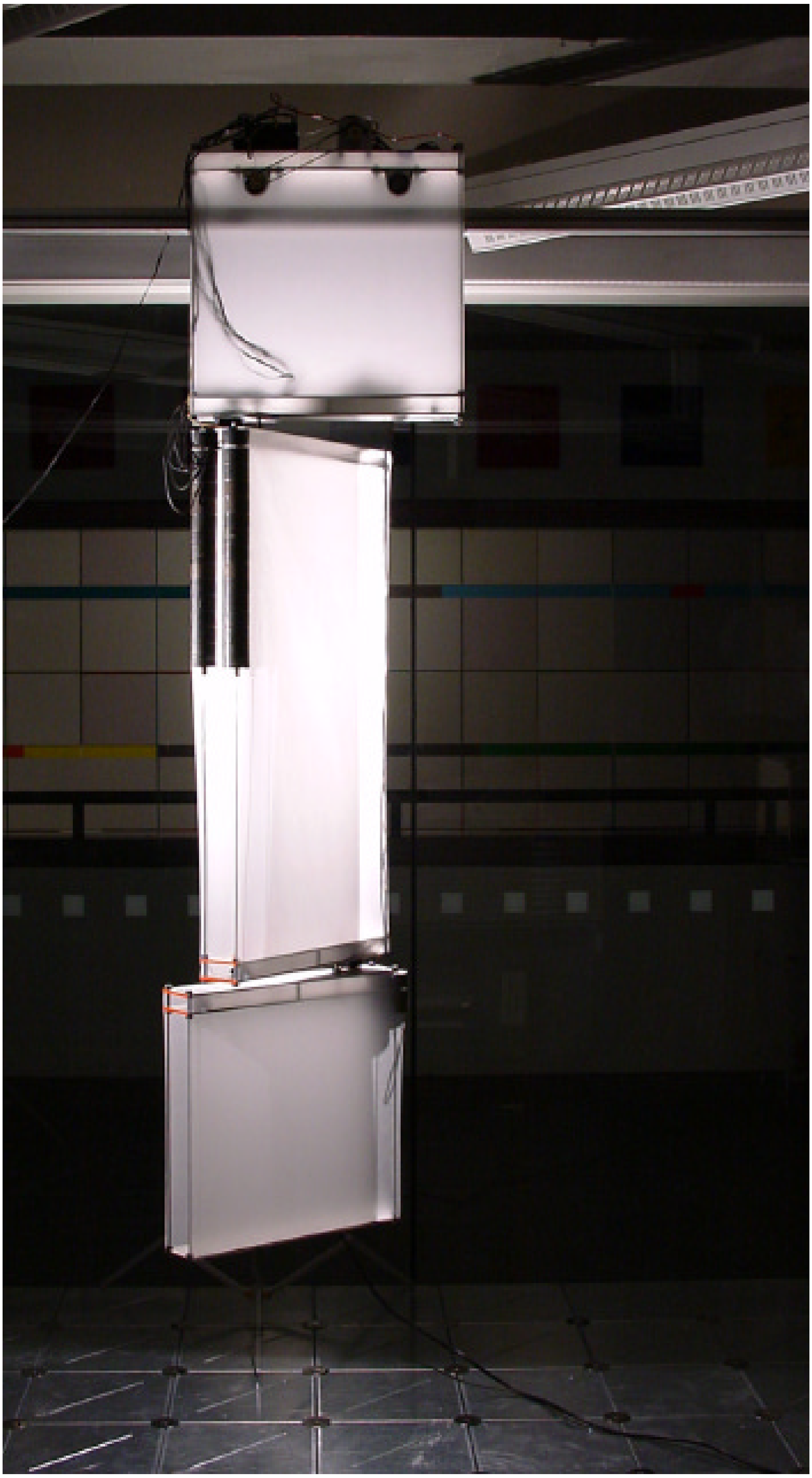
a direct result, a large force is required to stop it from turning.

3.3.2.2 Actuators

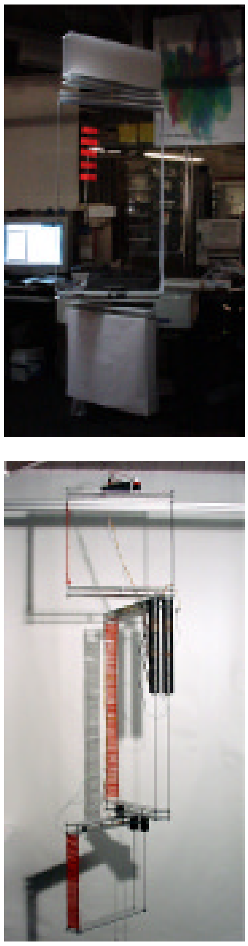
Trundle has three degrees of freedom. Its two cascading servo motors each have a range of movement from 0° to 180° giving it a wide range of motion. A standard DC motor mounted on the top facilitates lateral movement. These motors in combination with the physical constraints of the body define *Trundle's* movement.

TRUNDLE'S SERVO MOVEMENT
- Range of movement from 0–180°
- Position set in software
- Ease in and out of high speed to reduce overshooting
- Due to tremendous inertia, servos must move in moderated intervals

TRUNDLE'S DC MOTOR MOVEMENT
- 360° rotation in both directions
- Variable speed set through pulse-width modulator (PWM)



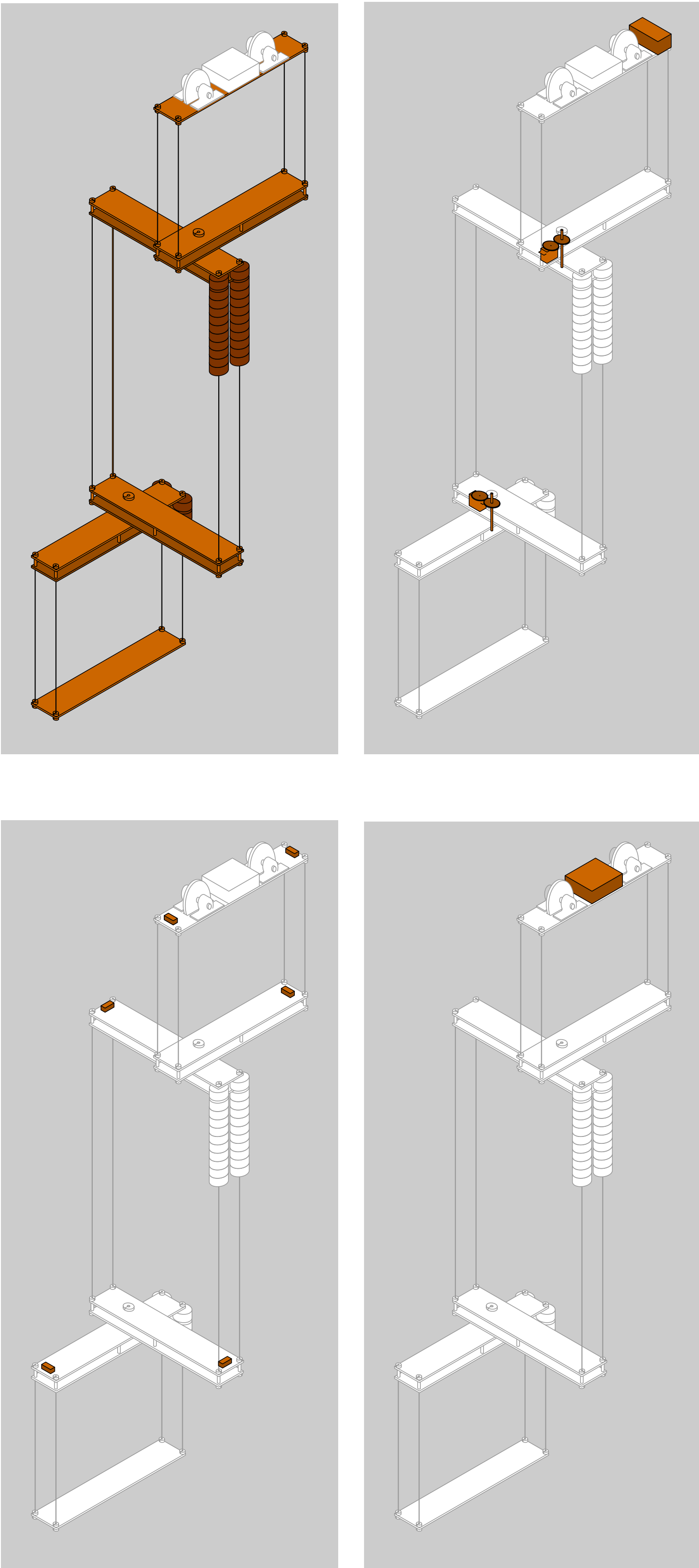
104 *Trundle* version 1.2. The structure is 6' tall and hovers 18" above the floor for a total height of 8.5'



105 A, B
Early evolution of *Trundle*

A Foamcore model

B Version 1.1



106 A–D
Schematics of *Trundle* version 1.2

A Structure

B Actuators

C Sensors

D Controller board

107 A–F
Details of *Trundle's* structure

A Thin wires carry the control signals

B The three sections are attached by steel rods

C Steel counterweights create balance

D Sensors are set within the structure

E Each piece rotates independently

F A thin translucent skin reveals the internal structure

• Ease in and out of speeds to avoid abrupt vibration

• Minimal speed change possible due to weight of sculpture

3.3.2.3 *Sensors*

Trundle senses the world through an array of sensors which allows it to receive information from its environment. In the spirit of experimentation, many different sensors have been tested during *Trundle's* evolution. The current version of *Trundle* uses six Sharp GP2D12 Infrared Rangers (IR) to sense the world:

SHARP GP2D12 INFRARED RANGER
• Continuous distance readings
• Reports the distance as an analog voltage
• Approximately 4"– 30" detection

This sensor works by sending a pulse of IR light through its emitter. If the light hits an object it is reflected back, creating a triangle between the send, receive, and reflection point. The emitter for this sensor is a precision lens that reflects light onto a small linear CCD array. The way the light falls on the CCD array makes it possible to calculate the distance from the object. Advantages to the Sharp GP2D12 are an immunity to ambient light interference, indifference to color, and low power consumption.

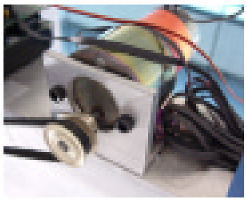
Trundle version 1.1 used a more diverse range of sensors. The first of these sensors explored was the Eltec 442-3 Pyroelectric Detector:

ELTEC 442-3 PYROELECTRIC DETECTOR
• High gain detector with integral analog signal processing
• Attached Fresnel lens makes detecting left and right movement possible

This pyroelectric sensor was used to capitalize on its unique ability to sense human movement. Unlike the IR distance sensors, the pyroelectric detector will not detect a stationary body. Allowing the sculpture to respond to movement creates an interaction scenario closer to dance than the simple avoidance and attraction possible with other sensors. There are two major drawbacks to this sensor. The major difficulty is the amount of noise in the output signal. First order filters were appropriate for all other sensors in the sculpture, but this pyroelectric sensor needs more conditioning. The other drawback is its lack of robustness for handling and soldering as the sensor is an extremely sensitive and easy to damage package.

The Daventech Ultrasonic Ranger sensors were purchased as a replacement for the Sharp IR sensors that were installed in *Trundle* version 1.0 to give the sculpture a longer range of sight.

DEVANTECH SRF04 ULTRASONIC RANGER
• Measures a range from 3cm to 3m



108 A, B
Trundle's motors

A DC motor

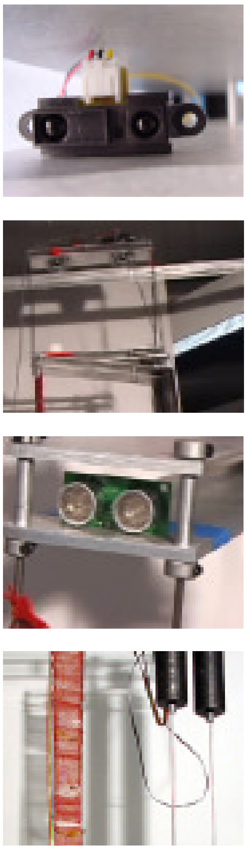
B Hi-Tech servo

• Cone of vision approximately 30°

These sensors are very impressive in their range and beam width, but in the space the sculpture was in, the sensors' active region had to be reduced because the sculpture was noticing too many nearby objects. A PIC12C508 is the core of this sensor, performing the control functions and stimulating the sending transducer. This sonar uses standard 40kHz transducers. The PIC waits for an active low signal and then produces eight cycles at 40kHz. At the end of these pulses, the processor begins to count and the echo line is raised. If a signal comes back it will lower the echo line and the width of this pulse corresponds to the distance from the object. To boost the signal going to the transmitting transducer, power is converted from 5 volts to 16 volts through a MAX232 IC. The receiver is a two stage op-amp circuit, each giving the signal a gain of 24 through an LM1458. The result of this amplification is input into an LM311 comparator which in turn is input into pin 5 of the PIC. One issue with this sensor is the lack of accurate values at distances of less than one inch. This is due to a direct coupling with the nearby transmitter and the transmitter's quality of continuing to resonate after the pulse has ended.

To give *Trundle* a surface skin that is sensitive to touch, experiments were made toward giving it a custom electric field sensor:

CUSTOM ELECTRIC FIELD SENSOR
• Large knit fabric integrated with conductive thread acts as an electrode
• Op-amp based analog circuitry converts touch into changing voltage



109 A–D
Trundle's sensors over the course of its development

A IR distance

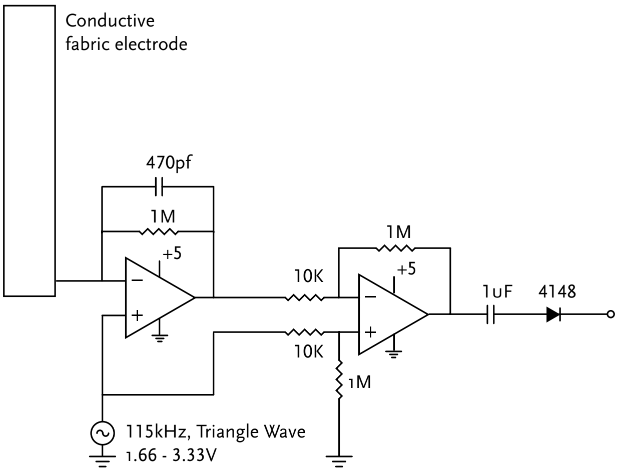
B Pyroelectric

C Sonar

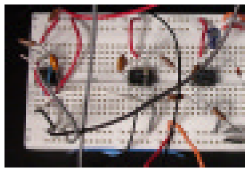
D Electric field

The areas for the skin are shown in figure 105 B. Each of the fabric areas is a custom designed knit piece with conductive threads integrated with traditional non-conductive wool yarn. Because of the desired interaction and the physical form of the sculpture, loading mode capacitive sensing was chosen as the technique. Out of interest in learning more about analog electronics, an entirely analog method for creating the sensor was chosen (fig. 110). The circuit is shown in figure 110. The design of this circuit is straightforward. As the conductive fabric is loaded by the proximity of a person the first op-amp increases its output to compensate in an attempt to make both the inverting and non-inverting terminals equivalent values. The second op-amp is configured as a difference amplifier. Accuracy is of extreme importance at this point in the circuit and was improved by using 1% resistors. Because there is so much gain, extremely small differences in the signal are magnified. As a result, the signal coming out of the difference amplifier must be further conditioned to be usable. The signal was conditioned with a capacitor and diode in series, but this gave the sensor a low resolution.

Driving the sensor with different signals was explored. Creating a near perfect sine wave was first considered, but after researching the complexity it

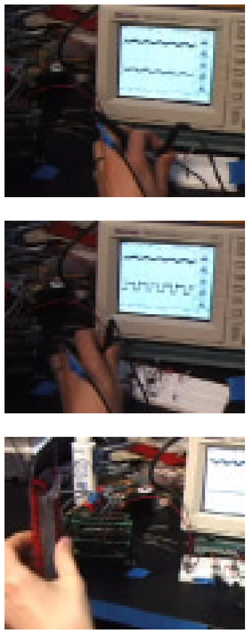


110 Schematic for electric field sensor



111 Breadboarded version of the electric field sensor

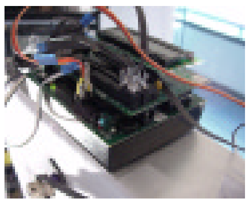
was determined to be unnecessary. A square wave with a 555 timer IC was created with the intent of running it through a low-pass filter to approximate a sine wave. Instead, the triangle wave biased around 2.5v already being created by the IC with the attached resistors was used as the input and the square wave was ignored. Resistor values were chosen to create a frequency of 115kHz, a frequency that was fast enough to enable the sensor without being too fast to outrun the slew rate of the selected 411 op-amps. In the course of building this circuit a MAX233 chip was attached to provide +12 and -12 supplies to drive the op-amps. This improved the resolution of the filter, but the signal was not as easy to interface with the controller board. The sensor was usable in this state, but there were areas for improvement. Accuracy could have been enhanced through more robust construction of the circuit. Building it on vector board would reduce the internal capacitance seen in the prototyped breadboard circuit. The size should have also decreased and the form should have been designed in an elegant way to be attached to the body of the sculpture.



112 A–C Looking at the signals from the electric field sensor

3.3.2.4 Control system

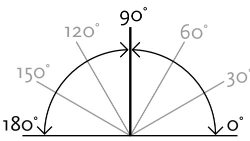
The core of *Trundle's* control system is a 68HC11 microprocessor which is situated in a Handyboard, an MIT designed controller board. *Trundle's* software for processing input and controlling its motors is written in the Interactive C programming language. The Handyboard provides a wonderful environment for creating fast prototypes. It contains 4 motor ports, 6 servo ports, 16 analog inputs, 9 digital inputs, and 9 digital outputs.



113 The Handyboard controller board

3.3.2.5 Form as communication

Humans anthropomorphize inanimate objects. We see creatures in the clouds, faces in knots in a plank of wood, and easily project intention onto simple moving objects such as a paper blowing in the wind. To be successful, *Trundle* must capitalize on this phenomena for it to interact with people. *Trundle* must be able to communicate its state so that people will know how to respond to its movement. *Trundle* is able to communicate through its form (body language) and through the quality of its movement. A mapping of possible forms and movements follows below:



114 Map of servo positions

POSITION OF TOP (T) & BOTTOM (B) SERVO JOINTS (FIG. 114 & FIGS 115)

T=90	B=90	Closed :: restrained, uptight
T=0	B=180	Open :: friendly
T=90	B=60	Bottom skewed :: curious, tentative
T=120	B=30	Inverted positions :: balanced

SPEED & QUALITY OF MOVEMENT

Slow	Sad, subdued
Short, fast	Nervous, anxious
Long, fast	Violent, aggressive
Short, smooth	Cautious
Long, smooth	Bold, confident

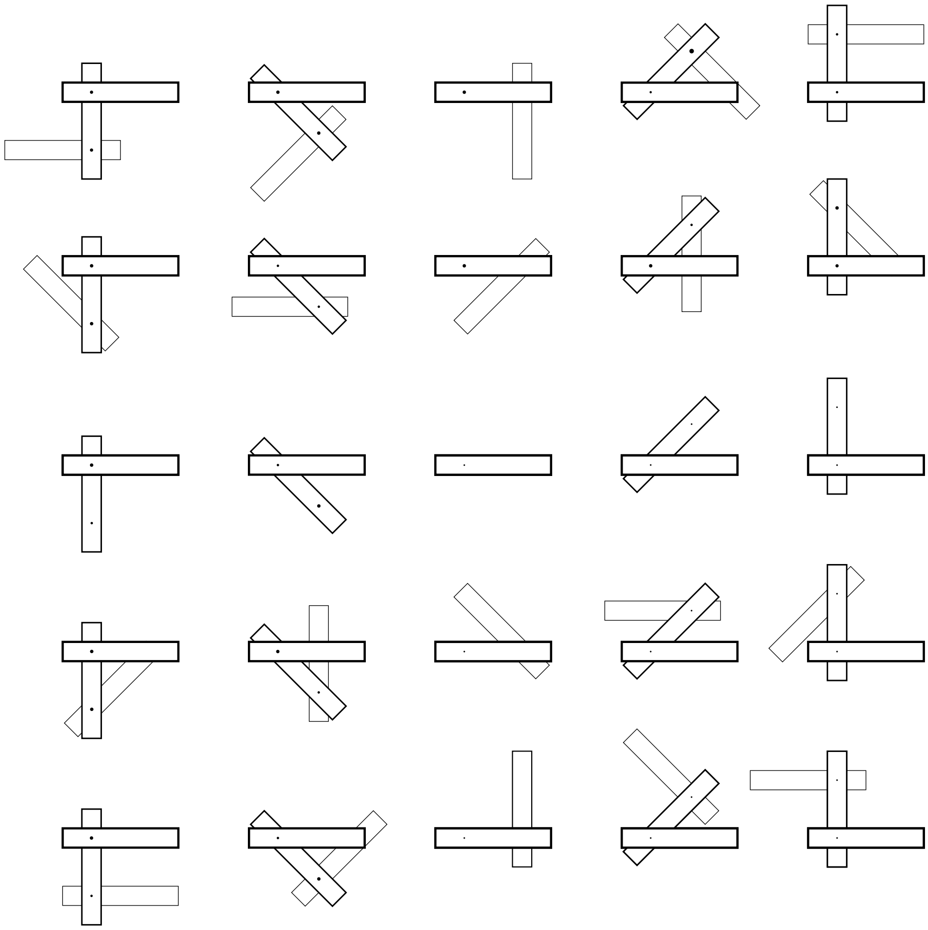
QUANTITY OF MOVEMENT

1 motor	Tentative
2 motors	Curious
3 motors	Excited, happy, urgent

In the final implementation, quick and short movements are used to represent discomfort and long, slow movements are utilized to represent calmness and curiosity. A closed physical form is used to show a lack of engagement and a smooth, constantly opening and closing form is used to convey interest.

3.3.2.6 Behavior

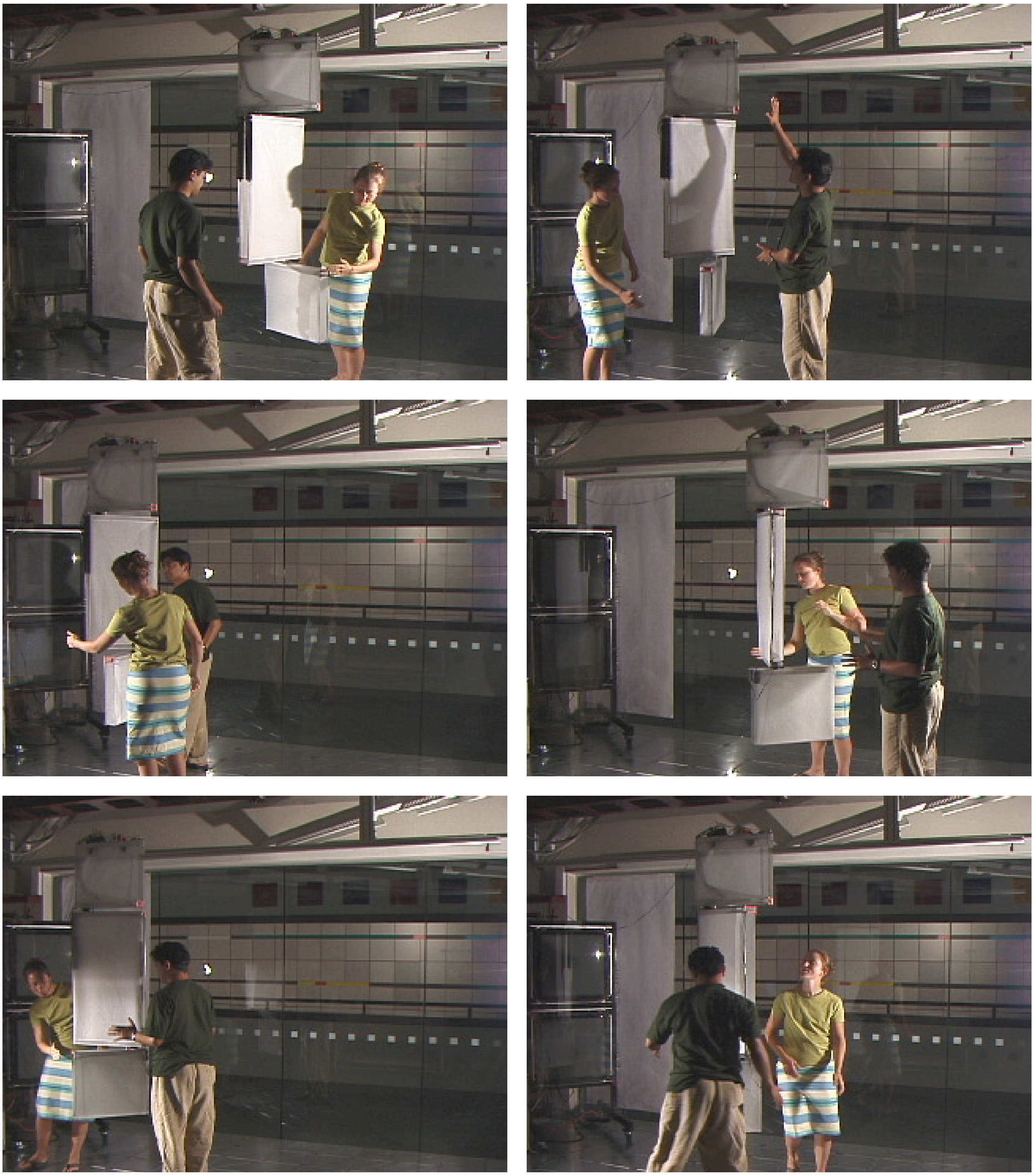
Using social language to describe the movement and interaction with *Trundle*, it can be said that *Trundle* seeks attention, but is shy. It changes its mood over time as a function of the amount of attention it receives. Mood is communicated through posture and quality of movement. When *Trundle* is first activated, its basic behavior is to seek out stimulus. This is achieved through slowly scanning its lower four sensors across the space. When it receives a stimulus through one of its sensors, it quickly jerks away and moves down the track until it finds a spot free of stimuli. In addition to a series of simple reflexes, the activity of *Trundle* is dominated by a number of absolute actions. These are analogous to the fixed action patterns found in many animals. For example, if all four of *Trundle's* lower sensors are activated, it will quickly jerk away and collapse



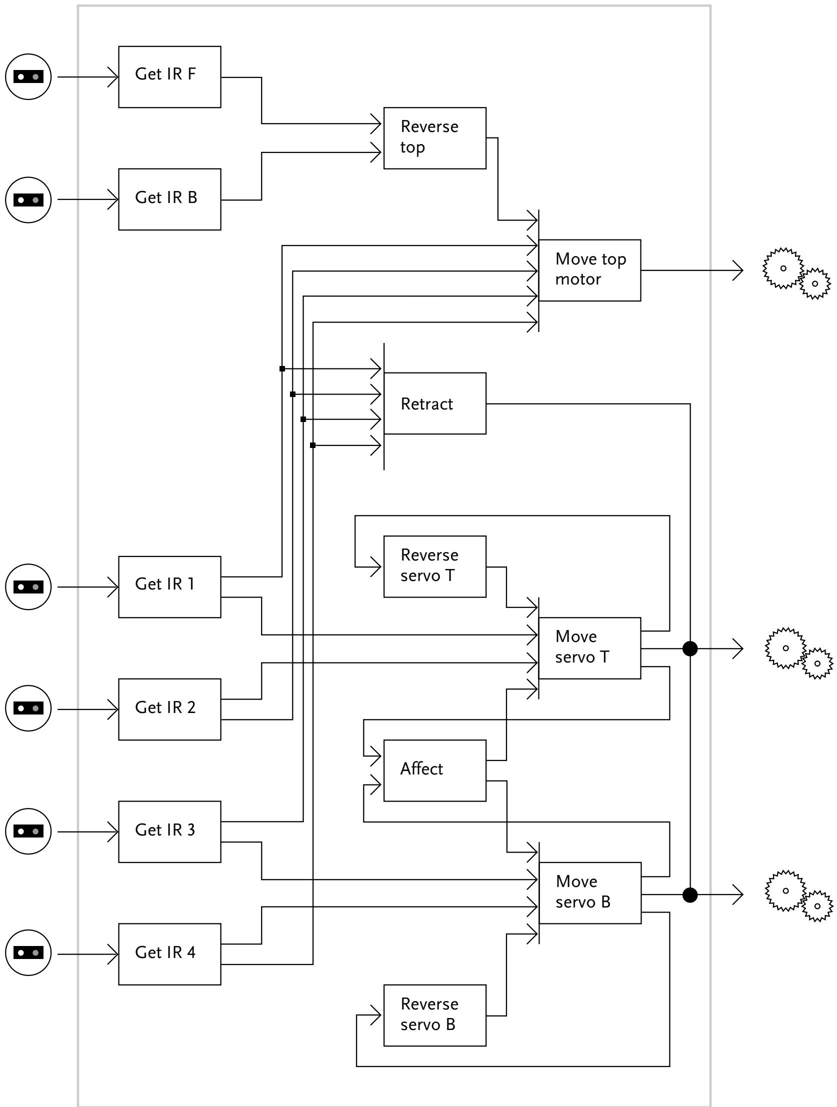
115 A–Y
The space of *Trundle's* possible positions as seen from the top

into its neutral state. It sets all of its excitation variables to neutral and slowly begins to expand the reach of its sensors, starting at the top and moving its way to the bottom of the sculpture. *Trundle* adapts its behavior over time by changing internal state variables which affect how the sculpture senses and moves. For example, if *Trundle* is constantly registering stimulus through its IR sensors, it can begin to look for signals at a closer range. This will either cause people to come closer or allow it to ignore large objects consistently in its proximity. *Trundle* also has a concept of affect. Through continual interaction with the sculpture, it may become excited and change the quality of its movements to become increasingly rapid and short.

Trundle's behavior is implemented in C code as a series of finite state machines (FSM). A map of its behavior architecture is displayed in figure 117. As a result of the organic process of programming the architecture, changes have been made to the original plan. It was found that the system was made more flexible by abstracting the sensor data retrieval and conditioning state machines from their initial couplings. For example, the original Reverse_top FSM had the ability to read the IR data embedded within it. By removing this from the

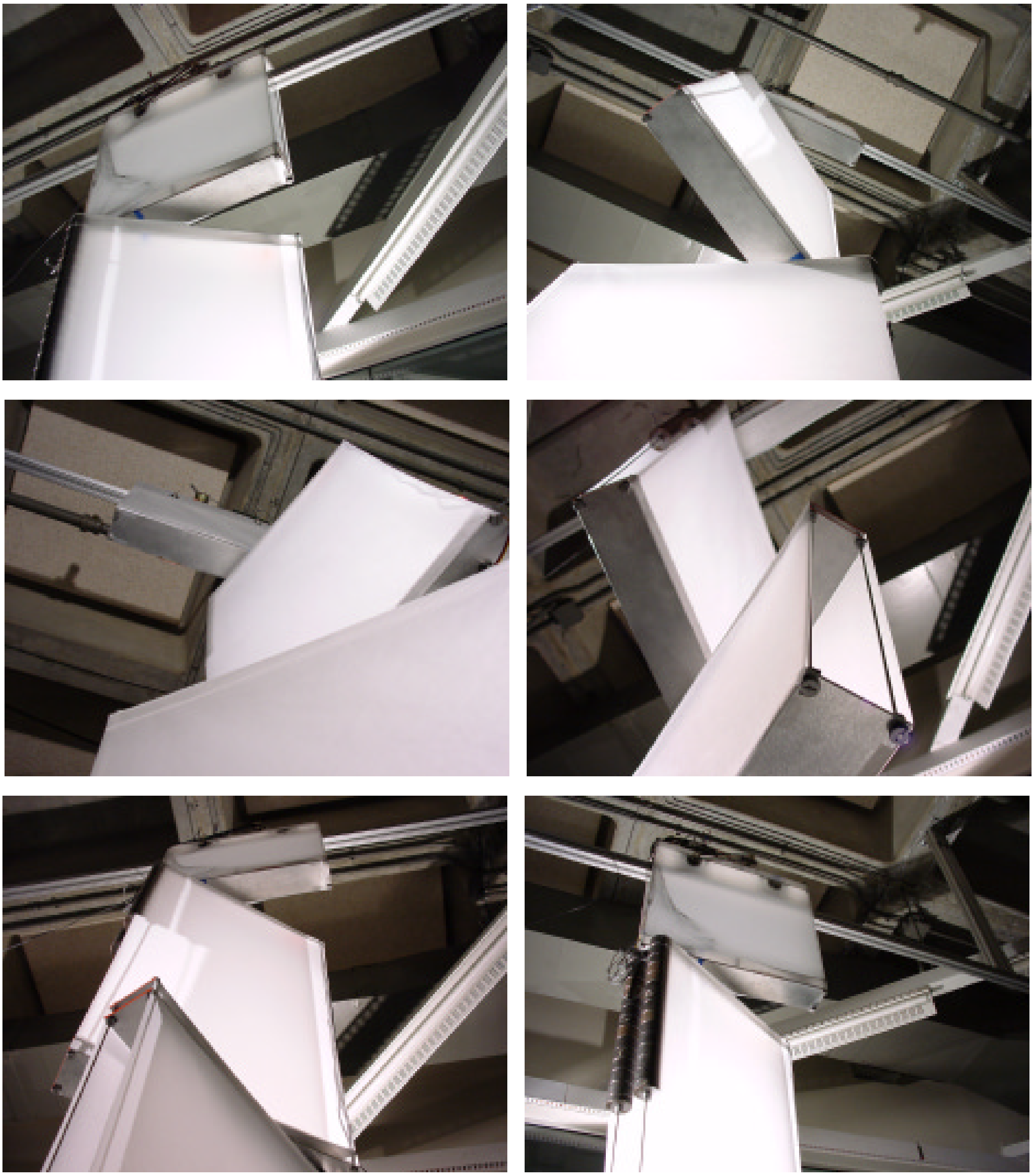


116 a–f. As people move through the environment, *Trundle* responds by changing its direction and orientation.



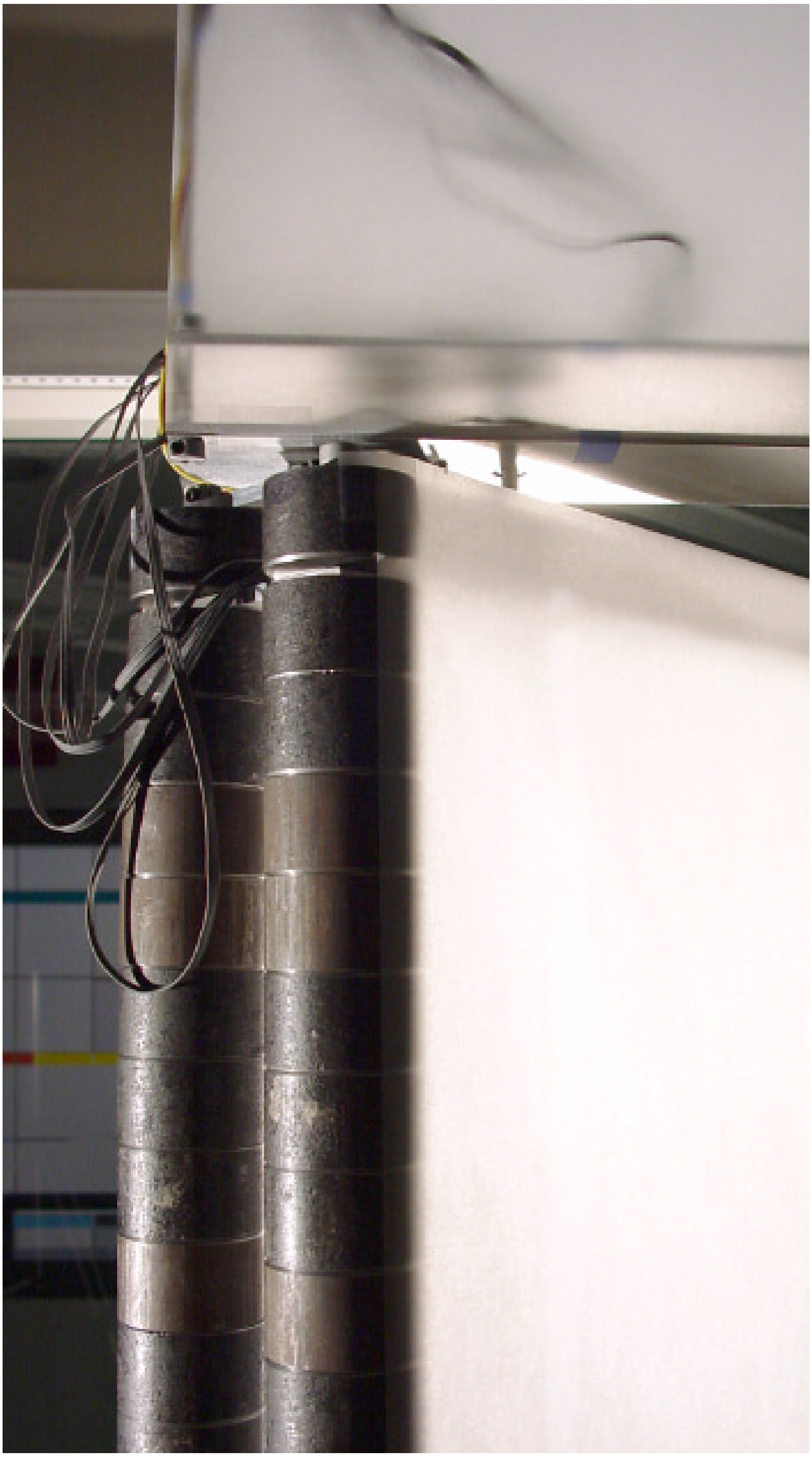
117 *Trundle's* behavior architecture

machine, this data can now be used by other FSMs as the architecture grows. The core FSMs are the Move machines. Each of these starts one of the three motors in motion. Due to the nature of the motors, these functions all differ. The Move_servo_T FSM, for example, includes a number of state variables that move the motor a specific distance represented in an increment variable every hundredth of a second. In contrast, the Move_top_motor FSM simply stimulates its motor with a constant value. Because this motor has no internal feedback (as the servos do) it requires external sensors to be aware of its position in the world. The Reverse_top machine continually monitors the location of the sculpture and when it sees there is no room to move, it reverses the direction. The Get_IR FSMs all share a similar form. All sensor data is conditioned by a simple low pass filter created through weighted averages.



118 A–F
Trundle searching the environment

119 Wires woven through the sculpture attach *Trundle's* sensors and motors to the control system



Discussion and Analysis

There is a canon of accepted methods for discussing and analyzing traditional works of painting and sculpture, but with what metrics is interactive work and behavioral kinetic sculpture evaluated? Within the context of the MIT Media Laboratory, the birthplace of this thesis, it is appropriate to discuss both its technical and humanist merits. In this chapter, the experiments presented in chapter three are discussed as both systemic machines and perceptual phenomena. The experiments are divided into categories and discussed in relation to other established works and to each other. They are also analyzed in regard to the quality of their interaction from a behavioral perspective. Other topics discussed include the concept of the artist as the primary generator of the work and the quickly changing tools used in the creation of these and similar experiments.

4.1 Systems and perception

Imagine sitting on a patch of tall green grass in a meadow overlooking a range of ancient mountains. You might hear leaves brushing against one another in the wind, feel the moisture in the ground, and watch the birds as they search for food. If you sit long enough and pay close attention, you may hear the insects at your feet or the sound of your own heart, but there is information flowing through the meadow that you will not detect. As humans, we experience the world through our bodies, and of the myriad signals that permeate our terrestrial environment, we are able to detect only a narrow range. Of the entire electromagnetic spectrum, for example, we are only able to visually perceive wavelengths from 700 nanometers to 400 nanometers, the area known as visible light which ranges from red to violet. Through the development of specialized machines, we are able to extend our senses and therefore develop a new perception of the world we inhabit. Even within the band of visible light, our eyes have limited range. With the development of microscopes and telescopes we are able to extend this range to distant galaxies and the inner workings of our own cells. In using these machines as an interpreter between the environment and our bodies, we are able to perceive the world in an objective, quantitative way. For example, rather than saying it is cold, we may say that it is precisely 20° Fahrenheit or rather than perceiving the color green, we may say that we are sensing a wavelength of 550 nanometers. Through the development of these machines, we have created an alternative way to experience the world—one that is quantitative and analytical. This view of the world is referred to in the context of this document as the *system* or *machine* view.

Humans interpret sensations in regard to our past experience. We do not merely sense phenomena and think to ourselves, "I am perceiving the color red." A strong red image may trigger a recent memory or make you feel warm. A specific smell may remind you of a visit to the hospital or that you have not eaten for a few hours. Every person has a unique history through which she/he interprets new experiences and we perceive these experiences in relation to each other. We are capable of making judgements such as "this one is larger than that one," "this feels warmer than that," or "that note sounds a little flat," but there are few if any of us that know "this is exactly 22.2 cm wide", "the temperature is precisely 68.4° Fahrenheit," or "the frequency of that sound is precisely 440Hz." These are the tasks for which we build machines to assist us. Experiencing the world through our bodies, without the aid of machines is referred to in the context of this document as the *perceptual* or *human* view. A perceptual view is unique to the individual, while a *system* view is outside the realm of individual experience and is therefore consistent. It must be stated, though, that once a person has experienced the world through the mediation of a machine and has an understanding of the system view, her/his perception of the environment will be altered as a result.

4.1.1 System vs. Perception

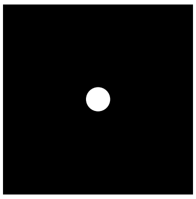
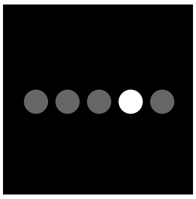
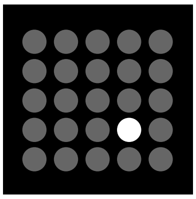
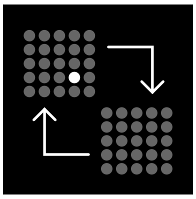
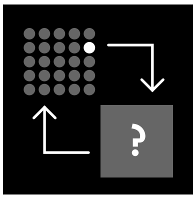
To design and build accurate and precise machines, a human mind must simulate the logic of the system view. A television set, as seen from its engineer's perspective, is a machine which receives an NTSC analog waveform from a requested band in the spectrum and then uses this signal to shoot electrons at its phosphor coated screen. A program transmitted on channel 2 has its video carrier at 55.25 MHz and its sound carrier at 59.75 MHz. The television's tuner, when tuned to channel 2, extracts the composite video signal and sound signal from the radio waves that are transmitted to an attached antenna. These waves are used to modulate the flow of a tight beam of electrons as they are fired from a cathode ray tube toward the screen, etc. The system view of the television is concerned with accurately converting the original wave into the correct intensity and location of the electron beam.

From a perceptual view a television set is a communication device for extending our vision and hearing beyond normal limits. People looking at it are usually concerned with the content of the images being displayed and not on the technique for making them appear. The focus is not on the quantitative information such as the exact color of each picture element on the screen, but on the screen's entire image and how it relates to the previous images and what the future images might be. The person looking at the television set is usually interested in the qualitative aspects of the story being told and how it relates to her/his own experience. A person might feel angry as the newscaster announces a hazardous environmental plan from the Bush administration or may feel happy when Chandler proposes to Moncia during an episode of the situation comedy *Friends*. Regarding the television as a physical object from a perceptual perspective we might touch the screen and feel that it is cold and hard and if we lightly tap it we might enjoy the sound. From a system perspective, the material of the screen is a composite material made from silicon dioxide, calcium carbonate, and sodium carbonate.

It is not correct to discuss *system* and *perception* in isolation from each other as there are many overlapping areas where the aspects of the system effect perception. Using the example of television, a system for transmitting and displaying grayscale images (black and white television) will produce different perception than a system for transmitting and displaying composite images of red, green, and blue signals (color television). The core of the television system, in fact, is built specifically for the perceptual properties of the visual and auditory capabilities of the human body. If these values are modified just slightly, the entire perception may change from a cohesive sequence of moving images to a field of illegible noise—the rhythm of the system will be out of synch with our perceptual capabilities.

4.1.2 System

The aesthetic value of kinetic sculpture, such as the work discussed in section 2.4, is not linked to its complexity or interest as a system. Although stunning and elegant, Calder's mobiles are simplistic when analyzed as systems. The aesthetic value of a behavioral kinetic sculpture is related to the complexity of its system only in regard to how the system effects perception. One of the elements of a behavioral kinetic sculpture is the quality of interaction

	Map	Properites	Examples: IMAGE	Examples: PHYSICAL
Static		· Objects · Unchanging · No movement	*Construction 99,* El Lissitzki *Flag,* Jasper Johns	*Bird in Space,* Constantin Brancusi *Superstructure on 4,* David Smith
Active		· Motion · Predetermined · Unaware of environment	*Contempt,* Goddard *Pas de Deux,* Norman McLaren	*Rotary Demi-Sphere,* Marcel Duchamp *Kinetic Construction,* Naum Gabo
Reflexive		· Receives stimulus from environment · Stimulus/action pairs unchanging	*Reflection Loop,* Kelly Heaton *Dakadaka,* Casey Reas & Golan Levin	*Magnetic Ballet,* Takis *Condensation Cube,* Hannes Haacke
Reactive		· Stores information · Multiple states	*CMYK,* John Maeda *Painting with Interactive Pixels,* Dag Svanæs	*Machina speculatrix,* W. Gray Walter *CYSP I,* Nicholas Schoffer
Adaptive		· Changes behavior · Unpredictable	*Evolving Virtual Creatures,* Karl Sims *Artificial Fishes,* Terzopolous et. al.	*Aibo,* Sony Corporation *Kismet,* Breazeal et. al.

120 System categories

experienced by a human, a more interesting system has the potential to produce a different quality of interaction through more complex behavior. Consider, for example, the difference between locking yourself inside an extremely simple system, a white walled room with rocks on the floor, and being immersed in a complex system, being outside on a bright day sitting beside a stream. In this and many other analogies, the more complex system yields a different kind of interaction with the environment.

4.1.2.1 System Categories

A system for discussing the work presented in this thesis is shown in figure 120. This system has five categories (static, active, reflexive, reactive, and adaptive) which describe the work from an analytical and machine view — if the machine is taken apart how many parts will be found and how do they relate? Works in the static category are immutable and unresponsive. Most of the history of the plastic arts refers to the work in this category — paintings, drawings, sculpture, and architecture are all static. The work included in the active category dates back to 2000 b.c. (section 2.1.1), but it also includes recent developments such as the cinema. These works include motion, but this motion is entirely predefined by the creator. In a film, for example, every time it is shown each frame follows one after another in a consciously chosen sequence defined by the director/editor. In contrast, the work included in the reflexive category receives information from the environment and uses this information as the basis for its future movement. These works are continually changing and their future position (within their physical constraints) is unpredictable. Reflexive works have one state, no memory, and are only aware of the present. An example of a reflexive work is a mobile, moving in the wind. Through an unpredictable stimulus such as the movement of air, it is not possible to know where the mobile will move next. The work in the reactive group has the minimum complexity necessary to achieve behavior. The concept of behavior is one of perception, but a system foundation is necessary to support it. The works in the reactive group are characterized by having multiple states and the ability to read and write information. The *CYSP I* sculpture (section 2.5.1.1) is one of the first reactive sculptures ever made. It used principles of cybernetics to convert light and sound from the environment into controlled movement. The adaptive category refers to systems with the ability to alter their behavior as a result of their interactions with the environment. An example of an adaptive work is the entertainment robot *Aibo* described in section 2.2.3.2. As with all reactive systems, *Aibo* responds to its environment, but as an adaptive system, *Aibo* changes its behavior through the course of its interactions with the environment to develop from an adolescent robot to a mature robot.

All of these systems, regardless of their sophistication, are not aware of their context within the environment. They are isolated behind their sensory interface to the world. For example, if one of its sensors detects pressure on the surface, a system does not know if it is a human giving it a push or another machine. If the temperature sensor on an adaptive sculpture was reading cold, it would not know if it was outside in the winter or merely inside a refrigerator. While these systems lack context for their actions, they are built to respond the correct way in a given situation and regardless of whether they are aware of it or not, they act as they should.

4.1.2.2 System Analysis

Most of the work presented within this thesis falls within the categories of reflexive and reactive systems. Early work for the *Reactive 006* project was static and the most recent work, the behavioral kinetic sculpture *Trundle*, is adaptive. A complete system analysis follows:

SYSTEM ANALYSIS	
Reactive 006	*Static, Active, Reflexive, Reactive*
Egg Machine	*Reactive*
Dakadaka	*Reflexive*
Cells	*Reactive*
Radial Plane Modulator	*Reactive*
Introspection Machine	*Reflexive*
Physical Box	*Reflexive*
Remote Box	*Reactive*
Ambient Box	*Reflexive*
Trundle	*Adaptive*

Because all but one of these experiments use elements unique to the medium of computation, there is only one experiment which has elements from the reactive and static category.

It is possible to create work that is reactive without computation. The work of George Ricky, Alexander Calder, Jesus-Raphael Soto, and Yaacov Agam are examples. In their work, energy and information is provided through forces such as currents of air and people's hands. Reflexive work created with a computer rely on an external power supply and input into the machine comes through devices such as a mouse, keyboard, or other sensors. Once this information enters the machine it is used briefly to change the system and is then replaced by a new value from the environment. In *Dakadaka*, for example, every new key that is pressed replaces the value of the previous key. The *Dakadaka* system is not aware of its past, only its present. The software for the *Introspection Machine* is also reflexive. In this experiment the quantized video signal input constantly updates each frame, replacing all of the previous information. As the video signal changes, the image responds. The fast replacement of variables in a reflexive piece does not necessarily create an instantaneous update of the information. Just as a stimulated muscle requires time to return to its relaxed state, many reflexive systems shift slowly from the new value to the previous one. In the *Introspection Machine*, for example, each aperture is constantly transitioning from one point to the next. This is done with the code:

```
if (abs(newposition-position)>0.01) {
    position = position + (newposition-position)/20;
}
```

In this example, the variable *position* is the current value for an element of the system and the variable *newposition* is the future goal for this value as declared by the incoming video signal. The values are brought closer and closer together, until they are within .01 of each other and then the process stops. Making reflexive sculptures such as the *Physical Box* and the *Ambient Box* creates new considerations for reflexive experiments. A digital system is created through logic and must be created piece by piece by the programmer, while physical systems are already a part of the physical world and therefore have many inherent properties. The *Physical Box* is simply a direct connection between the motor and the sensor, with no representation or signal conditioning, but its interesting movement comes from the physical tolerances of the wood from which it is built. The *Ambient Box* reacts to the sun directly through its solar panel and is able to store this information physically without an abstract representation by storing electrical charge in a capacitor.

The experiments that are a part of the reactive category are more complex than the reflexive experiments and require a different level of computation. *Egg Machine* is the largest system — it has over sixty independent moving elements. Each of these elements has one or more variables associated with it that determines its position, color, size, or speed. *Egg Machine* is able to shift between many states which reveal new elements or bring static ones into motion. For example, some of the elements do not appear or change unless another element triggers them. The Cells experiment contains fewer elements, but the movement is more complex than the geometric movement of *Egg Machine*. Each element in *Cells 4* continually measures the distance from two points on its body to three separate points on the screen and uses this information to determine the amount it should turn. In addition, the system stores and displays the previous 1,000 locations of each cell.

There are two primary ways in which a system can be adaptive. One is through changing its own program and the other is through maintaining and modifying a set of variables which determine its mood or level of development. Programs are often changed through simulating evolution. This technique was used in *Evolving Virtual Creatures* by Karl Sims, discussed in section 2.3.1.3. The *Trundle* sculpture adapts to its environment through changing its variables. Through maintaining a variable representing its affect, *Trundle* is able to change the way it responds to a stimulus over time.

4.1.3 Perception

It was once thought that our ability to be rational and analytical was our defining characteristic as humans, but as the machines we build become more rational and analytical than we are, we are beginning to see our uniqueness as humans as our model of perception, including our emotions and consciousness. At the present moment in their development, machines do a very poor job of simulating a human's perceptual view of the world and people are very poor at simulating a machine's system view of the world. In order to program computers, for example, we have developed many layers of language abstraction in an attempt to communicate with the machines in a language closer to our own. In terms of their power to calculate and manipulate numerical symbols, machines are far superior to their creators. Machines, however, are presently far inferior to humans in making perceptual judgements and recognizing subtle patterns in the environment. For example, a person can often recognize someone they know in a large crowd of people from 100 feet away based on the subtleties of her/his posture. For all of their processing speed and accuracy, there is presently no computer that can achieve such a feat.

Because our bodies are highly tuned to be constantly aware of the immediate physical environment, it is the perceptual qualities of sculpture, rather than the system qualities, that resonate deep within us. There is an extraordinary difference between reading about a work of sculpture in a book and experiencing it with our bodies. When we stand in the same room with a great work of sculpture, we immediately notice the relationship between it and ourselves. How large is it compared to my body? How does the form change as I walk around the surface? With kinetic sculpture there are more answers to be found through physical experience. Does it always move, or only occasionally? Does it move faster or slower than I do? When work is interactive, even more questions are revealed through personal contact. If I touch here, what will it do? Can it feel this? These are questions that are best answered based on an individual's relative experience. The answers are unique and different for every person.

4.1.3.1 Categories of perception

As a result of the subjectiveness of perception, it is not as easy to create refined and absolute categories for analysis. We can make qualitative judgements such as "it moves more like a machine than an animal," or "this sculpture makes me feel uneasy," but it is difficult to quantize these perceptions. In the 1967 book *Origins and Development of Kinetic Art,* Frank Popper develops "A sketch for an aesthetic of movement" based on the work of aestheticians such as Kant, Bergson, and Souriau. He presents a list of twenty-seven categories:

CATEGORIES OF THE INTELLECT

Surprise	*The humorous*	*Astonishment*
Ludic amusement	*The unexpected*	*The fantastic*
The impossible		

CATEGORIES OF THE ENVIRONMENT

Indentification with nature	*Life & vitalism*	*The machine aesthetic*

CATEGORIES OF SENSIBILITY

Hypnosis	*The irrational factor*	*Anguish*
Displeasure	*Nostalgia*	*Pure sensation*

CATEGORIES OF ACTION

The agogic	*Sexuality*	*Grace*
Ballet, acrobatics, sport		

CATEGORIES OF TRANSCENDENCE

Time & eternity	*Freedom & constraint*	*Evolution (progress)*
Rapture	*Spiritual energy*	*Synthesis*
The sublime		

These categories are not comprehensive and do not reflect the changing trends in critical theory over the past thirty years, but due to the formality of the experiments presented in this thesis, they serve as a good starting place for discussing perception in relation to this work.

When the element of interaction is added to a work of art, additional categories are necessary to fully describe the perception of the piece:

CATEGORIES OF INTERACTION

Machine	*Biological*	*Environmental*
Omniscience	*Participatory*	

These categories are analogous to the different kinds of interaction we have every day as we interact with our coffee makers, our pets, other people, the natural environment, and in playing games.

4.1.3.2 Perception analysis

The experiments presented in this thesis relate to a number of the categories of perception. Through short descriptions of these categories and references to other historical works, insight into perceptual qualities of the experiments are revealed.

Humorous

This category refers to work created in the spirit of Picabia and Klee and the kinetic artists Calder, Tinguely, and Bury. Humorous work communicates through parody, absurd contrast, and repetition. The *Egg Machine* experiment is humorous through its visual and aural repetition and its playful hues and sounds. The *Trundle* and *Reactive Boxes* experiments relate to this category through their projection of biological qualities of movement onto stiff geometric forms. Rather than moving like the stiff machines they appear to be, they move in a variable and intermittent fashion that corresponds to their environment.

Astonishment

Revealing hidden forms or presenting a concept in an innovative way is the basis of astonishment. Examples are the photographic motion experiments of Marey and Edgerton which disclose previously concealed elements of motion. The *Plane Modulator* experiment is relevant to this category in a similar way through its ability to reveal the virtual volume of a geometric object's movement through its simulated compression of time.

Ludic amusement
Swift and alert responses to stimuli as well as elements of game play and infancy characterize the ludic amusement category. Examples of work in this category include the whimsical painting of Miro and physical interactive works of Agam. The experiments *Dakadaka* and *Introspection Machine* relate to this category in their responsive interaction and their playful activity of converting symbolic keystrokes into kinetic images and through converting video images into an abstract alternative representation. There is a correspondence between this category and work that is a reflexive system.

Unexpected
The elements of chance and irregularity of movement that define this category may be achieved through randomness, the choice of using unpredictable materials such as water and fire, or through the development of an adaptive system. The Dadaist work of Hans Arp and reactive sculptures of Schöffer both contain elements of the unexpected through the inclusion of natural forces into the creation of the work and natural forces as the input to the work. The Cells experiment relates to this category through its complexity of movement — each of the small cells in this work have simple rules of behavior but their simulated complex environment makes their paths nearly impossible to guess. The *Trundle* sculpture achieves the unexpected through its adaptable control architecture. When *Trundle* is first activated, its movements are entirely predictable, but as it interacts with its environment, it changes its behavior so that it reacts to stimulus in a different way.

Life & vitalism
The quality of movement expressed in the work of Degas and the kinetic sculpture of Pol Bury is that of life and vitalism. The work of Vaucanson and Drotz is rooted in bringing the appearance of life to their mechanical constructions. The Cells, *Reactive Boxes*, and *Trundle* experiments all emulate life through their movement. The movements of *Trundle* are based on animal movement through the use of simulated emotions which change the quality of movement depending on the state of the sculpture.

Machine aesthetic
The employment of machine movement in an effort to identify with industry and mechanics is the core of the machine aesthetic. This property may be employed to praise the beauty of machines through utilizing geometric and sinusoidal movements in a similar way to Schöffer and the early Futurists or to parody industrial society through the creation of subversive mechanisms similar in

spirit to Tinguely's work. The *Plane Modulator*, *Egg Machine*, and *Introspection Machine* experiments all relate to the machine aesthetic. The movement and sounds in *Egg Machine* are all based on pure sinusoids. The geometry and quality of movement in *Plane Modulator* are extensions of the computer's ability to simulate pure geometry and to move an object at a constant speed. The *Introspection Machine* converts analog video images into perfect geometric circles and squares in a way that reduces the information into a minimal mechanical representation.

Pure sensation
The concept of pure sensation began with the work of Turner, Cezanne, Kandinsky, and Malevich through the abandonment of representation. In regard to kinetic sculpture, the work of Soto and George Rickey embody this quality. Both the *Dakadaka* and *Introspection Machine* experiments have elements of this category through their conversion of symbolic and representational content into pure abstraction.

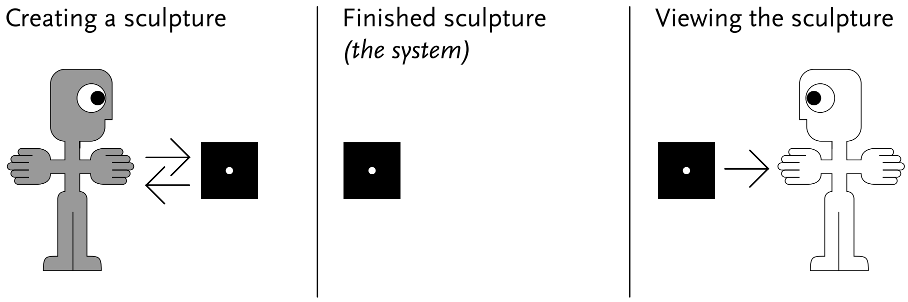
The Agogic
Agogic refers to nuance of tempo as differentiated from the concept of rhythm. The imperceptibly slow works of Bury and the modulating sculptures of Len Lye express agogic properties as do the *Plane Modulator*, *Reactive Boxes*, and *Trundle* experiments. The quality of tempo in *Plane Modulator* is dependent on the person interacting with the piece and if she/he is interested in modulating the speed control to alter the perception. The *Reactive Boxes* and *Trundle* both vary their speed as a method for expression and communication.

Time & eternity
Work that makes reference to this category deals with either the perception of time or the lack of perception of time. For example in his *Microtemps*, Schöffer creates a new perception of time through programming minute movements into his sculpture. The *line_mode* and *daka_mode* in the *Dakadaka* experiment reference time through a technique of layering. As these images develop, they build upon the past images in a way that preserves the history of the interaction.

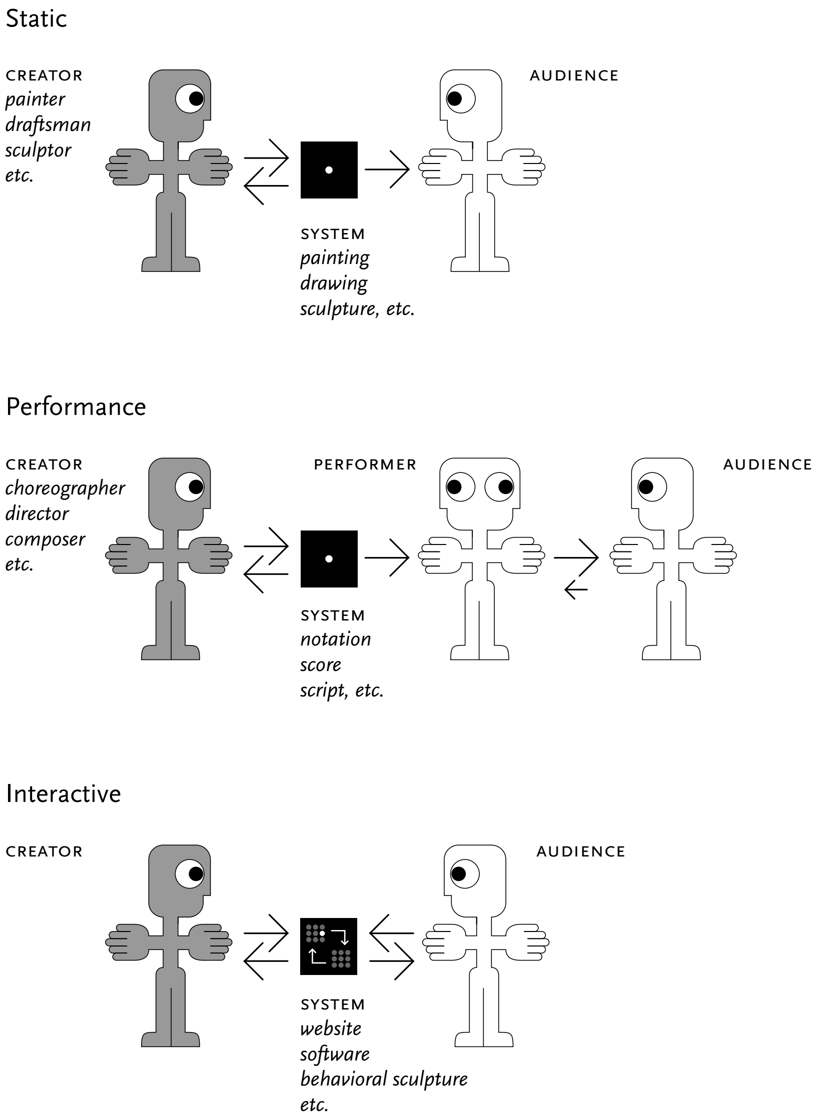
4.2 Interaction

As stated by Dag Svanæs in his paper "Kinaesthetic Thinking," interaction involves "not only a sensibility for movement but also a sensibility for orchestrated responses to movement [Svanæs]." Interaction is the sequence of a stimulus followed by a response. It is the quality in which something moves or responds in relation to a given stimulus. It is the way a caterpillar rolls into a ball when touched or the way a person might respond to a smile depending on her/his mood and the identity of the smiling person. It is through

121 The role of feedback in the cycle of a sculpture



122 The role of feedback in different contexts



our interactions and relationships with objects, machines, plants, animals, and other humans that we understand ourselves. Through interacting with a rock, for example, we learn that we are soft in comparison. Through interacting with a small child we are reminded of our former selves and of the complexity of actions such as walking which no longer require our conscious thought. It is through these complex interactions with our environment that we are able to learn and survive. In creating interactions between our engineered systems and ourselves we must utilize the skills that we use in our natural interactions with our environment. To develop a "sensibility for orchestrated responses to movement" we must be observant to the elegance of response in our natural environment.

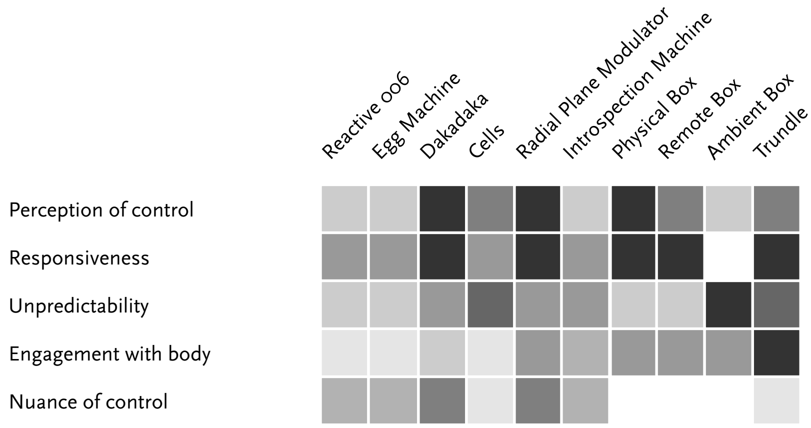
4.2.1 Feedback

Interaction is made possible by the continuous flow of information that permeates our environment. Our limited senses enable us to filter out a large part of the information that seems irrelevant, but our actions depend on receiving a constant stream of information in which to react. In *Design for a Brain*, W. Ross Ashby explains the relations between multiple organisms existing within a single environment:

> . . . consider a butterfly and a bird in the air, the bird chasing the butterfly, and the butterfly evading the bird. Both use the air around them. Every movement of the bird stimulates the butterfly's eyes and this stimulation, acting through the butterfly's nervous system, will cause changes in the butterfly's wing movement. These movements act on the enveloping air and cause changes to the butterfly's position. So the processes go on. The bird has as environment the air and the butterfly, while the butterfly has the air and the bird. The whole may reasonably be assumed to be state-determined . . . The organism affects the environment, and the environment affects the organism: such a system is said to have "feedback". . . When the bird and butterfly manoeuvre in the air, each manoeuvre of one causes reactive changes to occur in the other [Ashby p. 37].

In interacting with a system exterior to ourselves, it is the amount of feedback that determines how much information is communicated between the human and the system. If the system only accepts a small signal from a human, its changes may not fully reflect the intent of the communication. If a large portion of information the system uses to update itself is coming from signals sent by the human, is may seem as it the human is in *control* of the system.

Figure 121 shows the role of feedback within different stages in the creation of a traditional sculpture. During the period of time when the sculptor is creating the work, there is a tight feedback loop between the work and the artist. As the artist makes changes to the work, he sees this change in the surface of the sculpture and uses this information to make his next decision



123 Five qualities of behavioral interaction

about the form of the piece. Once the sculpture is finished, though, it is unchanging. If a person approaches the sculpture and looks at it, she/he will receive information about the shape and material of the sculpture, but the sculpture is not capable of receiving any information from the human. It is a mass of rock, wood, or other dead material that is not able to detect the environment. A condensed diagram for sculpture and other static forms of art is shown in figure 122. In comparison to the feedback diagram for the performance arts, one of the primary differences is a small amount of feedback between the audience and the art as embodied by the performer. In a performance situation, the performer receives information from both a static plan created by the artist and from the audience as she/he executes the plan. One may think of the feedback model for interactive arts as similar to performance, but the performer is embedded within the system. In interactive situations, the amount of feedback into the system may vary depending on the intent of the artist.

4.2.2 Qualities of behavioral interaction

The information transmitted as feedback determines the quality of the interaction. There are five categories that this information controls: perception of control, responsiveness, unpredictability, engagement with the body, and nuance of communication.

4.2.3.1 Perception of control

Depending on the amount of feedback the system uses to determine its future, the control of the movement of the system appears to either be within the control of the system (and therefore the creator of the system) or the control of the participant. A complete analysis of control follows below:

PERCEPTION OF CONTROL	
Reactive 006	*Creator*
Egg Machine	*Creator*

Dakadaka	*Participant*
Cells	*Mutual*
Radial Plane Modulator	*Participant*
Introspection Machine	*Mutual*
Physical Box	*Participant*
Remote Box	*Mutual*
Ambient Box	*Creator*
Trundle	*Mutual*

To build an interesting interaction, a balance must be created between lack of control and total control. At two ends of this spectrum are the *Radial Plane Modulator* and *Egg Machine*. In *Radial Plane Modulator* participants can start from a blank image and build from the bottom up. In this situation they spend a long time building, tweaking, and building again. In *Egg Machine* the system specification makes its movement and form constrained to a few narrow choices. Despite attempts of the participant to reconfigure the entire composition, the choices for configuration are narrow. An experiment like *Introspection Machine* creates a more balanced interaction.

4.2.3.2 Responsiveness

The concept of responsiveness relates to the content of the feedback immediately following a stimulus. For example, in *Dakadaka*, there is a quick, obvious visual confirmation after every key is pressed. Cells, however, provides feedback slowly over a period of a few minutes, which makes it difficult to tell to which stimulus it is responding. An analysis of the responsiveness of all the experiments follows:

RESPONSIVENESS	
Reactive 006	*moderately*
Egg Machine	*moderately*
Dakadaka	*extremely*
Cells	*moderately*
Radial Plane Modulator	*extremely*
Introspection Machine	*moderately*
Physical Box	*extremely*
Remote Box	*extremely*
Ambient Box	*n/a*
Trundle	*extremely*

It is beneficial for nearly all behavioral sculptures and behavioral software to have quick and accurate responses. If there is no response or the response is delayed, the participant will not be able to gauge her/his effect on the system. It is boring, however, if the extent of the reaction is restricted to this initial reflex. If these reflexes are able to combine to generate more complex actions that develop over time, the interaction will be deeper.

4.2.3.3 *Unpredictability*

If a system always responds the same way to an action, it quickly loses its interest. One of the most engaging qualities of an interaction is experimentation and anticipation; both of these are impeded by a totally predictable system. An analysis of predictability follows below:

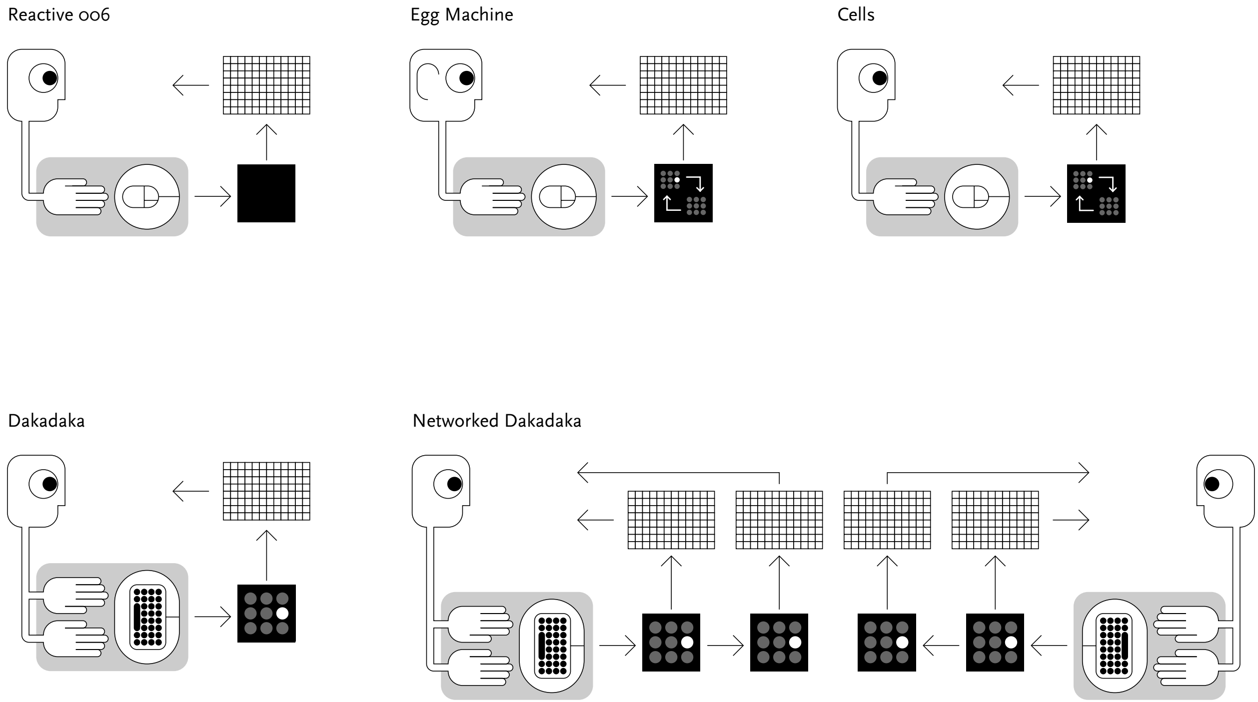
UNPREDICTABILITY	
Reactive 006	*Extremely predictable*
Egg Machine	*Extremely predictable*
Dakadaka	*Predictable*
Cells	*Moderately predictable*
Radial Plane Modulator	*Predictable*
Introspection Machine	*Predictable*
Physical Box	*Extremely predictable*
Remote Box	*Predictable*
Ambient Box	*Unpredictable*
Trundle	*Moderately predictable*

A balance must be met between the disinterest of unchanging reactions and pure chaos. Systems which appear random such as the *Ambient Box* sometimes create a surprise through an unexpected movement, but they do not engage as fully as a project like *Trundle*, where the participant is able to develop theories about its behavior and then test them through interaction. Correlations between the stimulus and the response fosters curiosity and experimentation.

4.2.3.4 *Engagement with body*

Feedback and interaction that is experienced through the entire body is the most engaging. The trend to build arcade video games that have increasingly more elaborate physical interfaces such as real skis for their downhill games and facsimile motorcycles for racing games is a good gauge of the importance of this principle. By engaging more than the eyes and hands, it is possible to absorb the entire body, not just the mind. Sculptural systems excel in this category because of their raw physicality—their materials, mass, and movement are rooted in the same environment as our bodies and we are able to connect with them as a result. All of the experiments in relation to interaction with the body are stated below:

ENGAGEMENT WITH THE BODY		
Reactive 006	*Hand, Eyes*	*Screen*
Egg Machine	*Hand, Eyes, Ears*	*Screen*
Dakadaka	*Both hands, Eyes*	*Screen*
Cells	*Hand, Eyes*	*Screen*
Radial Plane Modulator	*Both hands & arms, Eyes*	*Hybrid*
Introspection Machine	*One hand & arm, Eyes*	*Hybrid*
Physical Box	*Both hands, Eyes*	*Physical*



124 A–E
Diagrammatic representation of the screen-based projects

Remote Box	*Both hands, Eyes*	*Physical*
Ambient Box	*Both hands, Eyes*	*Physical*
Trundle	*Entire body*	*Physical*

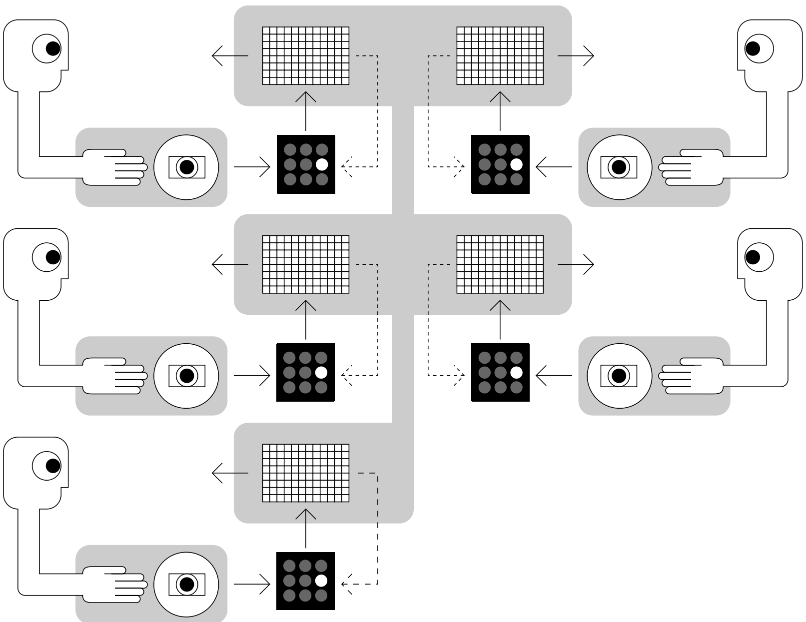
The hybrid and physical work has a sensual and direct quality that the screen-based work does not. In interacting with Cells, for example, the person either stands or sits in one place. All of the degrees of freedom in her/his body are constricted to small localized gestures with her/his hands. In contrast, interacting with *Trundle* involves approaching and walking around an object roughly the size of a person. Both the scale and range of movement are enlarged. The size of the work has an impact on the interaction, similar to the experience of watching a movie at home versus a large screen in the theatre. Small works engage the mind, but large works have the ability to overwhelm the senses.

4.2.3.5 Nuance of communication

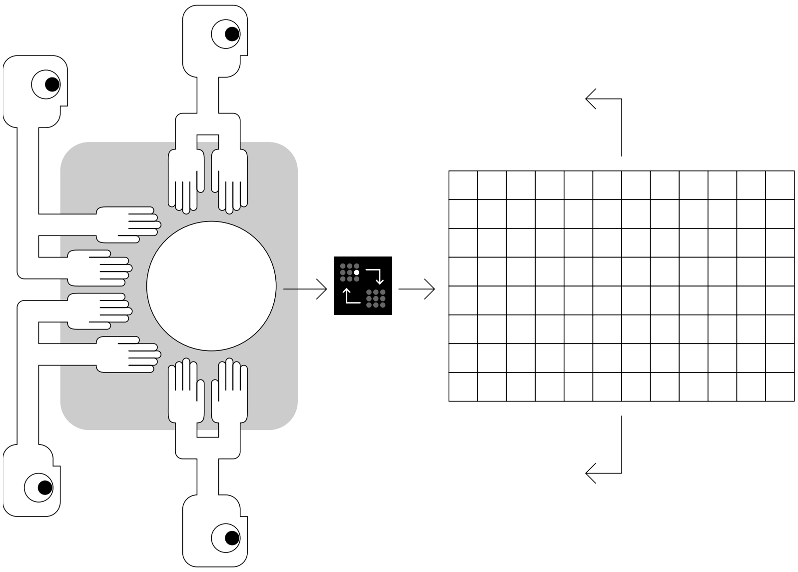
A related concept to engagement with the body is the nuance of information transmitted in the input. For example, a mouse gives very fine input over its limited range, but a crude sonar will only transmit the relative position of an object within a few inches. The granularity of an input is also a function of time. If an input is extremely frequent the information arriving into the system will always be current, but if there are many fast changes occurring and the input of information is very slow, the system will not receive all of the

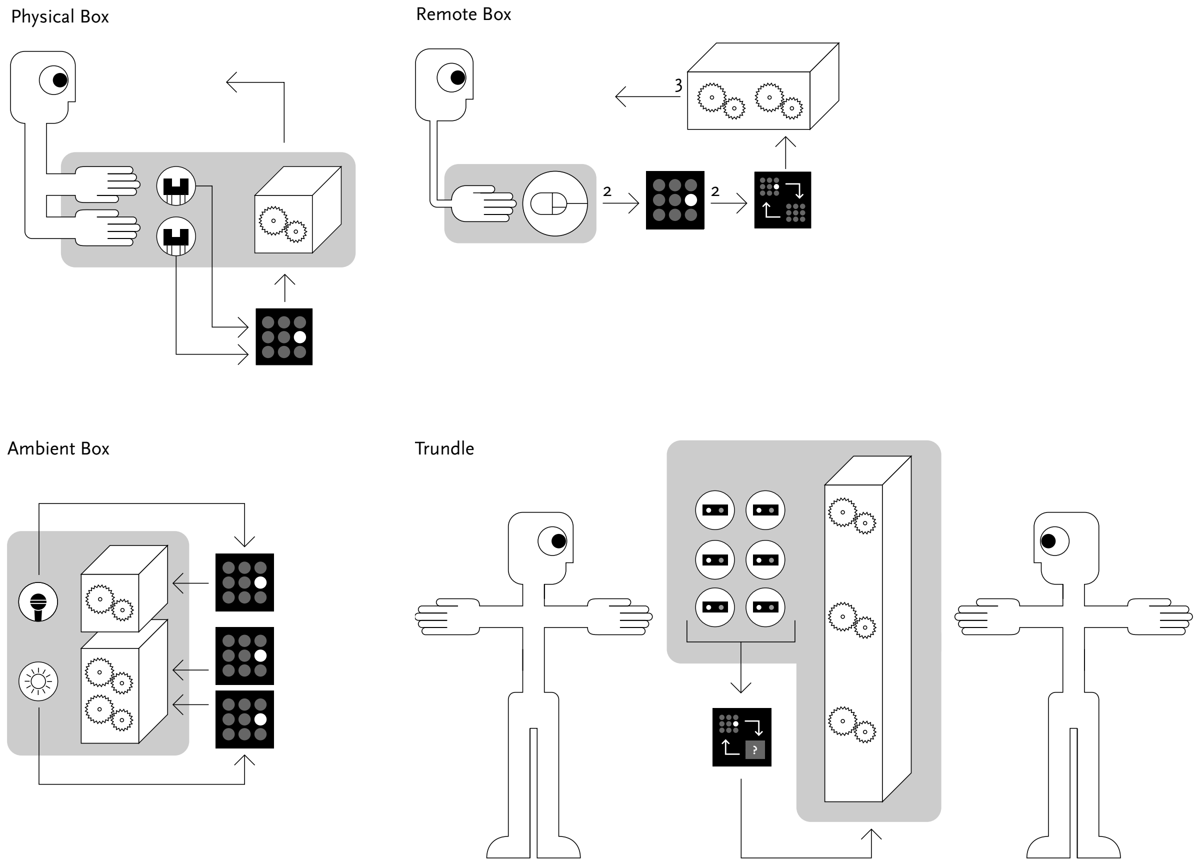
125 A, B
Diagrammatic representation of the hybrid projects

Introspection Machine



Radial Plane Modulator





126 A–D
Diagrammatic representation of the physical projects

relevant information. Below is a list comparing each experiment to its nuance of communication:

NUANCE OF COMMUNICATION	
Reactive 006	*good*
Egg Machine	*good*
Dakadaka	*moderate*
Cells	*poor*
Radial Plane Modulator	*moderate*
Introspection Machine	*good*
Physical Box	*extremely poor*
Remote Box	*extremely poor*
Ambient Box	*n/a*
Trundle	*poor*

The *Trundle* sculpture is the experiment that most fully engages the body, but it has a poor amount of nuance in its interaction. Although *Trundle* is aware of information taking place around its entire body, it is not able to notice a difference in a subtle gesture. Due to the high resolution of the mouse input device, screen based pieces such as *Reactive 006* are able to respond to slight movements on the scale of a millimeter. In comparison to the resolution of the human visual system and our natural ability to detect slight changes in the environment, the level of sensing detail in all of these experiments is crude.

4.2.3.6 Diagrammatic representation

Figures 124 to 126 present many of the qualities of behavioral interaction in a visual format. These simplified sketches of the systems provide visual overviews for comparing their complexity and their engagement with the body. The representation of the humans in these systems reflect the type of interactions with the body — hand, eye, arm, etc. Gray boxes signify areas of physical contact, for example, a hand is touching the mouse.

127 Alexander Calder in his studio

4.3 The sculptor as generator

The production of nearly every artwork relies on technology for its execution. It is easy to forget that revolutionary technologies such as paper, the printing press, lithography, photography, and motion pictures were at one time extremely experimental, expensive, and used only by niche communities of the wealthy and technically motivated. Until the 1980s, creating artworks with the technologies of computation suffered from similar barriers. As a result, artists often collaborated with computer scientists and engineers to realize their work. In the twenty years since, there has been a tremendous amount of experimentation focused around the potential of computation as a new medium. Unfortunately there are still perceived barriers to developing works of behavioral sculpture. As in the time that predated the original computer revolution in the late 1970s, there is a small group of hobbyists dedicated to creating work with the raw materials of behavioral kinetic sculpture. These are the people that may usher in the revolution of robotics, but who will be the next generation of behavioral kinetic sculptors?

4.3.1 Recent history

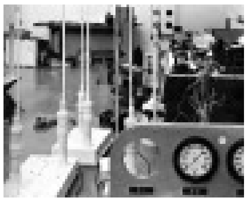
A quick overview of the history of kinetic art reveals disparate methods of production ranging from collaborator to auteur. While the construction of the *Standing Wave* (fig. 40) was completed entirely by Gabo, who was trained as an engineer, two of the first great works of kinetic art were produced in collaboration with technicians. Marcel Duchamp was possibly the greatest conceptual revolutionary in 20th century art and possessed considerable technical skill, but often collaborated with others during the production of his physical work. Letters written from Duchamp to the individual who commissioned *Rotary Demisphere* (fig. 41) reveals similar complications to those of modern artists:

Saturday, March 8, 1924
I have just seen the engineer Milde. He came to Man Ray's and seemed to understand perfectly what I wanted so I've asked him to prepare a cost estimate which he will bring to me Tuesday morning.

Wednesday, March 16, 1924
Yesterday I went to Milde's at 5 o'clock and he wasn't surprised by the rejection [of his estimate]; he explained to me how the form for the glass would cost 300 francs alone, and each single impression 100 or 150, that he would need fiber gears, etc. . . . etc. . . .

September. 15, 1924
I came back Sunday with pitiful results. I tried to speed our mechanic up and I almost (!) finished mounting the striped globe on the first plate. He's busy (!) with the motor. He's had a wooden triangle made to give more stability to the whole thing. All in all, I'm sure we'll get there but it will require your patience and mine [Duchamp p. 182].

128 Jean Tinguely in his studio



129 Takis in his studio at MIT's Center for Advanced Visual Studies

130 Pol Bury at work in his studio

During his nine month exchange with the engineer Milde, Duchamp was also working on the surface construction of the piece such as hammering the copper and applying velvet. Moholy-Nagy also collaborated with a technician in the creation of his *Light Prop* (figs. 43 a, b), a 5' tall apparatus of moving aluminum and chrome-plated surfaces driven by an electric motor and a series of chain belts.

The second generation of kinetic sculptors followed the lead of Alexander Calder, a tinkerer and builder from a young age. These artists grew up in an era after the invention of the automobile and the airplane and machines were a part of the fabric of their lives. The work of Tinguely, Bury, Agam, and Takis all reflect this attitude of freedom and expression through the creation of machines. With the exception of the complex creations of Jean Tinguely, these machines were simple systems often involving only one motor with simple linkages. As sculptors began to create works of greater complexity and felt a need to respond to the theories of cybernetics, they once again began to collaborate extensively. When Schöffer created his *CYSP I* (fig. 56) in 1956 it was one of the most complex electronic sculptures built to date. To build it, though, he required the assistance of a major international corporation, Philips, to fund it, and the assistance of engineer Jacques Bureau to build it. The result of this enormous effort and expenditure was a sculpture with little more than technical interest. More successful cybernetic sculptures were created by artists with engineering backgrounds. Both Tsai (fig. 57) and Seawright (fig. 58) created some of the strongest examples of cybernetic sculpture. To fill the demand for artists in need of technical assistance, Bell Labs physicist Billy Klüver founded E.A.T. as a matching agencies between engineers and artists. Although the work produced through collaborations between artists and engineers was mixed in terms of its success, it was successful in bridging these diverse cultures. Jack Burnam explains, “The major impression to come across is the subtle symbiotic relationship that developed between the artists and engineers, both hardly dreaming that such a rapport would be possible. That they did find common interests and means of working together was a discovery that dwarfed, in their eyes, all subsequent reactions [Burnam p.360].”

4.3.2 Contemporary perspective

The relationship between artist and engineers has changed very little since the problems of Duchamp and the pioneering E.A.T. project. The situation is described by MIT professor John Maeda as follows:

> With a very few exceptions, all of today’s computer art represents a collaboration between an artist and an engineer. The artist has the conception, but it is the engineer who understands the materials – the hardware and software – needed to realize this conception. ... In fact, in today’s computer art, the artist assumes the role of the creative genius while the engineer settles for the subordinate role of manual laborer. Although such collaborations can produce respectable artwork, they rarely lead to works of real power and inspiration. What is more, the situation is getting worse because relentless progress in information technology has widened the gap between artist and engineer: The artist has little understanding of the computer as a medium, and the engineer (who has no artistic training) is not allowed to unlock his creative potential in using the medium he has mastered [Maeda 1998].

As a result of this widening gap, artists are having less and less direct contact with their materials. This destroys the tight feedback loop between the artist and the work and inhibits exploration. In the current scenario, the artists must not only communicate their ideas to another individual but must make decisions and then wait for a period of days or weeks before seeing the results. If the decision they made turns out to be poor, the consequences for altering it are very high and compromises are often made. If an artist is able to learn the skills necessary for production, she/he is able to develop a tighter feedback loop between himself/herself and the work — opening up possibilities for innovation and serendipity.

Tinguely and Calder are arguably the most successful kinetic artists of their time and it is interesting to note that with the exception of their largest pieces, they were the principle generators of the work. Both of these sculptors build in the materials of their mature work from a young age and developed an unconscious control over the medium. When they worked they immersed themselves with the material with which they worked. They worked in an exploratory manner, experimenting and making decisions in an active way through a tight loop between action and decision.

The barrier to building behavioral kinetic sculpture may be the result of the diverse skills necessary for its creation. Knowledge of mechanical design, basic electronics, and the ability to write software is required for the creation of even the simplest work. In addition, aesthetic knowledge of three dimensional form, movement, and interaction is also necessary to creating a work of merit. As a result of this complexity, Simon Penny feels that collaboration is a necessity, although problematic:

> Not only does this go against the grain of the traditional character type of the "can-do" rugged individualist sculptor, but it necessitates deep and sensitive engagement with people trained in disciplines so distant from the goals of art that conversation can, at times, seem impossible. In the process of realizing an artists vision for a technological artwork, the task of solving technical problems and resolving communications issues among the collaborators is a labor in itself. The medium forces interdisciplinarity and hopefully, an artist with any sort of sensitivity cannot avoid considering the nature of the disciplines and technologies which he employs, which must in turn change the practice of art [Penny 1999].

This attitude may be the result of the poor resources available for teaching the required skills. There are no university programs currently in place to teach these skills, and until the technologies required for the production of this art become as ubiquitous as video cameras, there will not be a generation of artists who have an intuitive understanding of this medium. It is also necessary to develop tools to enable the manipulation of the raw materials at a higher level than the current practice of intricately machining custom parts and writing programs in C and assembly code.

Although my work is still primitive, I am able to build a large part of the systems myself and as a result am working toward a high degree of fluency in the medium. In creating the experiments that are the body of this thesis, I made a conscious decision to build as much of the projects as I was able. The software was written on top of existing libraries and I build custom functions to assist in the creation of the work. The physical and hybrid projects were created at the machine shops at MIT. Over the course of building these projects, I found that there were many levels at which to work. For example, in machining the *Trundle* sculpture, I chose to lathe the wheels myself from a piece of available plastic because the exact wheel size I wanted was not commercially available, but parts like the IR Sensors that were readily available and of better quality than I could have made myself were purchased.

4.4 Materials & Tools

In the traditional practice of creating sculpture, there are many levels of control at which the sculptor may engage the medium. In chiseling a work from a block of stone, the sculptor may begin by removing large chunks of material and progressively use more refined tools until they are working with small tools at an extreme level of refinement. If a sculptor is working in an innovative way some of the tools they use may be customized to match their preferences or to achieve a unique form. A more modern method of creating sculpture is through the assembly of pre-existing natural and industrial materials. Working in these different ways requires a different method of thought, understanding of the materials, and different sets of tools.

4.4.1 Software

There are many diverse ways to work in the medium of computation. There are currently a large number of tools in place to assist in the creation of static and active systems. High level visual environments such as Adobe Photoshop allow artists to directly manipulate visual form and continually refine an image. Tools such as Macromedia Flash allow the creation of precise animations through a process known as keyframing. The tools for creating more complex systems, however, are not as advanced and are not possible to create without working directly with the technology at a more basic level. Simple reflexive systems are easily created through small scripting languages such as Lingo and Javascript, but building complex reactive and adaptive systems requires working with computation at the level of a programming language such as C or Java. Despite years of research into visual control flow and data flow languages, there has yet to be successful visual environment built for the creation of interaction. As a result, contemporary artists working with interaction must confront computation within the terms of established programming practice — editing words in a text buffer and then running the program to see the results. These practices enforce a rigid method of thinking which only becomes fluid through years of working with the material.

The material properties of software are the qualities of the programming language used in the production of the work. Writing code in a scripting language like Perl is similar to building in plaster. Perl and plaster both enable a quick realization of the sought form, but plaster is brittle and breaks and Perl code can be messy and difficult to maintain. For a more elegant structure, a material requiring precision and a high level of skill must be used — granite for a sculpture and assembly language for a program.

Most of the experiments created for this thesis were built using C/C++ and OpenGL. The Aesthetics and Computation Group's ACU software library was used as the basis for these applications. Although the visual elements of projects like *Egg Machine* could have been created with a simpler scripting language such as Lingo, these languages can only support a limited complexity and extensions of this project would not be as possible. At the end of two years of building in the medium of computation with these complex tools I am just beginning to use them fluently and see the full potential of the medium.

4.4.2 Physical

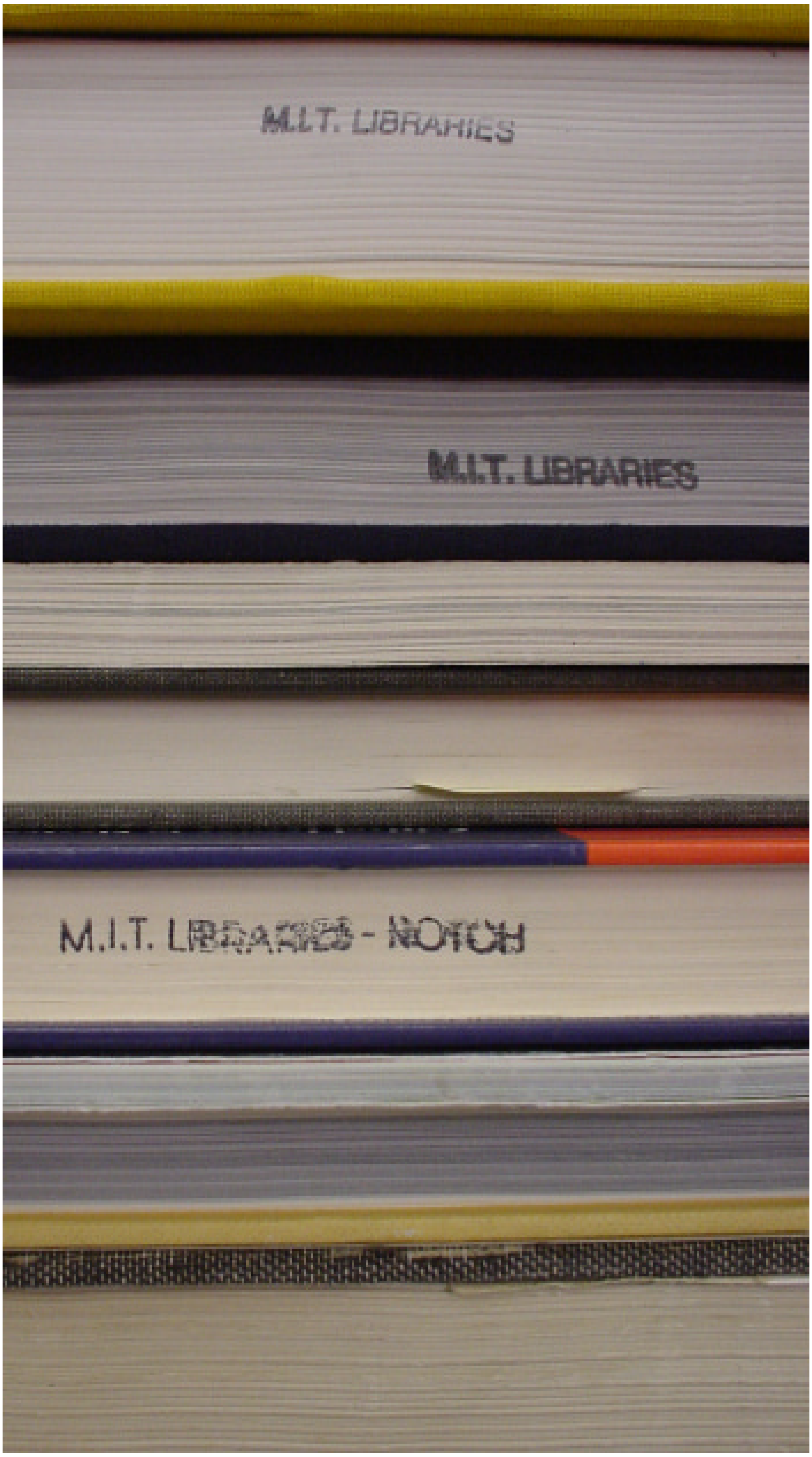
While software tools did not come into existence until the 20th century, physical tools are thousands of years old. The myriad tools available for physical construction are tailored for specific materials. The creation of sculpture requires awareness of these tools and materials. Unlike software, every element of a sculpture is visible to the human eye. Software may be written in a haphazard manner, but as long as the finished interface is clean and the code is logically equivalent, it is not noticeable. A kludge built into a sculpture, however, is visible and this element becomes a part of the object. Historically, if a sculptor wants to realize their vision, they typically had two choices — to build it themselves or to commission the work to be built by a craftsman. A third choice of constructing with fabrication tools such as a lastercutter, waterjet, and 3D printer has recently emerged. These technologies enable the creation of physical form quickly and without the years of knowledge necessary to gain mastery of a craft.

In building *Trundle*, I made the decision to construct it entirely with manual tools such as a hand-controlled milling machine and lathe. I did this to achieve a better understanding of the materials, many of which I was using for the first time. In constructing with fabrication equipment such as the lasercutter the pleasure of doing the work with your hands is absent and a detailed understanding of the material may never develop. For more intricate projects, though, such as the interface for the *Radial Plane Modulator*, I chose to use both the laser cutter and the waterjet to reduce the time necessary for the creation of many repetitive and precise cuts.

131 Natural ecosystems such as this geyser in Yellowstone National Park in Wyoming are a potentially rich inspiration for the future of behavioral kinetic sculpture.

Conclusion

This thesis presents the concept of behavioral kinetic sculpture within the context of automata, behavioral robotics, behavioral software, and previously established forms of kinetic sculpture. Experiments created by the author leading up to the sculpture *Trundle* are discussed and analyzed in relation to these related ventures and a method for critiquing and discussing behavioral kinetic sculpture is presented and explained. It is the hope of the author that in the near future, this new sculpture will flourish as created by a new generation of artists, working directly and intuitively at the junction of physical kinetic form and the medium of computation. As more robotic products enter our homes and we begin to communicate more with intelligent synthetic systems, an alternative, non-commercial vision is necessary to challenge cultural assumptions. Just as the thirty year old conceptual ideas of the desktop metaphor have been woven so deeply into the fabric of our culture that it seems to be as permanent as the ideas of a table of contents and index are to books, we are entering a time when our relationships with interactive physical objects is being defined. Will these interactions reinforce existing concepts or will they enable us to develop a language of physical interaction that extends our perception and reinterprets our ideas of what it means to be human?



132 The majority of the references used in this thesis were borrowed through the wonderful MIT library system

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