

the linear change of waveform segments causing non-linear changes of timbral presence

Dr. Arun Chandra
Institute of Applied Arts
National Chiao Tung University
and
Wolfram Research, Inc.*
arunc@cc.nctu.edu.tw

Keywords: waveforms, cybernetics, transformations, time-based modulation.

Abstract

Relatively minor structural manipulations of a waveform's *state* can have dramatic consequences on both the timbre and the perceived fundamental of the resulting sound, where a *state* has a length on the order of two milliseconds. The initial state is specified by describing: 1) the number of *segments* it is to have; 2) the *type* of each segment; 3) the *sequence* of segments; and 4) the number of iterations of that state. Algorithms have been developed for generating continuously changing waveforms from a specified initial state. The perceived fundamental frequency is the result of the changing length of the *state*, and the timbre is the result of the variety of amplitudes, and the disjunct and conjunct relations between neighboring *segments*.

Currently, a *segment* can be one of three *types*: 1) a wiggle, a sequence of samples at one amplitude; 2) a twiggle, a sequence of samples whose amplitudes have a linear rise to and fall from a specified peak; and 3) a ciggle, a sequence of samples whose amplitudes rise to a specified peak and return to their starting magnitude in two second-order polynomial curves.

To avoid unwanted disjunct amplitude changes between neighboring *segments*, each *type* can be *slanted*, that is, its starting amplitude is the previous segment's ending amplitude.

After a set of *segment* specifications has been made, the initial *state* of the waveform is created by specifying a *sequence* consisting of a subset of the defined *segments*. This *sequence* is then iterated and written to disk (or memory) until the desired duration for the resulting sound is reached.

Algorithm for transformation: Each variable within a *type* specification is given a maximum and a minimum limit between which it can grow or shrink, and a *rate* at which it will change. Upon each iteration of the waveform state, each variable changes by its specified *rate*. If a variable reaches one of its limits, it reverses the direction of its change.

Experiments have been made on: 1) the difference between the use of unique and common cycle lengths for variables that have different minima and maxima, where a *cycle length* is the number of iterations required by a variable to return to its starting magnitude; 2) possibilities of harmonic reinforcement due to the result of common cycle lengths given to

*consulting

amplitude variables; 3) possibilities of multi-voiced timbres resulting from groups of unique and common cycle lengths applied to amplitude and sample length variables; 4) possibilities of using mixed *types* within an initial *state*.

Introduction

In the 1950s, W. Ross Ashby published his book *An Introduction to Cybernetics* [Ashby, 1956], which presented structural transformations in a way that allows their description to be independent from their medium of implementation. At that time, the science of cybernetics, started by the work of mathematician Norbert Wiener [Wiener, 1950, 1954] and engineer Claude E. Shannon [Shannon, 1949], generated an enormous amount of interest due to the possibilities it offered with regard to devising a language for the analysis of systems that was independent of any one field. People from many disciplines were attracted to it: the anthropologist Margaret Mead, the biologist Heinz von Foerster, the mathematician John Neumann, the psychologist Gregory Bateson, and many others, all took part in the “Macy” conferences in the early 50s, and the subsequent founding of the American Society for Cybernetics [von Foerster, 1974, 1984].

In the 1970s, the composer Herbert Brün (who had been involved with compositional experimentation with technology since his work in the 1950s at the Cologne Radio Studios in West Germany), began work at the University of Illinois on his project *SAWDUST*, with the assistance of Gary Grossman, and later Jody Kravitz and Keith Johnson [Roads, 1985]. *SAWDUST*, originally written for the VAX 11/780 and then ported to a 386-PC, took its synthesis paradigm not from the mathematical models of Fourier synthesis, but the transformational ideas of cybernetics. *SAWDUST* allows for the specification of square waves, which are then subject to linear transformation from a specified initial to a specified final state. The program currently has five transformational algorithms: *vary*, *turn*, *merge*, *mingle*, and *link*.

Project *wigout*

The project *wigout* is divided into four parts:

1. the specification of waveform segments (completed).
2. variable sequences for the creation of *states* (completed).
3. transformations (one algorithm has been completed).
4. FFTs and movie displays for observing the changing frequency spectrum (to be completed this summer).

Specifying the waveform segments

Currently, a *segment* can be one of three types:

wiggle All the samples have the same amplitude

twiggle The amplitudes rise to a fluctuating “peak,” then return to their starting value. Both rise and fall are linear.

ciggle The amplitudes rise to and fall from a fluctuating “peak,” following the path of two second-order polynomials.

The above-mentioned “peak” requires some explanation. The “peak” is a point (located between the specified starting and ending samples) that has two variables: an amplitude (-32768 to 32767), and a location (0.0 to 1.0). Both variables of the “peak” can fluctuate between their specifiable minima and maxima, each at a specifiable rate. Future plans include the stipulation of a variable number of “peaks,” each with its minimum, maximum, and rate of change. Currently, a *segment* can have one “peak.”

The disjunction of amplitudes between adjacent *segments* will be one of the contributing factors to the prominence of particular frequencies in the resulting sound spectrum. The amplitude range used is 16-bits, giving a dynamic range of about 96 dB. Thus the differences possible between adjacent *segments* range from 0 dB (when adjacent *segments* have the same amplitude) to 96 dB (when one segment is at -32768 and the other is at +32767).

Since the amplitudes of adjacent segments are continuously varying, the resulting sound spectrum will also be constantly shifting. To better control this phenomena, each segment can be “slanted,” that is, its starting amplitude can be the ending amplitude of the previous segment, allowing for a degree of control over unwanted disjunctions

Creating variable sequences for the “states”

A state is a sequence of segments that is iterated until the desired duration for the sound is reached.

Preferred sequences can be specified containing the repetition of segments within a state. In an example shown below with *ciggles*, four segments are defined (c0, c1, c2, c3), then eight are used to create the state (c0 c1 c2 c3 c1 c0 c2 c1).

The purpose of this flexibility is to test the consequences of parallel movements of segments within a state. The hypothesis is that such parallel movement could create a second “fundamental” frequency, with the possibility of independent control from the first fundamental, *i.e.*, the possibility of generating a multi-voiced texture from a single waveform transformation. Further experimentation along this line needs to be pursued.

The length of a specified state is the sum of lengths of its constituent segments. There are practical limits on the total length of a state, *e.g.*, it cannot be shorter than 0 samples. The maximum length is theoretically infinite. Given that human hearing has a range of about 20–20000 Hz., the practical limits for the length of a state are 2 and 2205 samples, at a sampling rate of 44100 samples per second. At 48000 samples per second, the upper limit would be 2400 samples, but the lower limit would remain the same.

One set of investigations will be to explore the consequences of using sub-audio lengths of states on the resulting sounds, given a fixed set of changes in the segments.

Specifying the transformations

Currently, one algorithm for transformation is proposed. Upon each iteration of the state:

- if a variable has a rate of change that is non-zero, that variable will change its magnitude by that rate.
- if a variable of a segment has a rate of change that is zero, that variable will repeat its magnitude.

Every variable within a segment is given an initial value, minimum and maximum limits, and a rate of change. Thus, every variable that has a non-zero rate of change has a cycle length of:

$$cycles = \frac{2(max - min)}{rate}$$

After *cycles* number of iterations, the variable returns to its initial magnitude.

This suggests possibilities of experimentation with concomitant cycles that:

- have the same length, but different minima and maxima.
- have different lengths, but the same minima and maxima.
- have lengths that are integer multiples of each other, *i.e.*, that follow the harmonic series.
- have lengths that are relatively prime.

To be explored is application of the above criteria simultaneously to all segments within a state, and to all variables within each segment.

Evaluation of the resulting harmonic spectrum

The theoretical fundamental of the resulting waveform will be based on the current length of the state (the sum of all the segments). The harmonic spectrum will be the result of the current configuration of the amplitudes within that state.

Since both the length of the state and its set of amplitudes will be changing, analysis of the resulting harmonic spectrum will require taking an FFT (Fast Fourier Transform) of every state. Since states will be on the order of two milliseconds in length, a great many FFT “snapshots” will have to be taken of the changing waveform. The FFT will thus be implemented on a DSP for speed. The result will be displayed graphically, allowing for continuous observation of the changing spectrum. This work is currently in progress.

Segment type: *wiggle*

A *wiggle* has two variables, an *amplitude height* (± 32767), and *sample length* (0–1000).

Below is an example of an input file for creating seven segments, each of which is a *wiggle*.

The first line of each segment has its identifier and its *type*. The second line refers to the sample lengths, from left to right: the initial, maximum, minimum, and rate of change. The

third line refers to the amplitudes, and again specifies the initial, maximum, minimum, and rate of change.

```
#init max   min   rate
w0  wiggle
100  100   20   4.5   # identifier, type
10000 20000 -20000 10   # (samples) initial, max, min, rate
                        # (amplitudes) initial, max, min, rate

w1   wiggle
20   130   20   4.5
-10000 10000 -10000 20

w2   wiggle
50   100   20   4.5
10000 20000 -20000 30

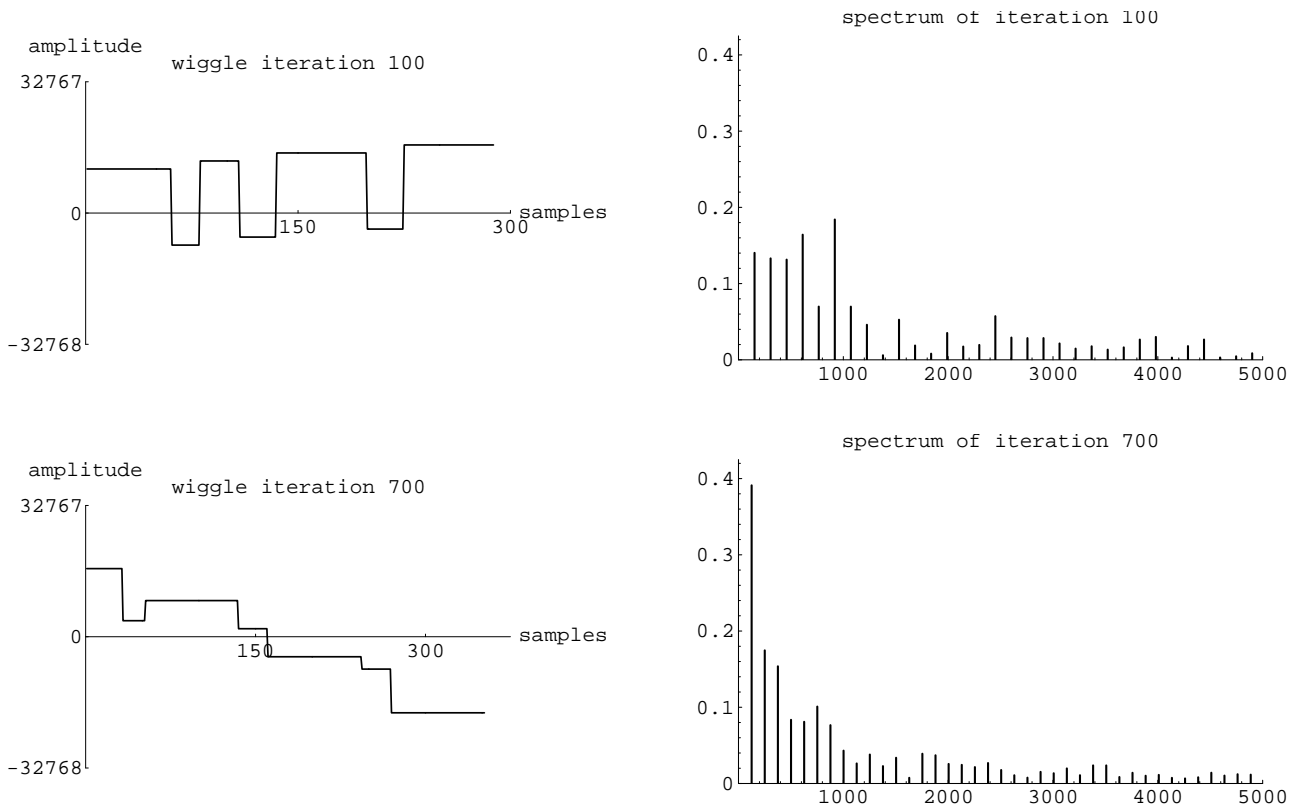
w3   wiggle
1    130   20   4.5
-10000 10000 -10000 40

w4   wiggle
1    100   20   4.5
10000 20000 -20000 50

w5   wiggle
1    130   20   4.5
-10000 10000 -10000 60

w6   wiggle
1    100   20   4.5
10000 20000 -20000 70
```

Graphs of this waveform at the 100th and the 700th iterations, followed by their respective harmonic spectra, are given below.



Here are the same segments, with the same variable magnitudes, but three of the seven segments are slanted. The data are followed by their waveforms, and the spectrum for each waveform. Note that the iteration number for each waveform below is the same as that of the

waveforms above.

```
#init max min rate
w0 wiggle # identifier, type
100 100 20 4.5 # (samples) initial, max, min, rate
10000 20000 -20000 10 # (amplitudes) initial, max, min, rate

w1 wiggle slanted
20 130 20 4.5
-10000 10000 -10000 20

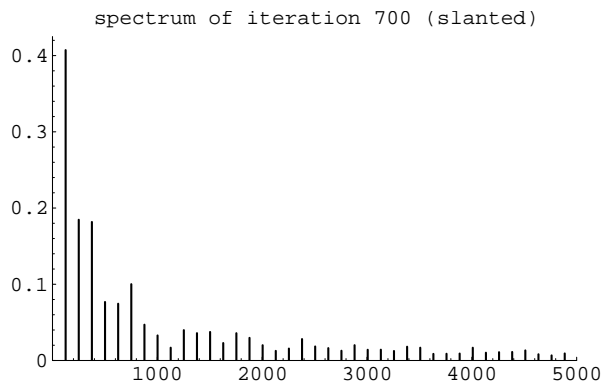
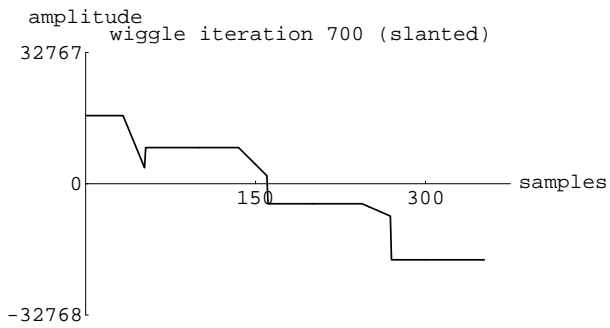
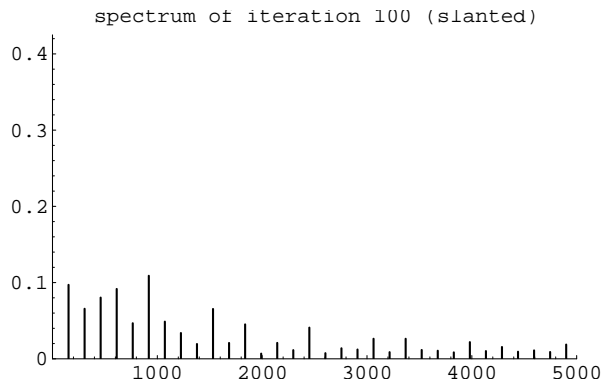
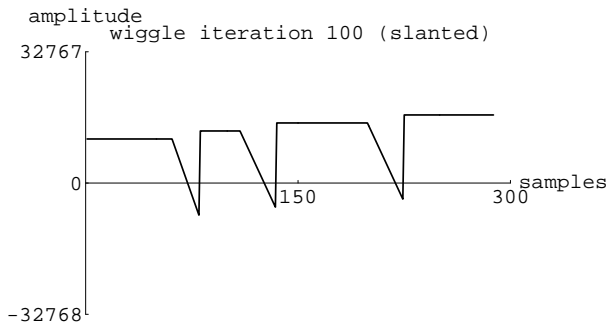
w2 wiggle
50 100 20 4.5
10000 20000 -20000 30

w3 wiggle slanted
1 130 20 4.5
-10000 10000 -10000 40

w4 wiggle
1 100 20 4.5
10000 20000 -20000 50

w5 wiggle slanted
1 130 20 4.5
-10000 10000 -10000 60

w6 wiggle
1 100 20 4.5
10000 20000 -20000 70
```



Segment type: *twiggle*

A *twiggle* is a triangular *wiggle*. The idea behind a *twiggle* was to have a “triangle” in which all three sides could be in flux. Thus, there are four variables:

1. the base height (amplitude)
2. the base width (number of samples)

3. the peak height (amplitude)

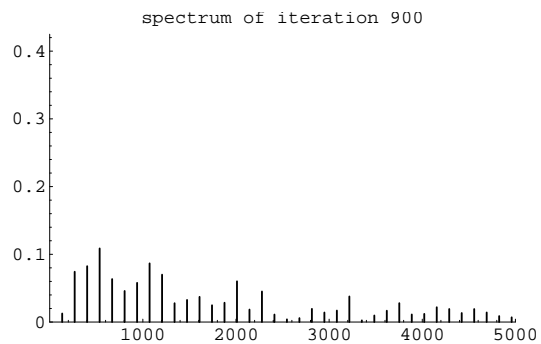
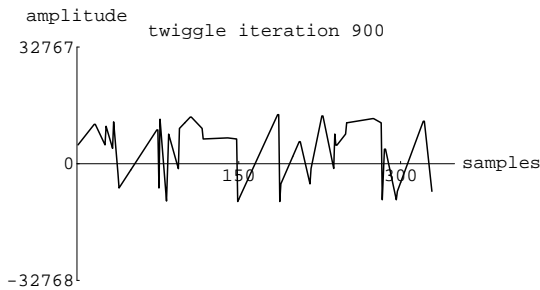
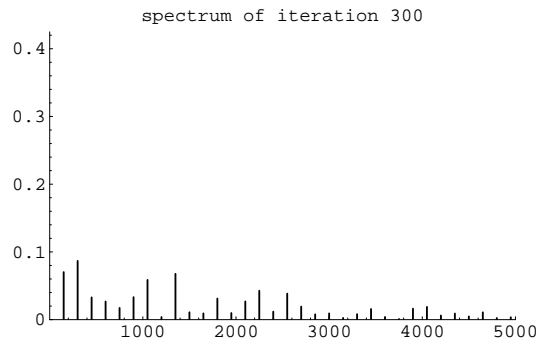
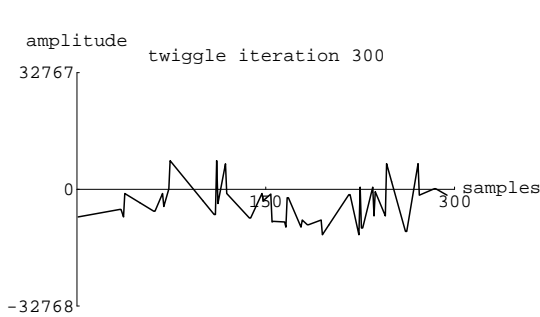
4. the peak location (between 0 and 1, the starting and ending samples of the base)

Below is a portion of the input file used to generate a *twiggle* with 15 segments. For the sake of brevity, only the data for the first and last segments are given. As the *wiggles* examples above, the columns from left to right are: initial value, maximum, minimum, and rate of change.

The number in the final column below (after the hash mark) is the *cycle length* of the variable, the number of iterations after which that variable returns to its starting magnitude.

```
#   init      max      min      rate      # cycles
t0  twiggle
    5         40       5        5.384615   #   13 (samples)
   -14000    14000   -14000   543.689331 #   103 (amplitude)
   -14000    14000   -14000   27.846842  #  2011 (peak height)
  0.000000  1.000000  0.000000  0.153846   #   13 (peak loc.)
.
.
t14 twiggle
   12        40       5        0.985915   #    71
  -7777     14000   -14000  312.849152 #   179
  -7777     14000   -14000  26.502603  #  2113
 0.222222  1.000000  0.000000  0.028169   #    71
```

Plots of the waveforms and their spectra are below.



Segment type: *ciggle*

A *ciggle* is a *twiggle* with curved sides. Whereas the *twiggle* connected the base of its triangle to the peak with straight lines, a *ciggle* connects the base to the peak with a curved line.

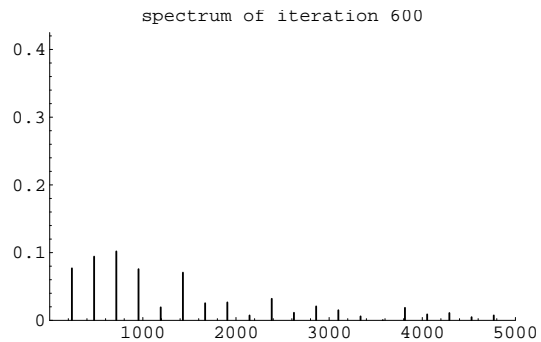
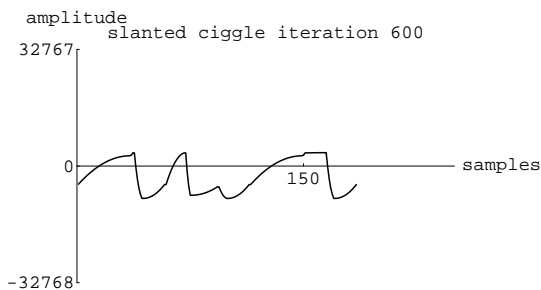
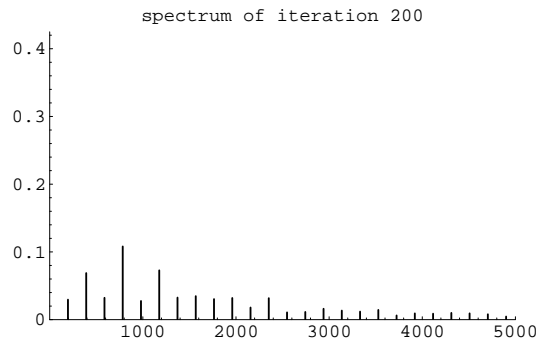
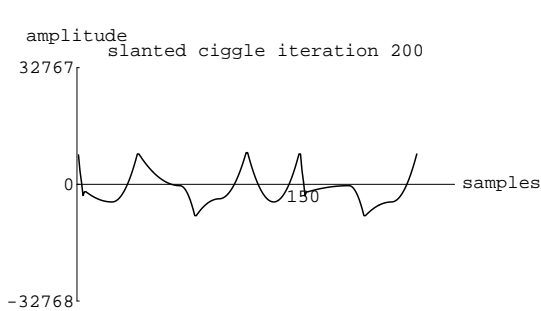
The general function used to calculate the curves was written by Jerry Keiper of Wolfram Research, Inc.:

$$y = y1 + (x - x1) \left(\frac{-y1 + y2}{-x1 + x2} + \frac{(x - x2) \left(\frac{y1 - y2}{-x1 + x2} + \frac{-y2 + y3}{-x2 + x3} \right)}{-x1 + x3} \right)$$

Below is the input file for a sequence of four *ciggles* in which all are slanted. The example data file is followed by plots of the waveform, and their spectra.

In this examples, four segments (c0—c3) are used to construct a waveform that has eight segments in the following sequence: c0 c1 c2 c3 c1 c0 c2 c1.

#	init	max	min	rate	# cycles
c0	twiggle	curved	slanted		
	21	40	5	-1.147541	# 61
	-666	14000	-14000	-53.897980	# 1039
	-3333	14000	-14000	10.356945	# 5407
	0.380952	1.000000	0.000000	0.004515	# 443
c1	twiggle	curved	slanted		
	22	40	5	1.186441	# 59
	-222	14000	-14000	54.211037	# 1033
	-2888	14000	-14000	-10.345465	# 5413
	0.396825	1.000000	0.000000	-0.004454	# 449
c2	twiggle	curved	slanted		
	22	40	5	-1.320755	# 53
	222	14000	-14000	-54.316196	# 1031
	-2444	14000	-14000	10.337825	# 5417
	0.412698	1.000000	0.000000	0.004376	# 457
c3	twiggle	curved	slanted		
	23	40	5	1.489362	# 47
	666	14000	-14000	54.848186	# 1021
	-2000	14000	-14000	-10.334010	# 5419
	0.428571	1.000000	0.000000	-0.004338	# 461



Acknowledgements

Herbert Brün and Keith Johnson taught me about SAWDUST, the principles of its algorithms, and its radical address to compositional premises.

I'd like to thank Wolfram Research, Inc., for their contributions of time and support on their computers and equipment.

Jerry Keiper and Robert Naiman, both of Wolfram Research, Inc., generously contributed their skills in mathematics and numerical analysis, and patiently answered the many questions I had on implementation.

The functions for plotting the FFTs were written by Theodore Gray of Wolfram Research.

I prototyped the synthesis algorithms for *wigout* using *Mathematica V2.1*, then rewrote them in C for speed. The graphics in this article were made with *Mathematica V2.1*. *wigout* currently runs on a NeXT 68040 workstation.

References

- Ashby, W. Ross.** *An Introduction to Cybernetics*. London: Methuen and Company, Ltd., 1956.
- von Foerster, Heinz, editor.** *Cybernetics of Cybernetics*. Urbana, Illinois: Biological Computer Laboratory, Report Number 73.38, University of Illinois, 1974.
- von Foerster, Heinz.** *Observing Systems*. Seaside, California: Intersystems Publications, 1984.
- Gray, Theodore W. and Glynn, Jerry.** *Exploring Mathematics with Mathematica*. Redwood City, CA: Addison-Wesley Publishing Company, 1991.
- Roads, Curtis, editor.** *Composers and the Computer*. Los Altos, California: William Kaufmann, Inc., 1985.
- Shannon, C.E., and Weaver, W.** *The Mathematical Theory of Communication*. Urbana, Illinois: University of Illinois Press, 1949.
- Wiener, Norbert.** *Cybernetics*. Cambridge, Massachusetts: MIT Press, 1950.
- Wiener, Norbert.** *The Human Use of Human Beings*. Garden City, New York: Doubleday, 1954.