Audio Synthesis methods

Digital Signal Processing with Computer Music

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Tuesday 16th November 2021

Outline

General perspective

- Overview of audio synthesis
    - relate to DSP concepts and techniques

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    - relate to DSP concepts and techniques
- Audio production must relate to perception
    - how do we hear?
    - psychology of music (discuss with Dr Spiro)
- Building blocks of today's sonic/music programming environments
    - (discuss with Dr Aaron)

Why building blocks?

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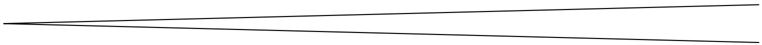
- Why synthesise audio at all?
    - (just take the Fourier Transform of what we want and call it a day)
- Why consider audio in terms of frequency?
    - (the eardrum responds to changes in pressure, that's all)

The inner ear

Basilar membrane cross-section

- not to scale
- unrolled



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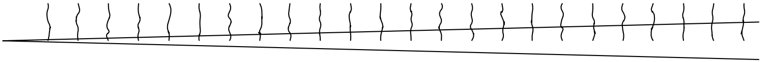

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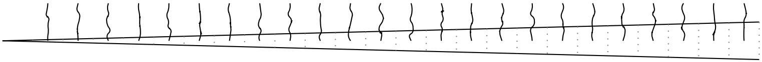
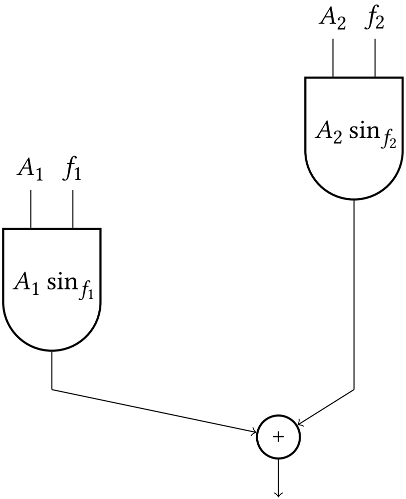
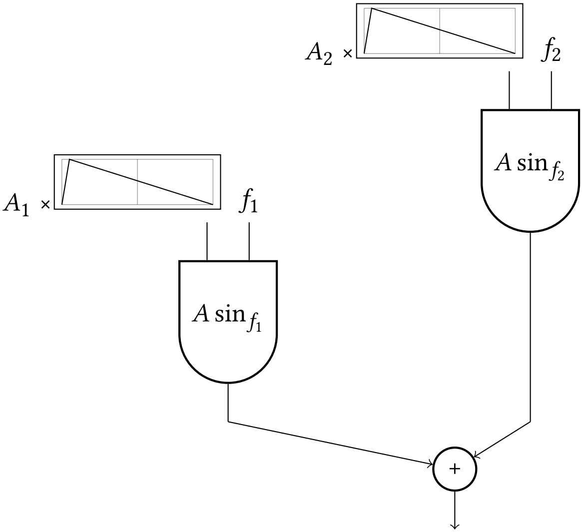


First try



Second try



Efficiency

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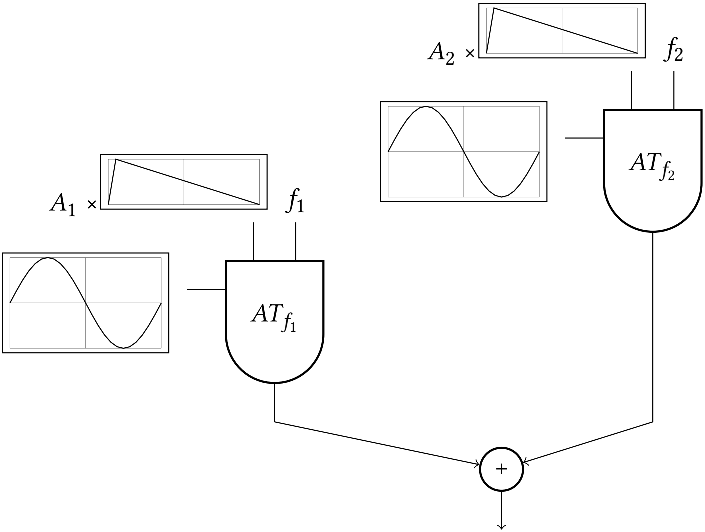
How long does it take to compute $\sin(x)$?

- (it depends)
- around 60 cycles for x in [0,1]
- around 180 for x in [0,1000]
- 2.5M-7.5M cycles for 44100 sin computations
  - ”only” at most 1000 different oscillators, even on high-end laptops
  - (and very few indeed on old computers)

Efficiency: wavetables



Wavetables

- recover a factor of 10 or so by using table-lookup
- reuse tables for common functions (e.g. $\sin(x)$)
- SNR depends on interpolation strategy:
    - truncation (no interpolation): SNR 48dB
    - linear: 109dB

Origin of unit generator

Max Mathews and Joan Miller, Music III (1960)

- *Bicycle Built for Two*

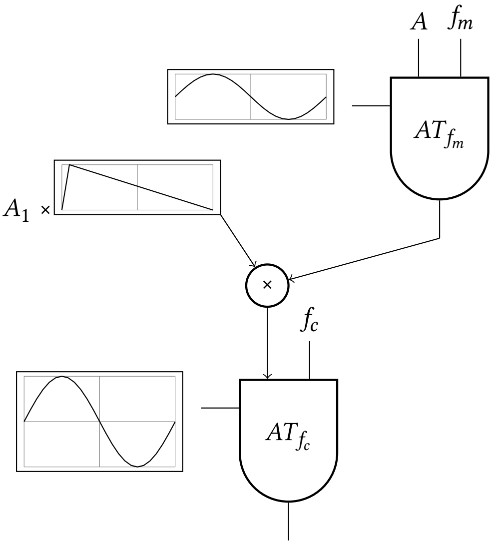
A unit generator is

> *[...] a small block of computer instructions performing a given operation such as that of an oscillator, an adder or a random noise generator [...]*

(Mathews and Miller, 1964)

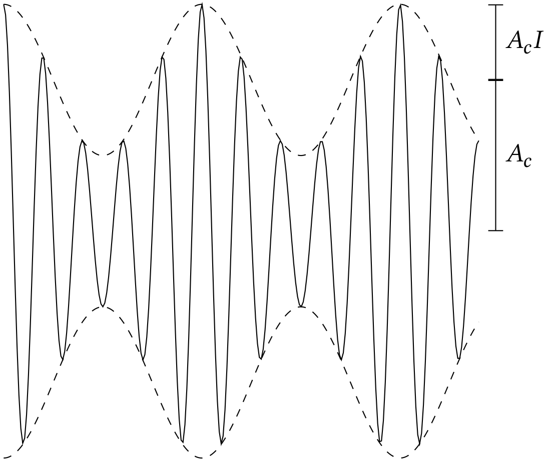
- Combine unit generators into *patches* (or *instruments*)

Example: amplitude modulation



Amplitude modulation

$$S(t) = A_c \cos(2\pi f_c t) \times [1 + I \cos(2\pi f_m t)]$$



Amplitude modulation

Index of modulation I: "how much modulation"

$$\cos(A)\cos(B) = \frac{1}{2}\left[\cos(A+B) + \cos(A-B)\right]$$

$$S(t) = A_c \cos\left(2\pi f_c t\right) + \frac{A_c I}{2}\left[\cos(2\pi(f_c + f_m)t) + \cos(2\pi(f_c - f_m)t)\right]$$

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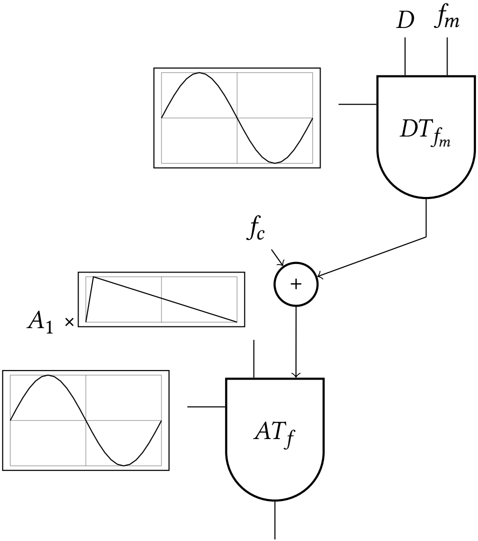
- position of sideband frequencies = $f_c \pm f_m$
- number of non-zero sideband pairs = 2
- relative amplitude of each sideband = $\frac{I}{2}$
- bandwidth = $2 f_m$

Example: frequency modulation



after Chowning (1973)

Frequency modulation

$$S(t) = A \sin\left(2\pi \int^{t} f(\tau) \mathrm{d}\tau\right)$$

$$f(t) = f_c + D \sin(2\pi f_m t)$$

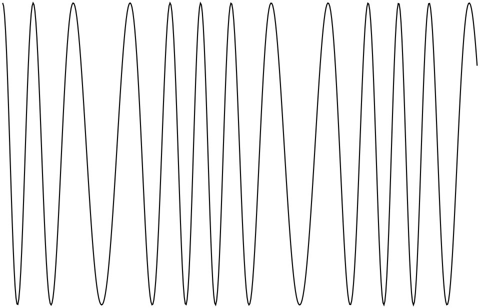
$$S(t) = A \sin\left(2\pi \int^{t} f(\tau) \mathrm{d}\tau\right)$$

$$S(t) = A \sin\left(2\pi f_c t + \frac{D}{2\pi f_m} \sin(2\pi f_m t)\right)$$

Frequency modulation

Write $D = 2\pi I f_m$

$$S(t) = A \sin\left(2\pi f_c t + I \sin\left(2\pi f_m t\right)\right)$$

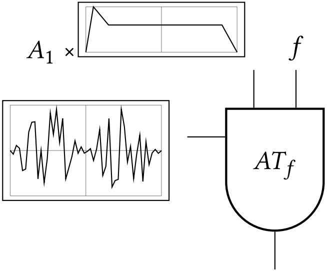


Frequency modulation

$$S(t) = A \sin(2\pi f_c t + I \sin(2\pi f_m t))$$

- position of sideband frequencies = $f_c \pm k f_m$
- number of non-zero sideband pairs ~ $(I + 1)$
- relative amplitude of each sideband ~ $J_k(I)$
- bandwidth ~ $2(D + f_m) = 2 f_m (I + 1)$

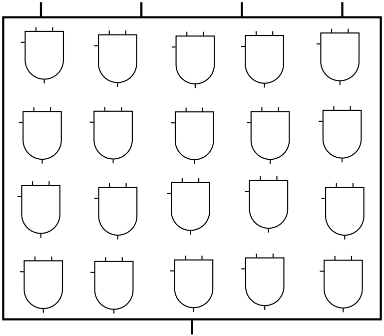
Example: sampled instruments



Sampled instruments

- record target sound
- identify steady-state sample
- use envelope to generate transients
    - e.g. ADSR: Attack, Decay, Sustain, Release
    - (arbitrary envelopes are available)

Example: granular synthesis



Waveguide

A waveguide is

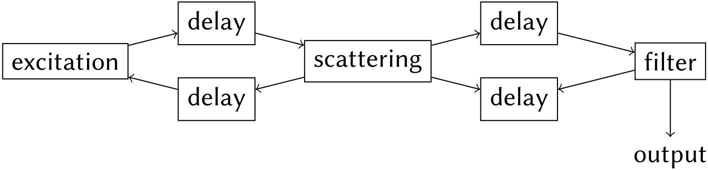
a computational model of medium along which waves travel

("Digital Synthesis Waveguide"; cf. waveguides used in transmission engineering)

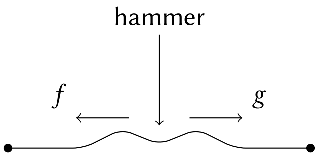
$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2}$$

$$y(x,t) = f(x+ct) + g(x-ct)$$

Waveguide


excitation
delay
delay
scattering
delay
delay
filter
output

Example: Karplus-Strong



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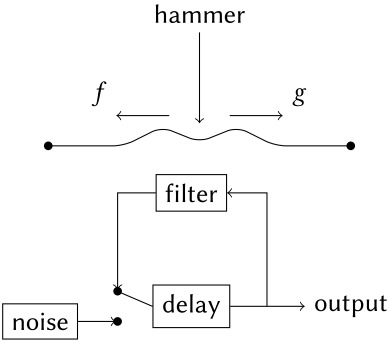
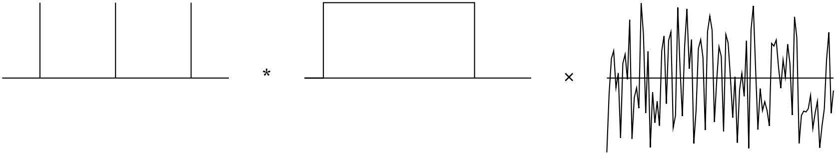


- typical filter: two-sample average

Karplus-Strong

- Why does Karplus-Strong even sound pitched?



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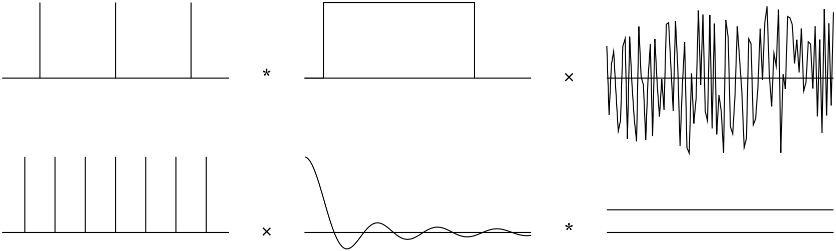

Karplus-Strong

- why initialize buffer with white noise?
- how to decouple period from decay time?
- (more interesting sounds using the same setup?)

Waveguides and unit generators

Can be made compatible:

- switch (noise vs feedback) based on zero-crossing of trigger signal;
- delay modifiable (up to some maximum);
- parameterise filters;

Include physical modelling (including impossible instruments) in unit generator paradigm

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- historical:
  - how to get “rich” sounds cheaply?
  - how to mimic/simulate/model physical processes?
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  - how to mimic/simulate/model physical processes?
  - how to explore possible sound worlds?
- musical:
  - how can we use digital signals to produce music?
  - why do we find some sounds pleasing?
  - who is "we" anyway? (and what is "computer music"?)

Further Reading

- Hermann Helmholtz (tr. Ellis), *On the sensations of tone*, Longmans (1885)
- James Jeans, *Science & music*, Cambridge (1937)
- Max Mathews and Joan Miller, *Music IV programmer's manual*, Bell Labs (1964)
- John Chowning, *The Synthesis of Complex Audio Spectra by means of Frequency Modulation*, JAES 21:7 (1973)
- John R. Pierce, *The science of musical sound*, Scientific American (1983)
- Curtis Roads, *The computer music tutorial*, MIT (1996)
- Scott Wilson, David Cottle and Nick Collins (eds.), *The SuperCollider Book*, MIT (2011)
- Ray Wilson, *Make: Analog Synthesizers*, O'Reilly (2013)