2018 Fall
CTP431: Music and Audio Computing

Sound Synthesis (Part 1)

Graduate School of Culture Technology, KAIST
Juhan Nam

Outlines

- Signal model (analog / digital) – Part 1
  - Additive Synthesis
  - Subtractive Synthesis
  - Modulation Synthesis
  - Distortion Synthesis

- Sample model (digital) – Part 2
  - Sampling Synthesis
  - Granular Synthesis
  - Concatenative Synthesis

- Physical model (digital) – Part 2
  - Digital Waveguide Model

Signal Model

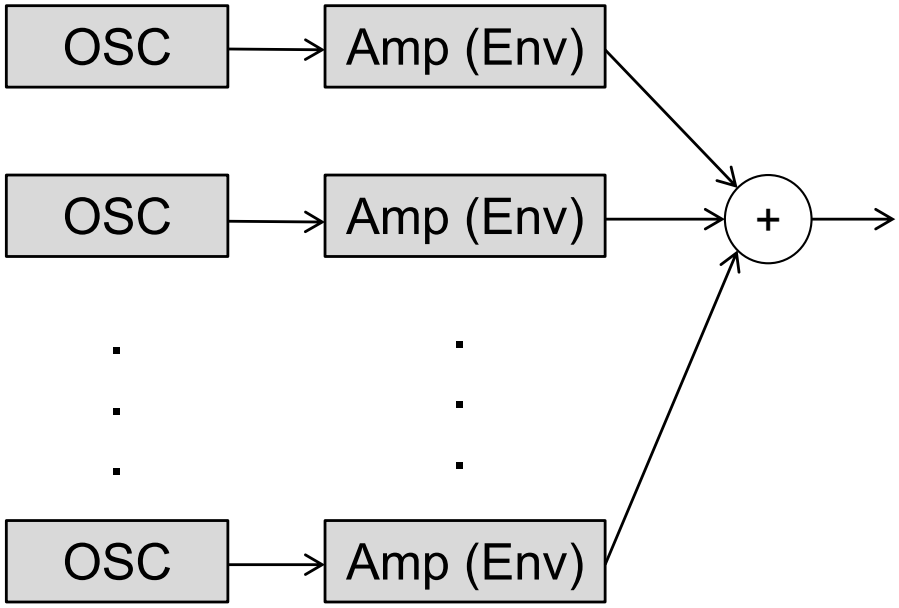
- Modeling the patterns of musical tones using elementary waveforms
  - Time domain: ADSR
  - Frequency domain: spectrum

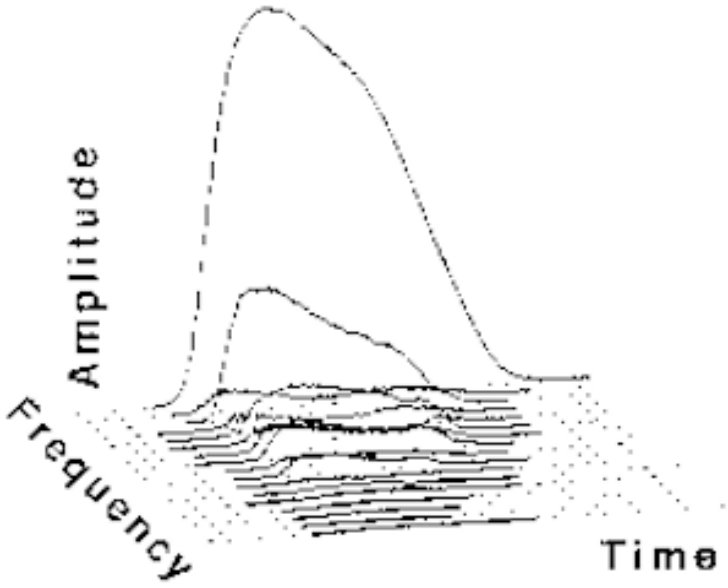
- Types of signal models
  - Additive synthesis: a set of sine waveforms
  - Subtractive synthesis: sawtooth, square waveforms + filters
  - Frequency modulation synthesis: a pair of sine waveforms
  - Distortion synthesis: sine waveforms + nonlinear units

- These techniques date back to the analog age

Additive Synthesis

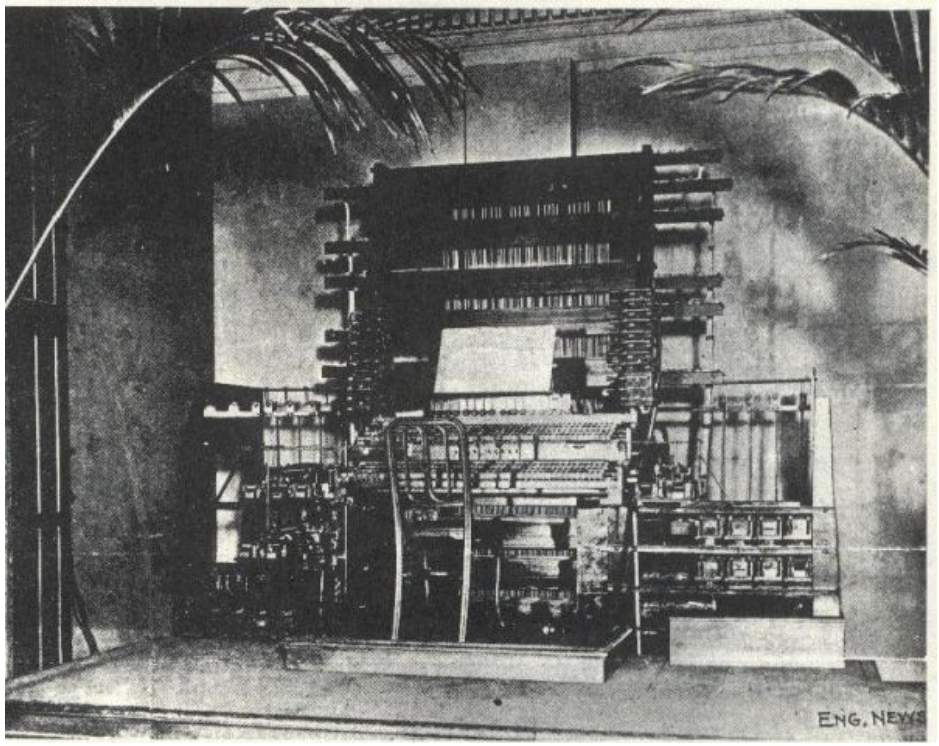
- Synthesize sounds by adding multiple sine oscillators
  - Also called Fourier synthesis

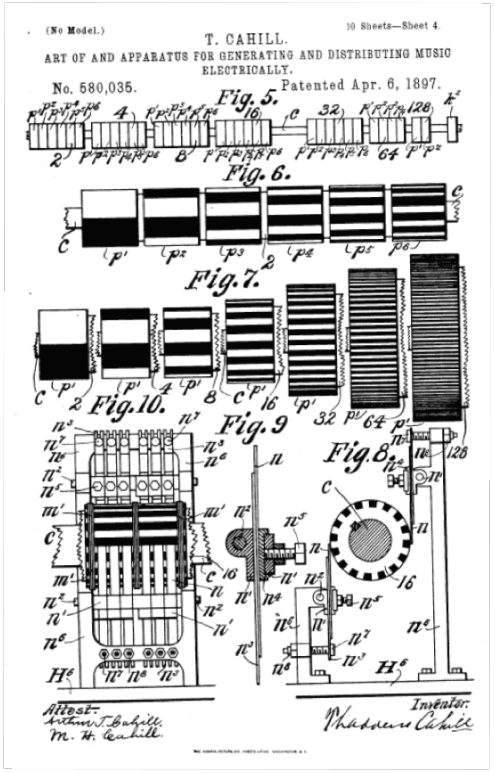




Telharmonium

- Additive synthesizer using electro-magnetic “tone wheels” (Cahill, 1897)
  - Transmitted through telephone lines
  - Subscription only but the the business failed

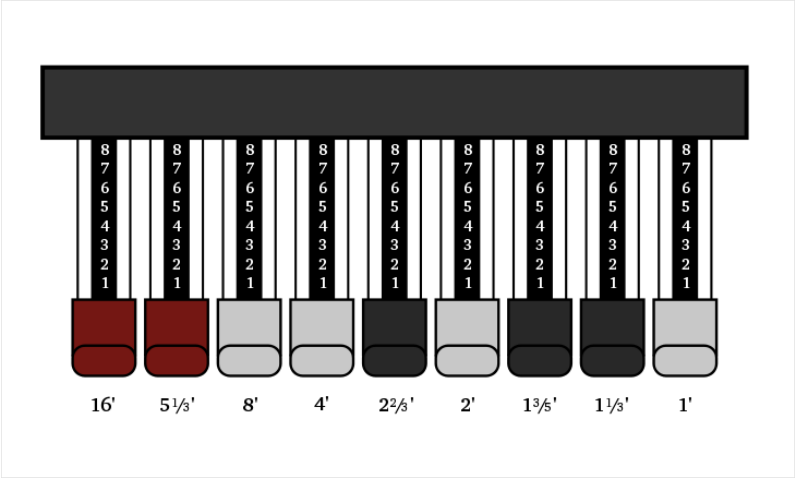




Tone wheel

Hammond Organ

- Drawbars
  - Control the levels of individual tonewheels



Theremin

- A sinusoidal tone generator
  - Two antennas are remotely controlled to adjust pitch and volume

Theremin
(by Léon Theremin, 1928)

Theremin (Clara Rockmore)

https://www.youtube.com/watch?v=pSzTPGlNa5U

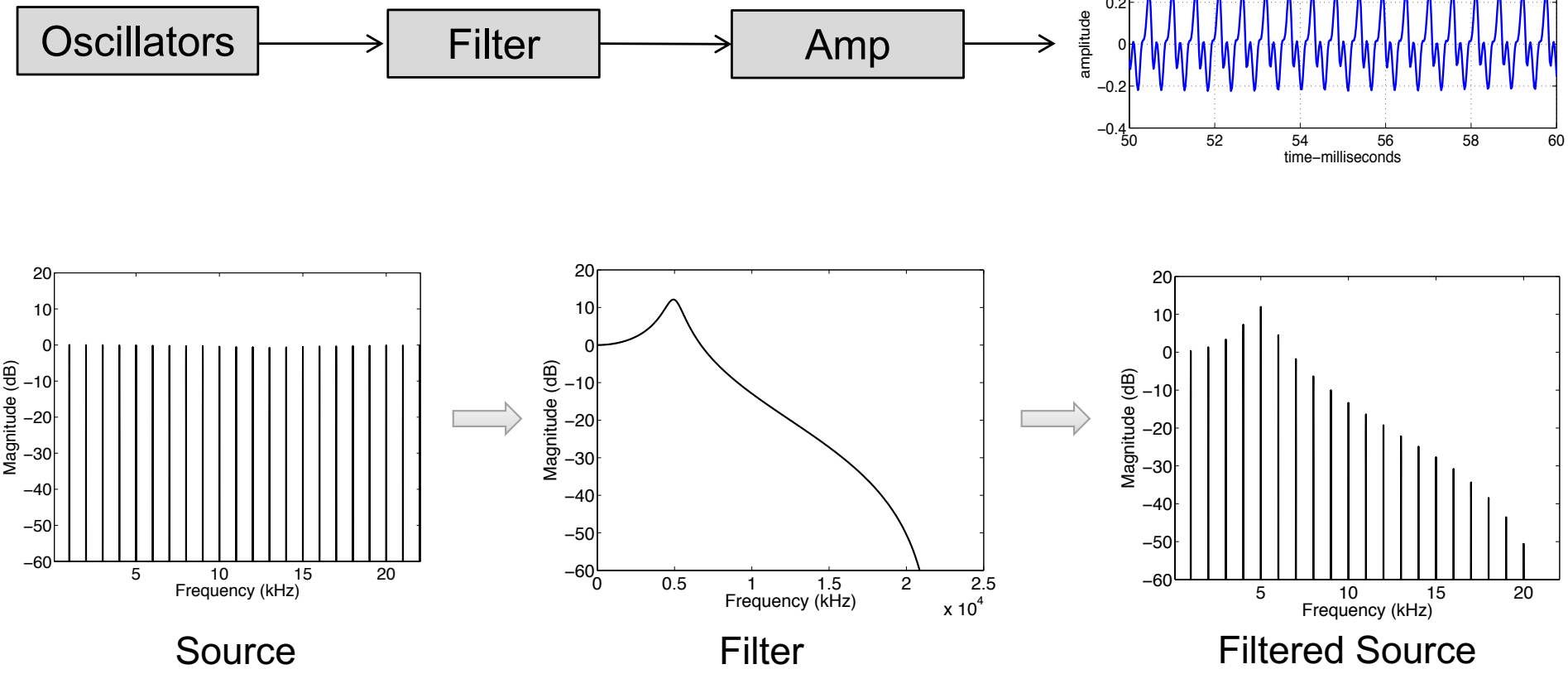
Sound Examples

- Web Audio Demo
  - http://femurdesign.com/theremin/
  - http://www.venlabsla.com/x/additive/additive.html
  - http://codepen.io/anon/pen/jPGJMK

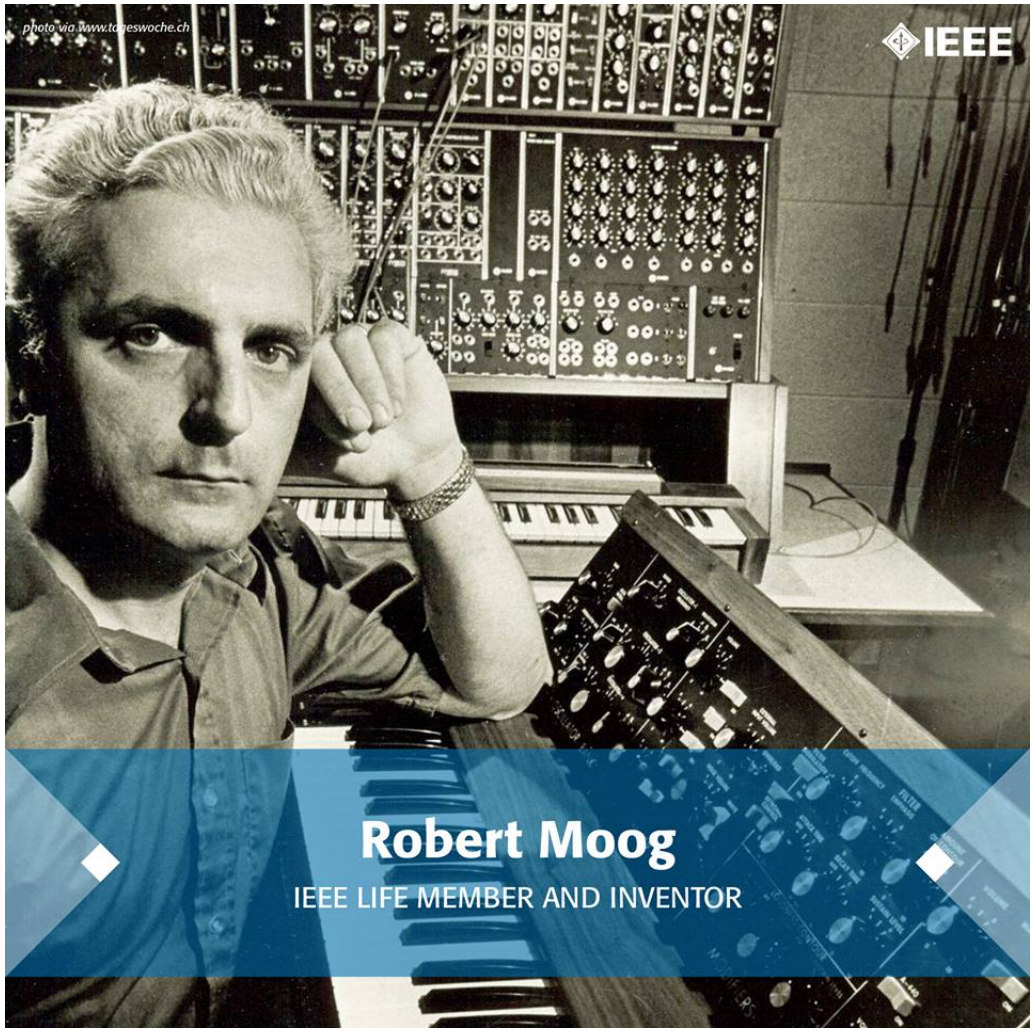
- Examples (instruments)
  - Kurzweil K150
    - https://soundcloud.com/rosst/sets/kurzweil-k150-fs-additive
  - Kawai K5, K5000

Subtractive Synthesis

- Synthesize sounds by filtering wide-band oscillators
  - Source-Filter model



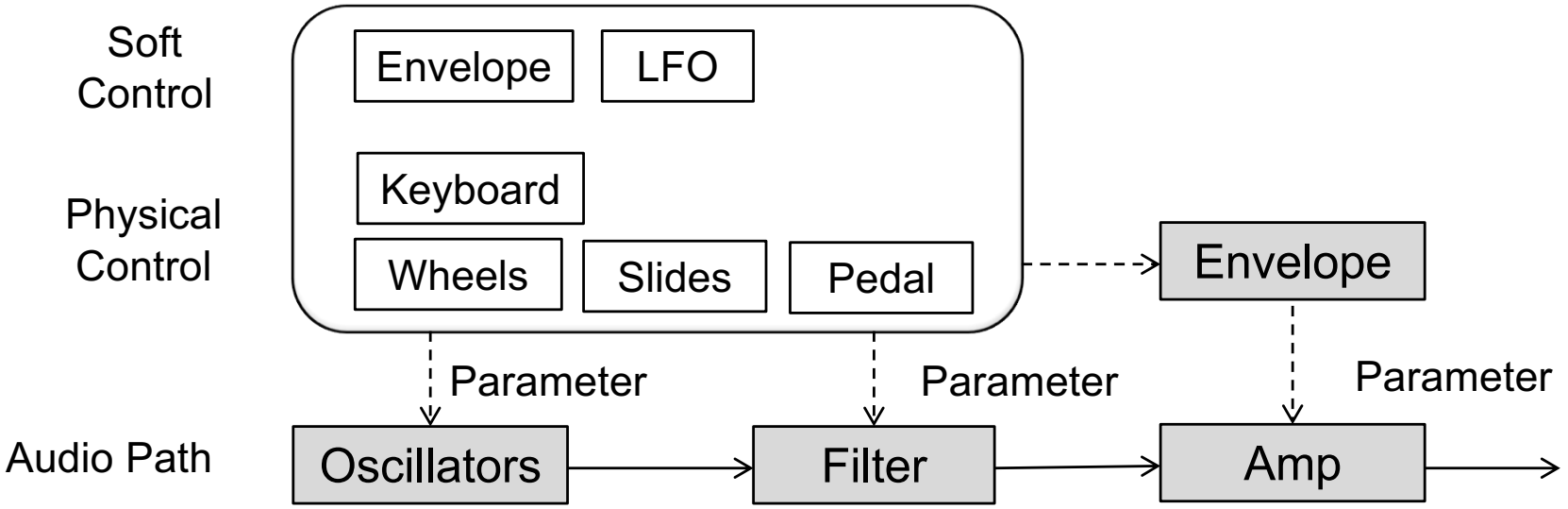
Moog Synthesizers



MiniMoog (1970)

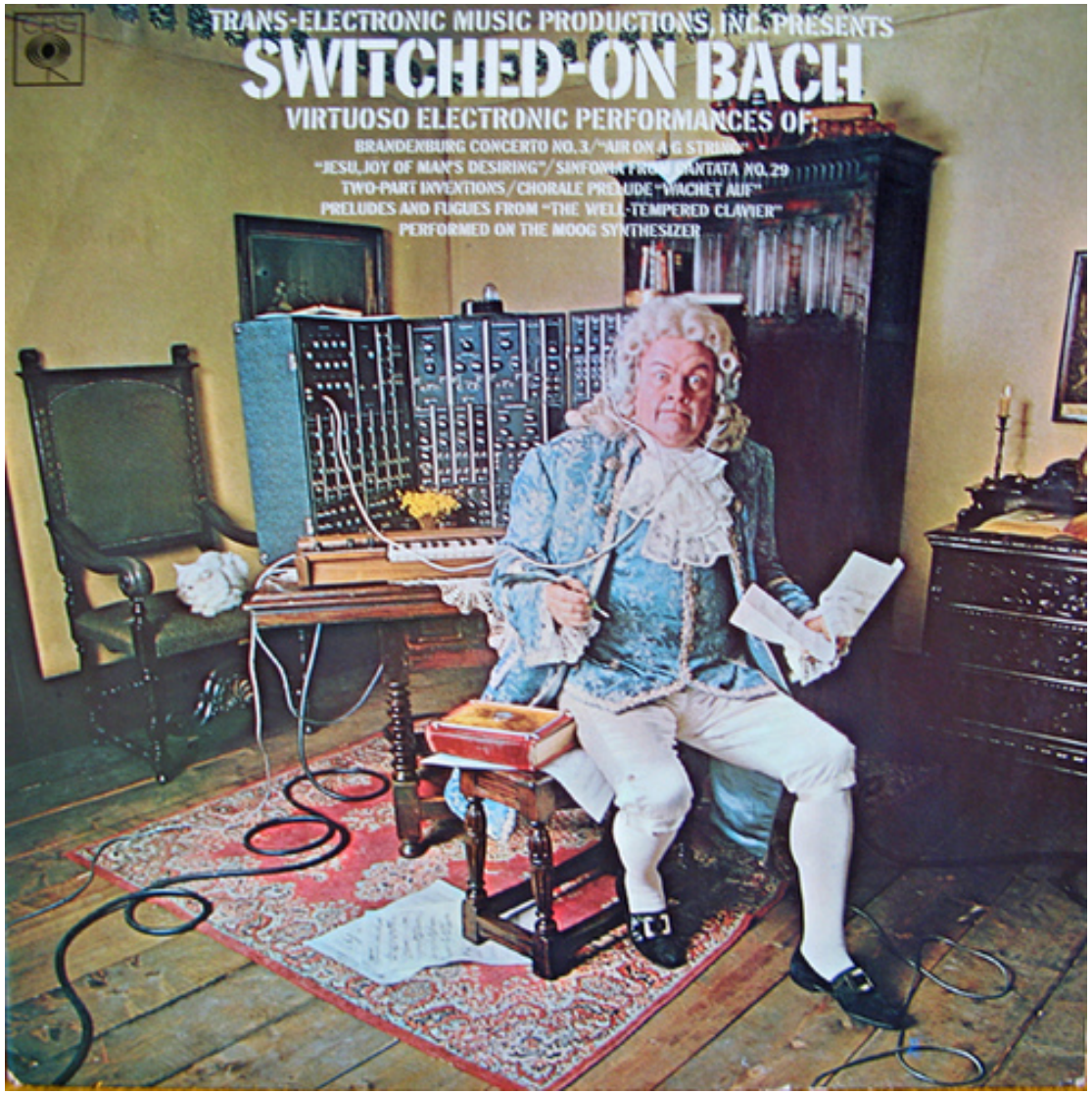
Moog Synthesizers

- Architecture



$$\text{Parameter} = \underbrace{\text{offset}}_{\text{(static value)}} + \underbrace{\text{depth*control}}_{\text{(dynamic value)}}$$

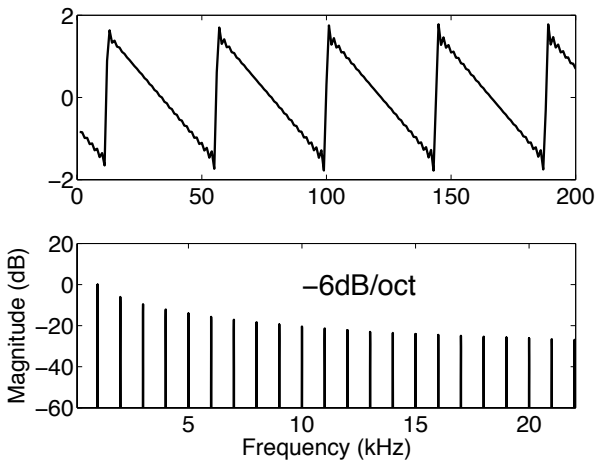
(e.g. filter cut-off frequency)



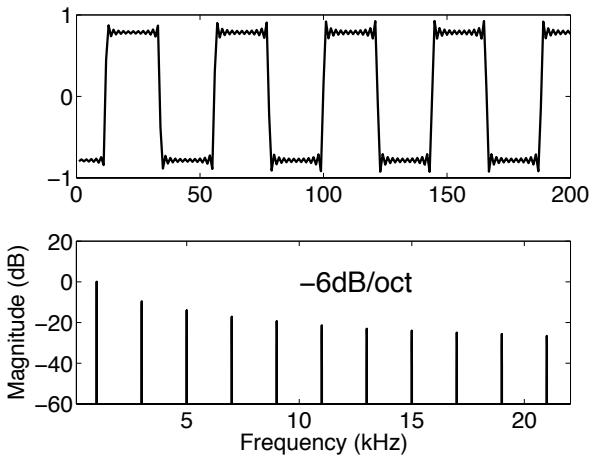
"Switched-On-Bach" by Wendy Carlos (1968)

Oscillators

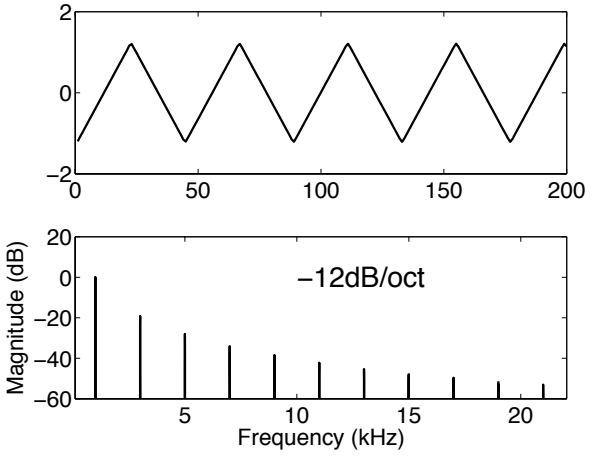
- Classic waveforms



Sawtooth



Square

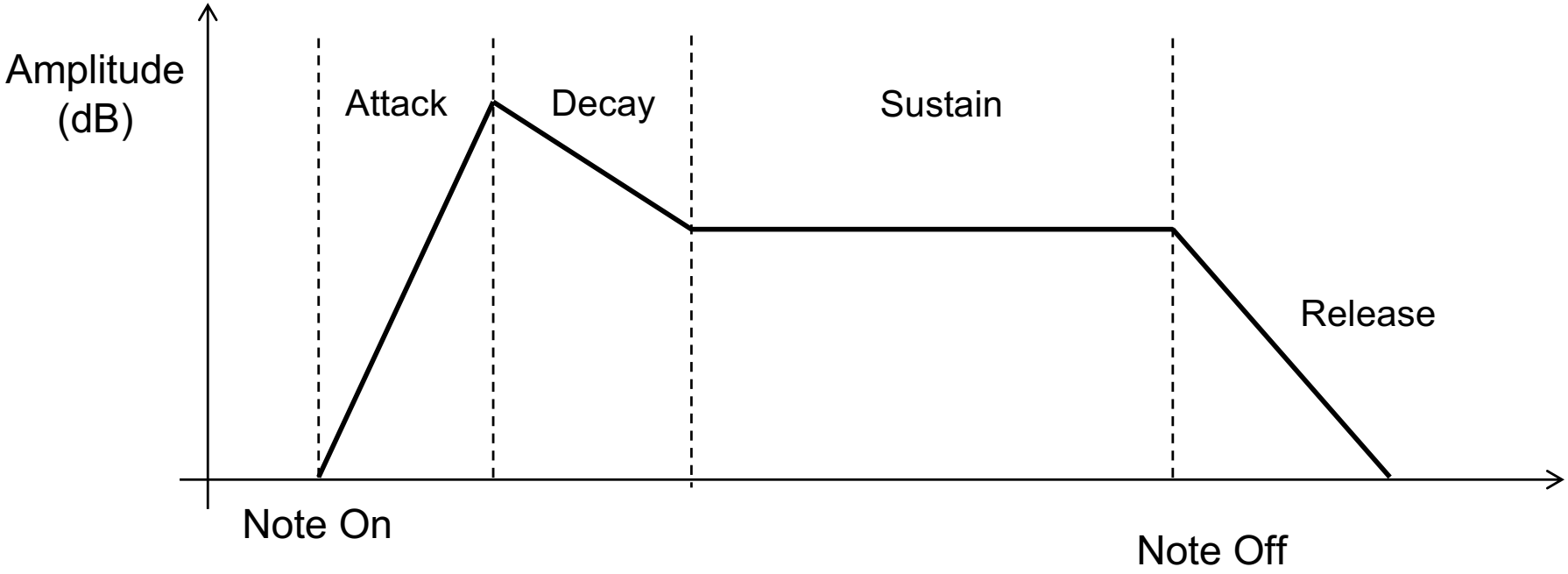


Triangular

- Modulation
  - Pulse width modulation
  - Hard-sync
  - More rich harmonics

Amp Envelop Generator

- Amplitude envelope generation
  - ADSR curve: attack, decay, sustain and release
  - Each state has a pair of time and target level



Examples

- Web Audio Demos
  - http://www.google.com/doodles/robert-moogs-78th-birthday
  - http://webaudiodemos.appspot.com/midi-synth/index.html
  - http://aikelab.net/websynth/
  - http://nicroto.github.io/viktor/

- Example Sounds
  - SuperSaw
  - Leads
  - Pad
  - MoogBass
  - 8-Bit sounds: https://www.youtube.com/watch?v=tf0-Rrm9dI0
  - TR-808: https://www.youtube.com/watch?v=YeZZk2czG1c

Modulation Synthesis

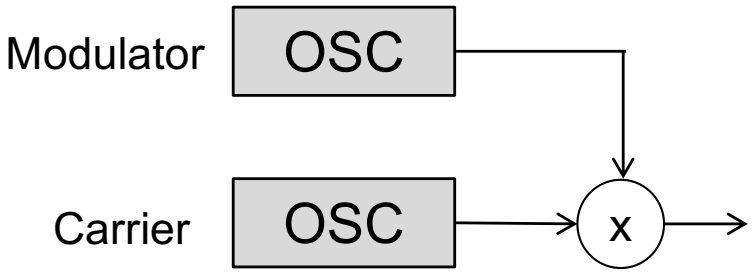
- Modulation is originally from communication theory
  - Carrier: channel signal, e.g., radio or TV channel
  - Modulator: information signal, e.g., voice, video

- Types of modulation synthesis
  - Amplitude modulation (or ring modulation)
  - Frequency modulation

- Decreasing the frequency of carrier to hearing range can be used to synthesize sound
  - Generate new sinusoidal components
  - Modulation is non-linear processing

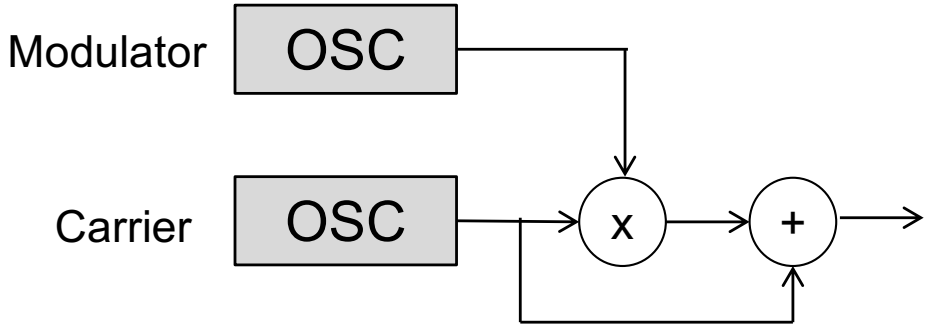
Ring Modulation / Amplitude Modulation

- Change the amplitude of one source with another source
  - Slow change: tremolo
  - Fast change: generate a new tone



$$a_m(t)A_c\cos(2\pi f_c t)$$

Ring Modulation

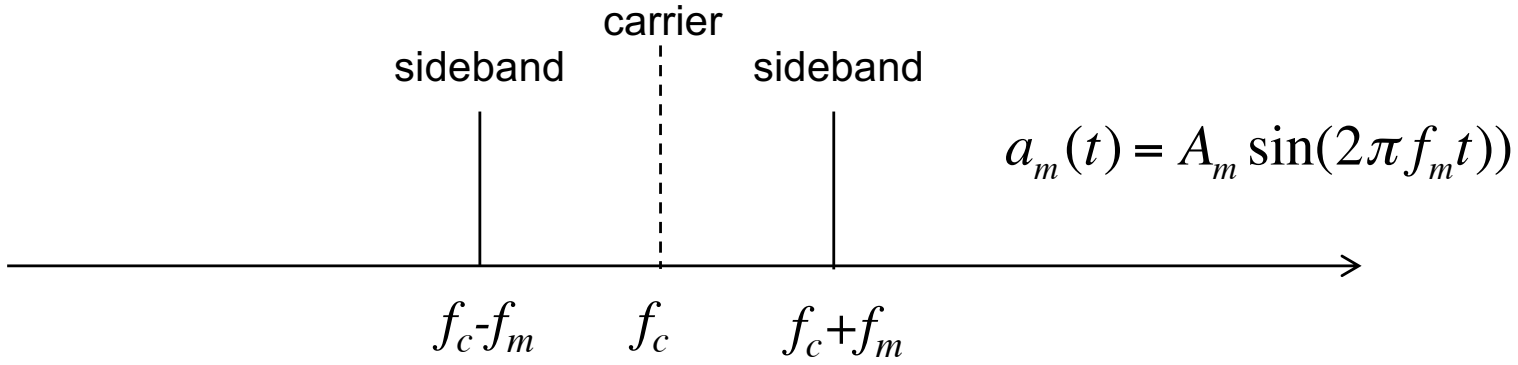


$$(1+a_m(t))A_c\cos(2\pi f_c t)$$

Amplitude Modulation

Ring Modulation / Amplitude Modulation

- Frequency domain
  - Expressed in terms of its sideband frequencies
  - The sum and difference of the two frequencies are obtained according to trigonometric identity
  - If the modulator is a non-sinusoidal tone, a mirrored-spectrum with regard to the carrier frequency is obtained



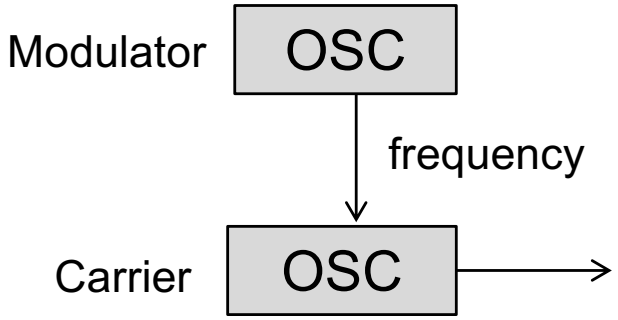
Examples

- Tone generation
  - SawtoothOsc x SineOsc
  - https://www.youtube.com/watch?v=yw7_WQmrzuk

- Ring modulation is often used as an audio effect
  - http://webaudio.prototyping.bbc.co.uk/ring-modulator/

Frequency Modulation

- Change the frequency of one source with another source
  - Slow change: vibrato
  - Fast change: generate a new (and rich) tone
  - Invented by John Chowning in 1973 → Yamaha DX7



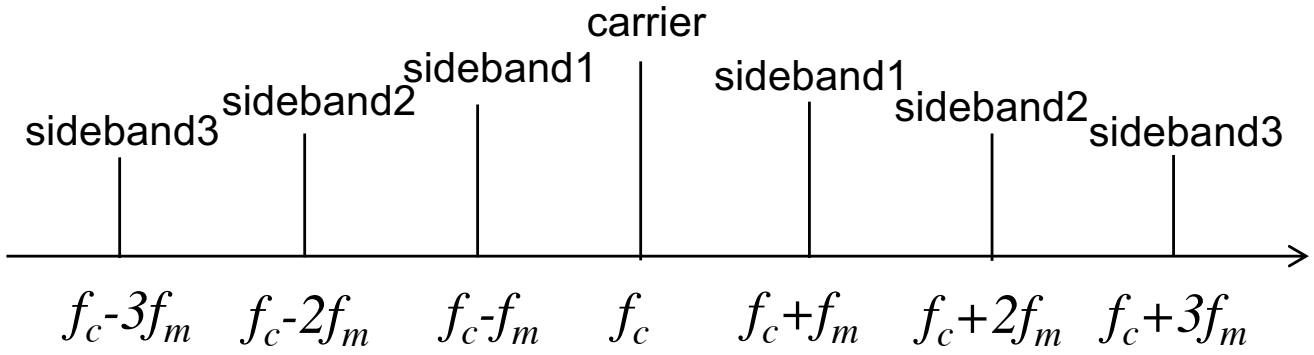
$$A_c \cos(2\pi f_c t + \beta \sin(2\pi f_m t))$$

$$\beta = \frac{A_m}{f_m}$$ Index of modulation

Frequency Modulation

- Frequency Domain
  - Expressed in terms of its sideband frequencies
  - Their amplitudes are determined by the Bessel function
  - The sidebands below 0 Hz or above the Nyquist frequency are folded

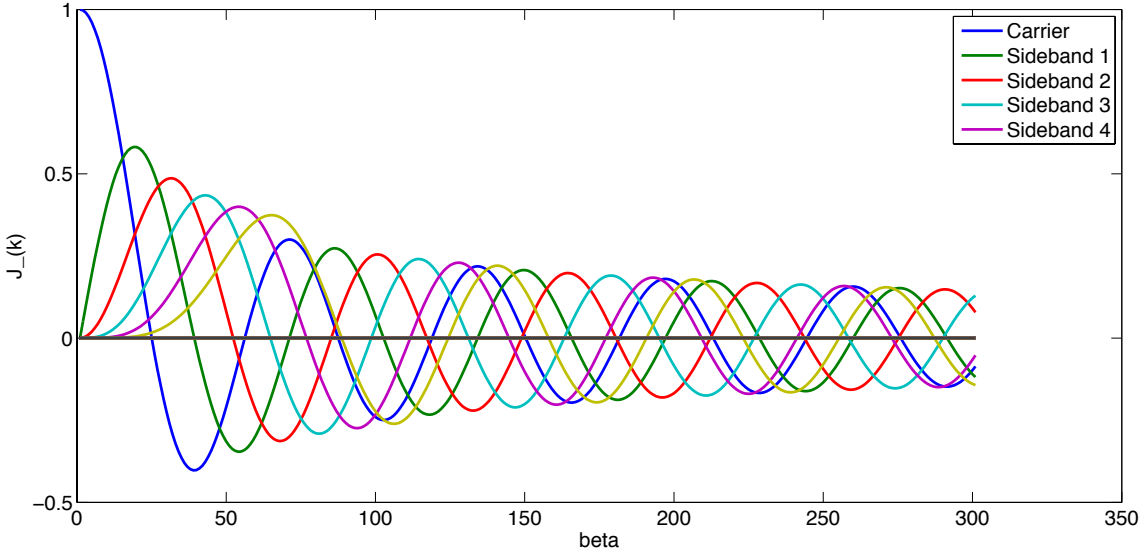
$$y(t) = A_c \sum_{k=-\infty}^{k=-\infty} J_k(\beta)\cos(2\pi(f_c + kf_m)t)$$



Frequency Modulation

- Bessel Function

$$J_k(\beta) = \sum_{n=0}^{\infty} \frac{(-1)^n (\frac{\beta}{2})^{k+2n}}{n!(n+k)!}$$



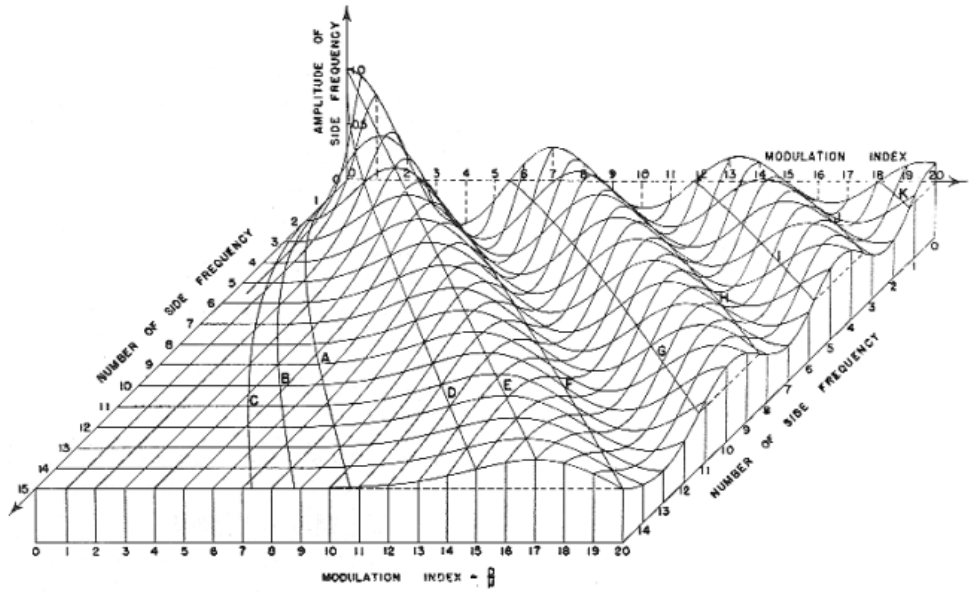
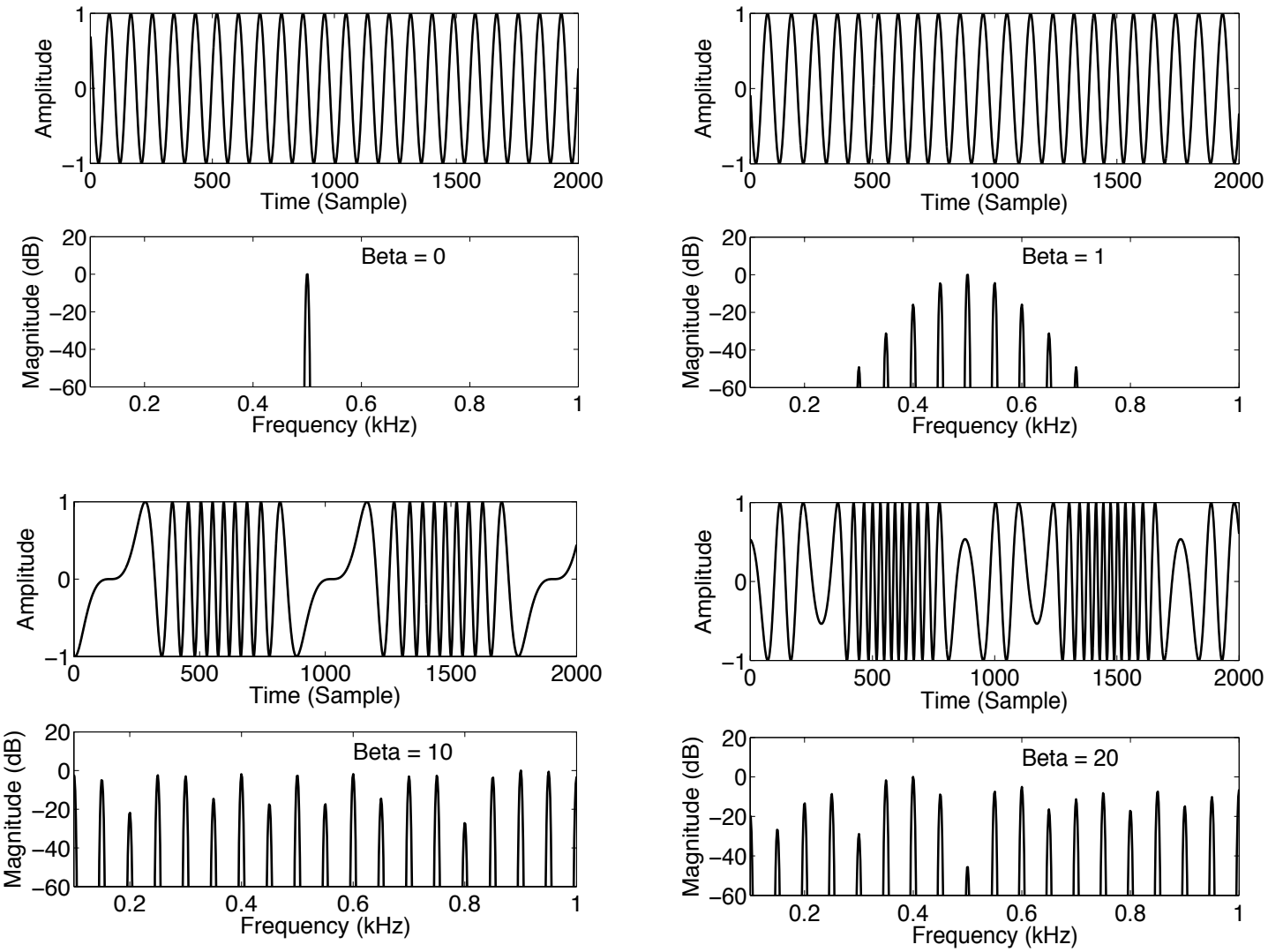


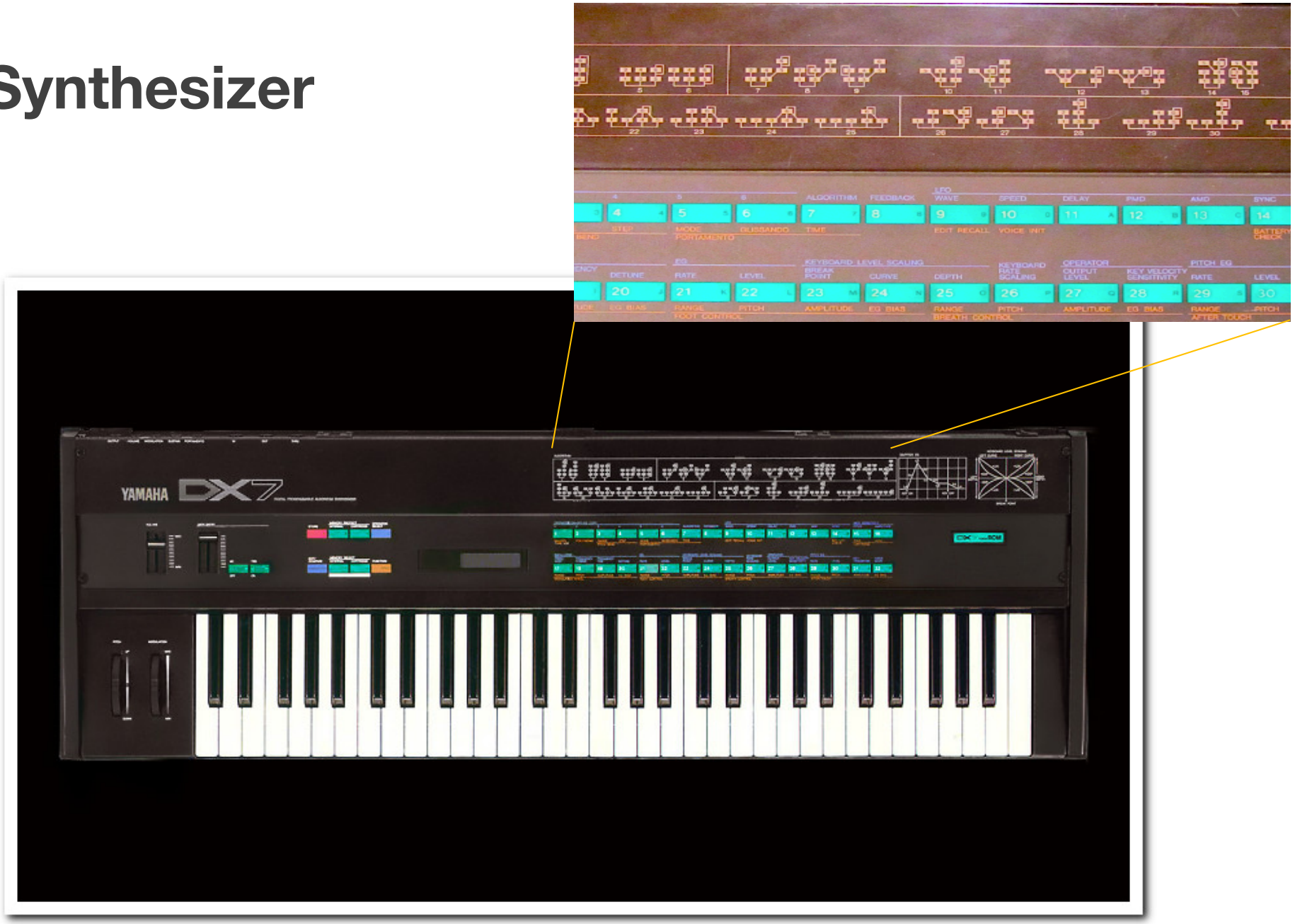
Fig. 4—Side-frequency amplitudes.

The Effect of Modulation Index



$$f_c = 500, \quad f_m = 50$$

FM Synthesizer



Yamaha DX7 (1983)

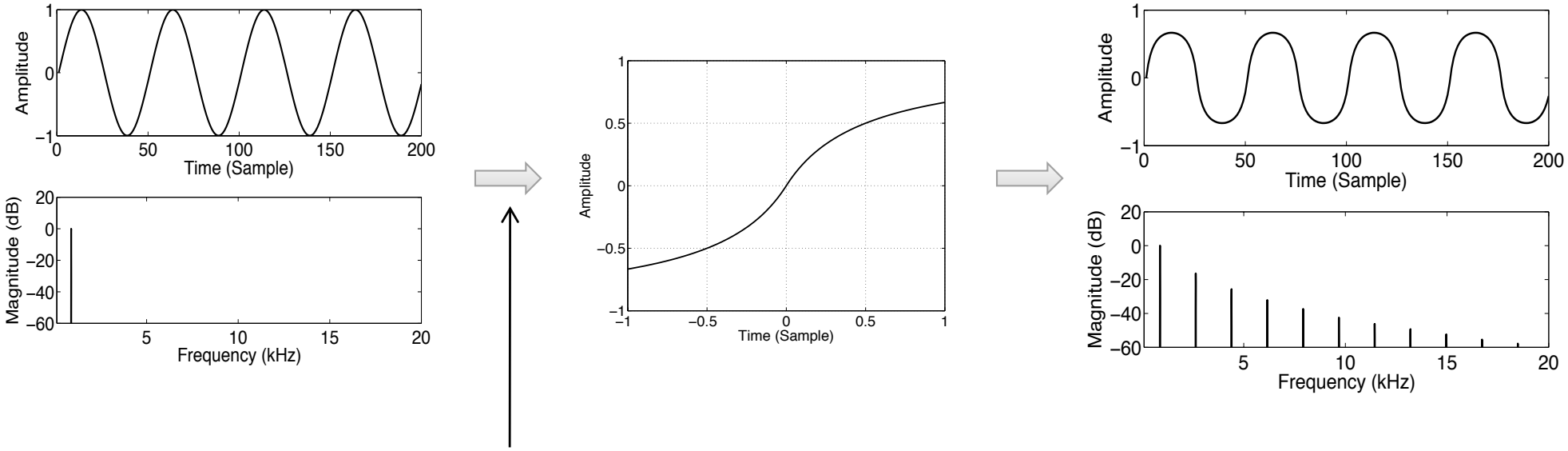
Examples

- Web Audio Demo
  - http://www.taktech.org/takm/WebFMSynth/

- Sound Examples
  - Bell
  - Wood
  - Brass
  - Electric Piano
  - Vibraphone

Non-linear Synthesis (wave-shaping)

- Generate a rich sound spectrum by distorting sine waveforms using non-linear transfer functions
- Also called “distortion synthesis”



x’=gx: g correspond to the “gain” of the distortion

Distortion Transfer Function

- Examples of transfer function: y = f(x)
  - $y = 1.5x' - 0.5x'^3$
  - $y = x'/(1+|x'|)$
  - $y = \sin(x')$
  - Chebyshev polynomial: $T_{k+1}(x) = 2xT_k(x)-T_{k-1}(x)$

$T_0(x)=1$, $T_1(x)=x$,
$T_2(x)=2x^2-1$, $T_2(x)=4x^3-3x$