Today's agenda

General background

- describing, controlling, expressing

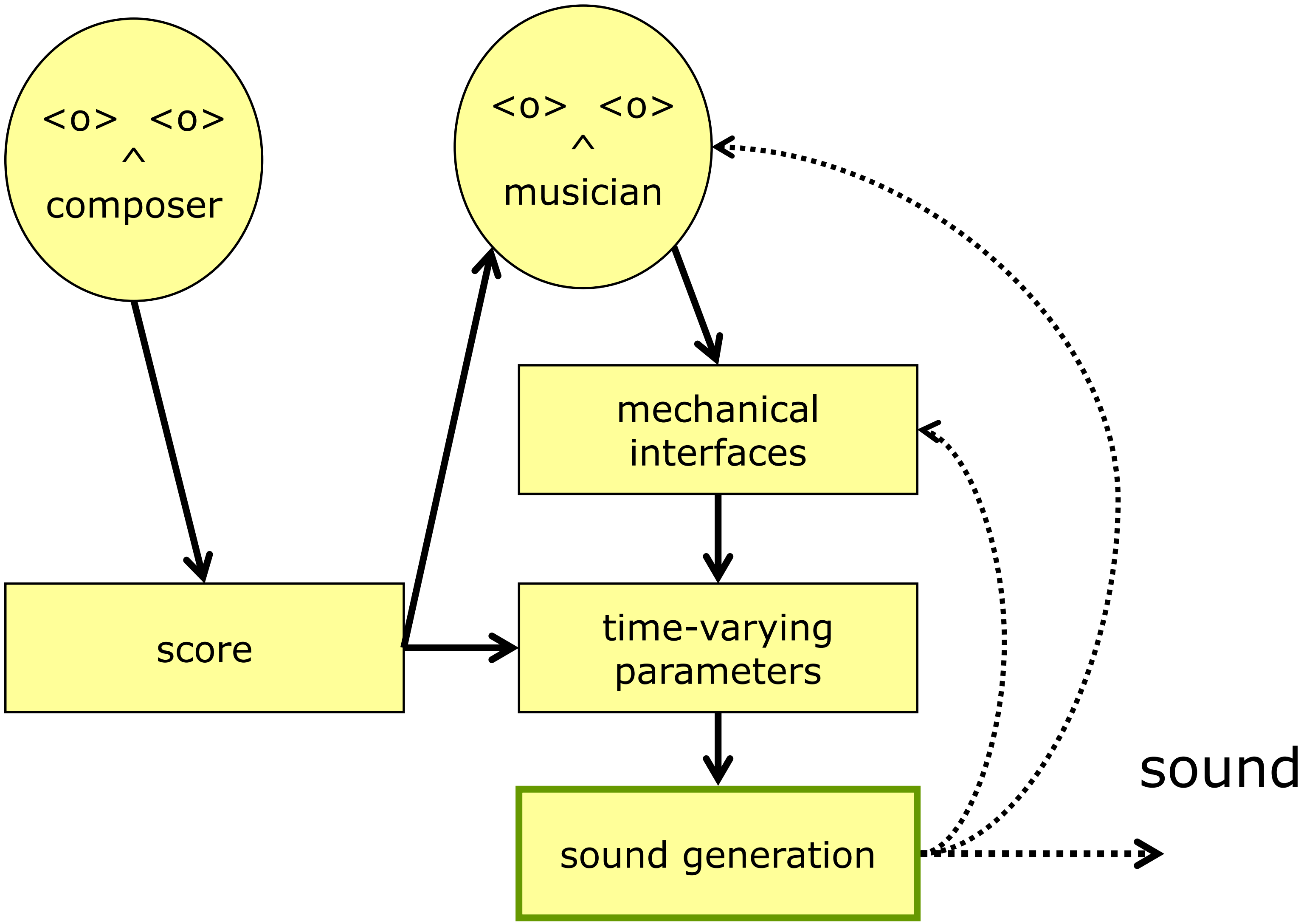
Goals of music synthesis

- novelty or fidelity? the roles of instruments

Synthesis methods

sampling, additive, subtractive, wave-shaping, granular, FM, physical models, waveguides

Making musical sounds with algorithms



Goals of synthesis in music

novelty
– sounds hitherto unheard (electroacoustic avant-garde)

fidelity
– modeled on existing acoustical instruments

expressiveness
– how many degrees of freedom in the sound?

liveliness
– does the tone remain interesting when it is sustained?

1. What should be the sound?

How does one describe an unheard sound?

How are sounds described by our auditory system?

Pressure signal in real time

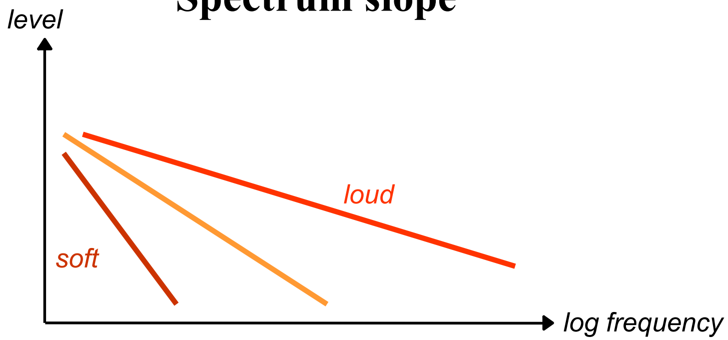
Power spectrum in real time

Power spectrum on log frequency scale

Timbre and spectrum

Gross generalisations can help characterize the **spectrum envelope** of the sound with regard to slope, centroid position and shape. This applies both to tones and to aperiodic sounds.

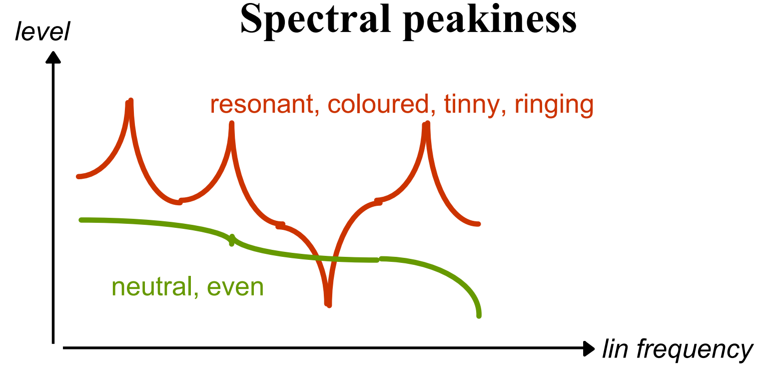
Spectrum slope



Determines the **strength** or **effort** in the sound.

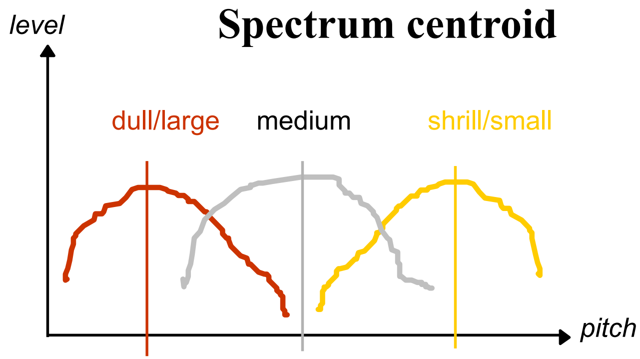
Originates in oscillator non-linearities.

Spectral peakiness



How many and how sharp are the resonances?

Spectrum centroid

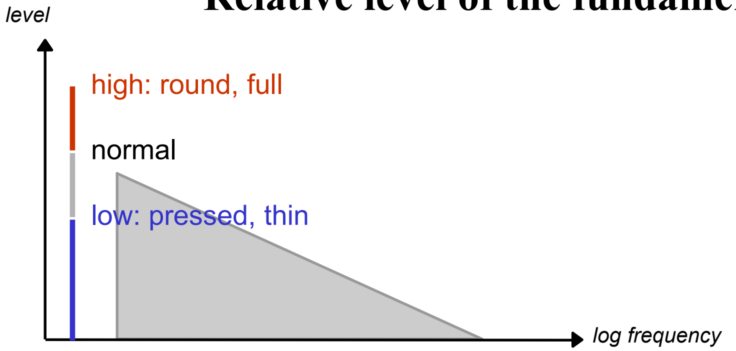


Suggests the **size** of the sound source

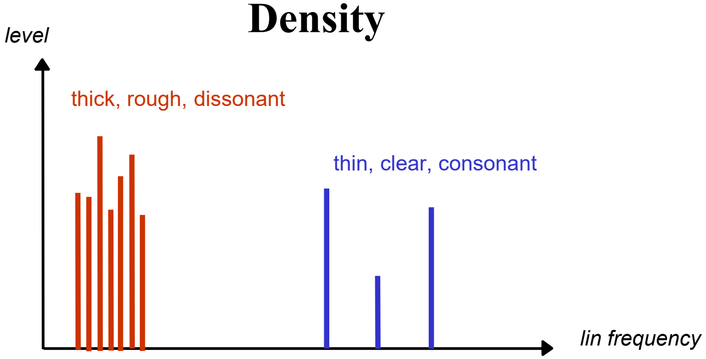
Timbre and partial tone structure

Some general aspects of the **partial tone structure** are also descriptive of most sounds that have pitch.

Relative level of the fundamental

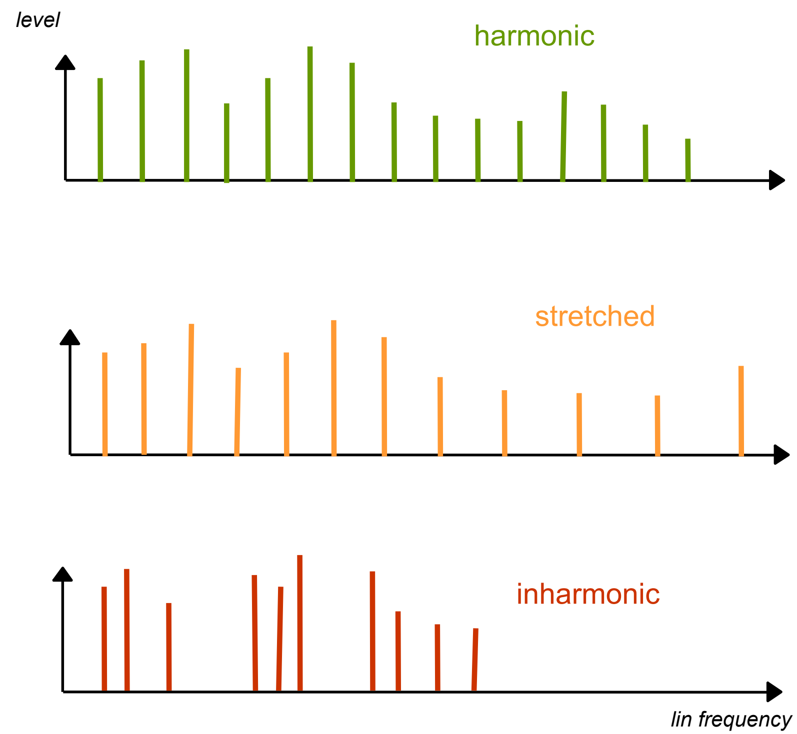


Density



How many partial tones per critical band?

Harmonicity

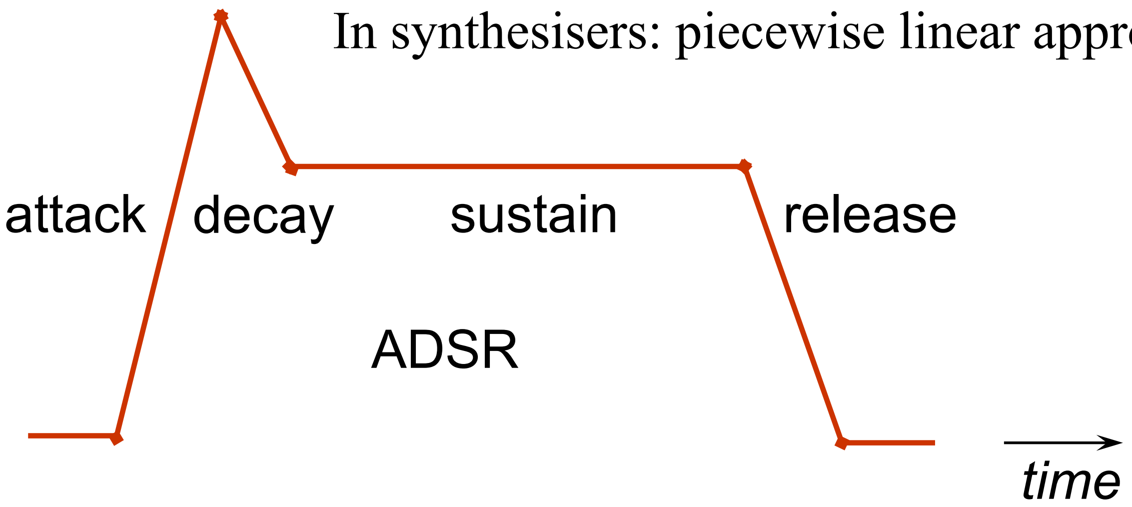


Temporal envelopes

All things change, in time.

Show

In synthesisers: piecewise linear approximations



If it moves, you'll notice it.

New events catch your attention.

Repeated events lose in interest.

ENTROPY?

A tone with an appropriate amount of variation is more resistant to perceptual suppression.

Two kinds of useful variability

non-linear dynamics,
chaos theory

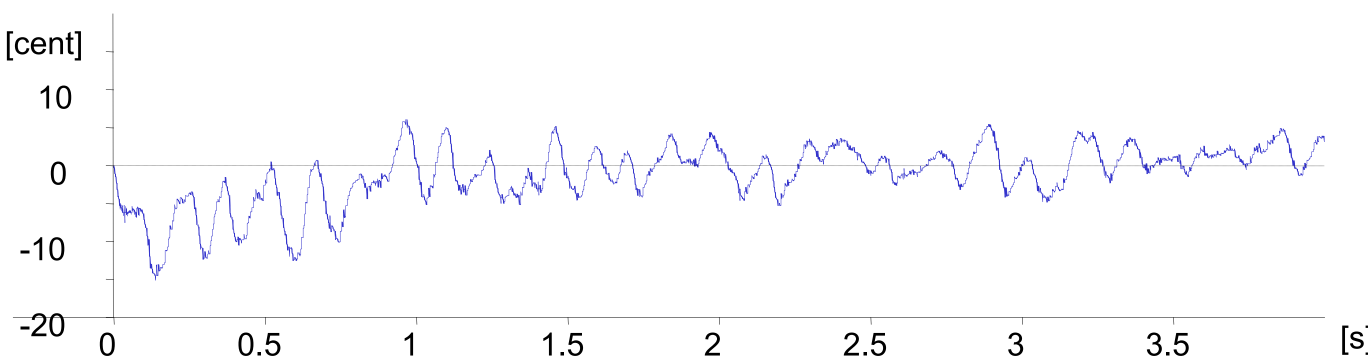
Inherent noise or pseudo-noise

Is the oscillator’s **attractor** stable, yet moving?

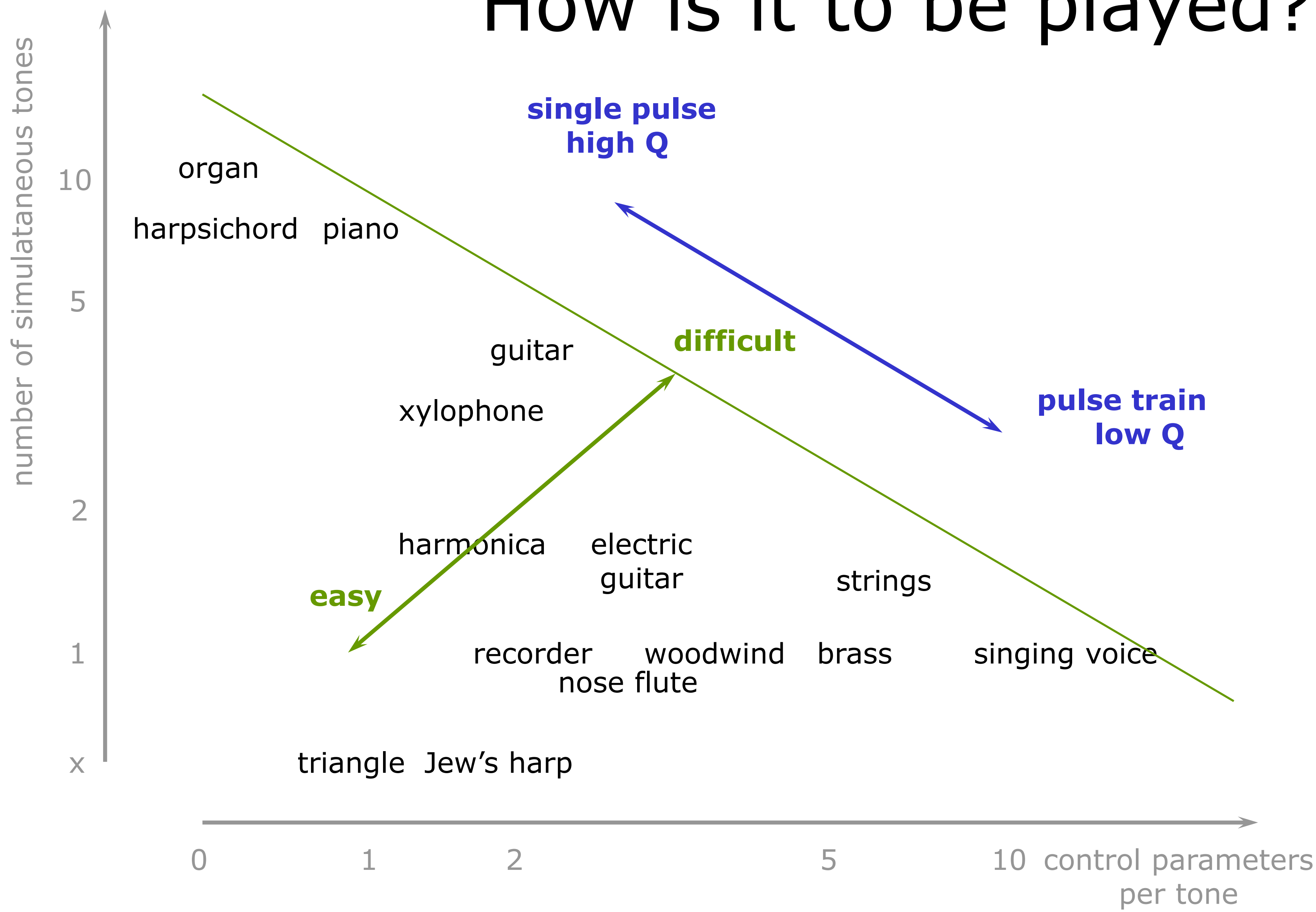
control theory

Fluctuations in the **control circuit** player instrument

Tolerances, time constants, feedback



How is it to be played?



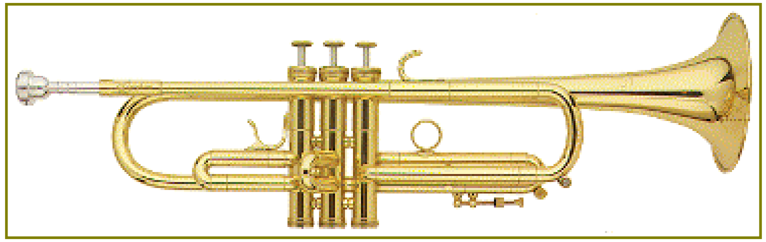
How is it to be played? (continued)

The more parameters that *can* be controlled,
the greater the powers of expression.

The more parameters that *must* be controlled,
the harder the instrument will be to play.

The connection between the control gestures
and the perceived sound is a complex chain
of causes and effects.

Degrees of Freedom

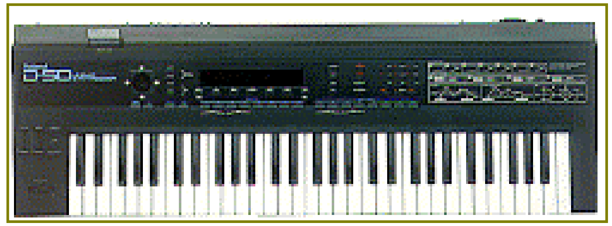


Control - what the player can do	**Internal state** - what happens inside the instrument	**Sound** - what it sounds like
mute	output impedance	open - closed
		loudness
air pressure	amplitude	
lip tension	flow derivative	breathy - pressed
	fundamental, noise	
lip mass	tone number	full - thin
tube length	tone series	pitch

support

embouchure

Degrees of Freedom



Control - what the player can do	**Internal state** - what happens inside the instrument	**Sound** - what it sounds like
key number		pitch
pitch wheel		loudness
key velocity		vibrato depth
modulation wheel		sustain
sustain pedal		many more
key pressure		
patch change	change setup	a different instrument!

Acoustical instruments

- basic tone production requires practice
- the sound is variable by default
- most controls affect all sound parameters
- the player must supply the acoustic energy
- inherently expressive
- multimodal feedback: forces, vibrations
- durable/repairable

Conventional synthesizers

- basic tone production requires no practice
- the sound is constant by default
- each control affects one parameter
- the socket in the wall supplies the energy
- inherently *in*expressive
- only acoustic feedback
- perishable (spare parts?)

The ’role’ of an instrument

Are instrument sounds the “typefaces” of music?

Strings	Celesta
Woodwind	Marimba
Brass	Hammond
Percussion	Kazoo

Adolphe Sax
1814-1894
Belgium

Digital synthesis – the legacy

Any waveform is possible…
… but how?

High sampling rates, slow computers
$\Rightarrow$ lean computations

Then: how can we generate rich spectra with a minimum of operations?

Now: how can we control the algorithms in expressive ways?

Types of numerical synthesis

Un-synthesis: waveform memory, “sampling”

Spectral models

- Additive synthesis
- Subtractive synthesis = source + filter, such as formant filters
- SMS – separation into periodic (harmonic) components, transients and noise

Abstract algorithms

- Wave-shaping: controlled distortion
- Frequency modulation: sideband generation
- Amplitude modulation
- Aggregation of *grains,* or of wave packets, *wavelets*

Physically based numerical models

- Wave equation, modal analysis, lumped masses + springs
- Numerical waveguides and meshes

http://www.acoustics.hut.fi/publications/reports/sound_synth_report.pdf (Tolonen)

Sampling

MOST COMMON METHOD TODAY

Play back prerecorded waveforms at different speeds

Captures "authentic" sound within certain limits
Works rather well with transient sounds
Works OK for background accompaniment
Easy to implement in computer hardware

Parrot effect: a given tone always sounds identical
Difficult to make sustained tones (looping, control)
Not all sounds transpose well in frequency
When speeding up the waveform, aliasing may occur
Hard to scale for playing intensity
The sound's properties are completely unspecified
Requires a lot of memory space

And is this *synthesis*?

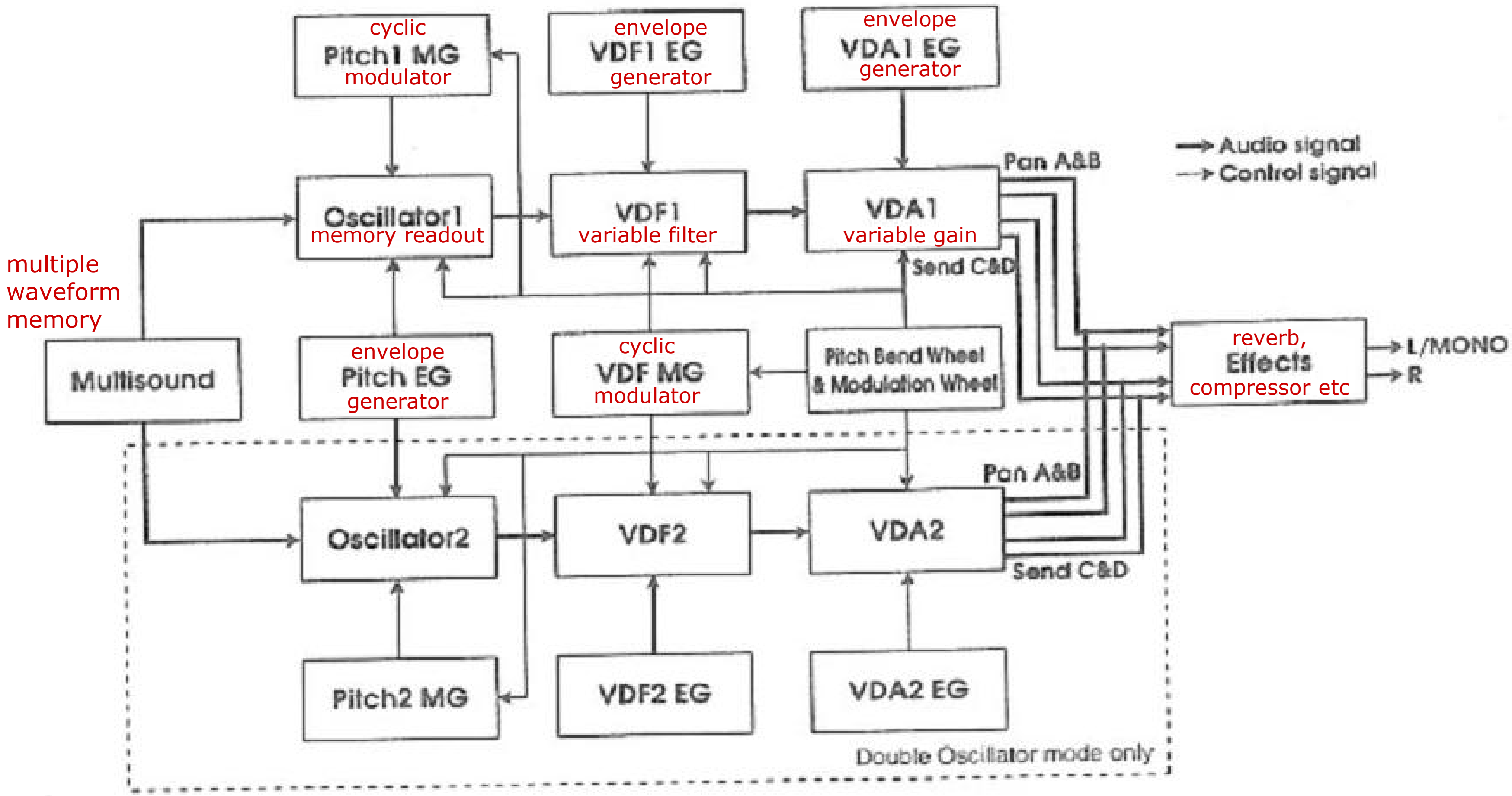
Sampling

Many tricks are used to improve the sound of sampling:

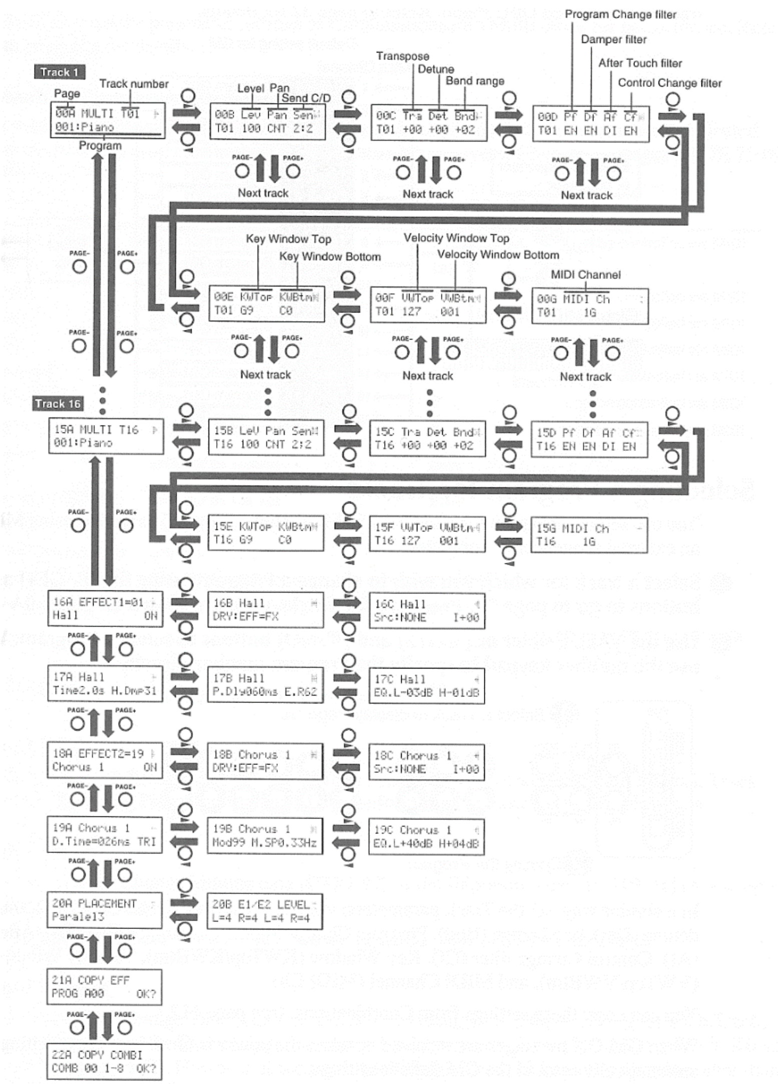
- time-varying filtering with envelopes and/or oscillators
- modulation of playback speed with envelopes and or oscillators
- mixing/crossfading/interpolation of several simultaneous waveforms
- complex looping schemes

=> example: KORG X5 block diagram

KORG X5 Block diagram sampling synthesiser (1997)



KORG X5 Menu
2 x 16 chars LCD



Many synths are like this:

Complex, far removed from music

An Artificial Intelligence system was developed to control this synth.

Single-period sampling

with phase-adjusted interpolation and parameter smoothing

M.Sc thesis at KTH CSC by Arne Wallander, 2006

Now commercial at **www.wallanderinstruments.com**

To create a new instrument:

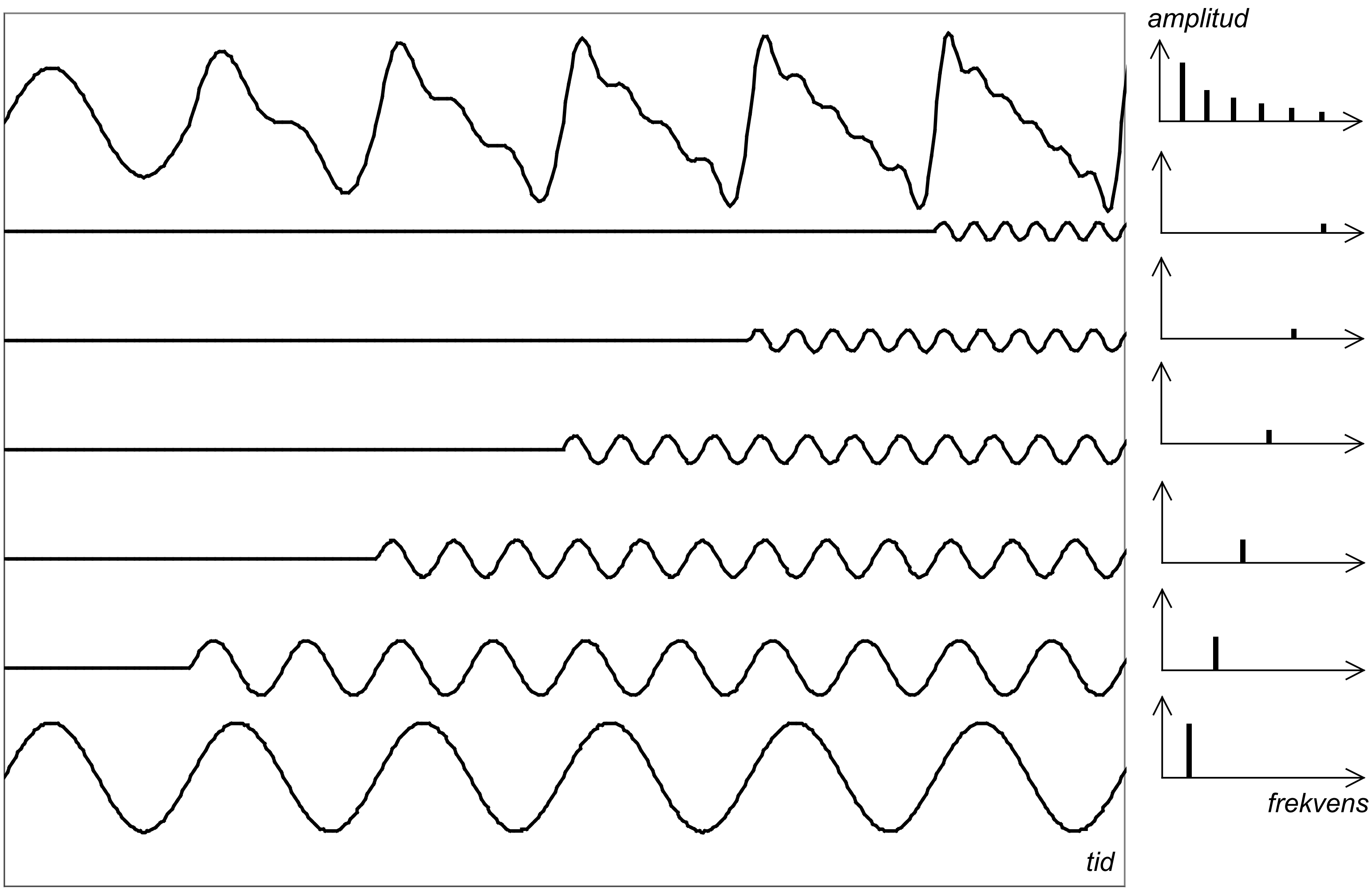
- Sample one single period of the original waveform at at least four different pitch/dynamic combinations
- Perform a complex Fourier transform and align the phase of all the harmonics
- Inverse-transform back to the time domain
- Now you can interpolate freely between the original waveforms

Extremely small memory footprint (< 50 kB per instrument)
Most of the processing is pre-processing at the factory
No parrot effect; good control of sustained tones
Generic procedure for capturing any melodic instrument
Works well with wind instruments, thanks to breath controllers

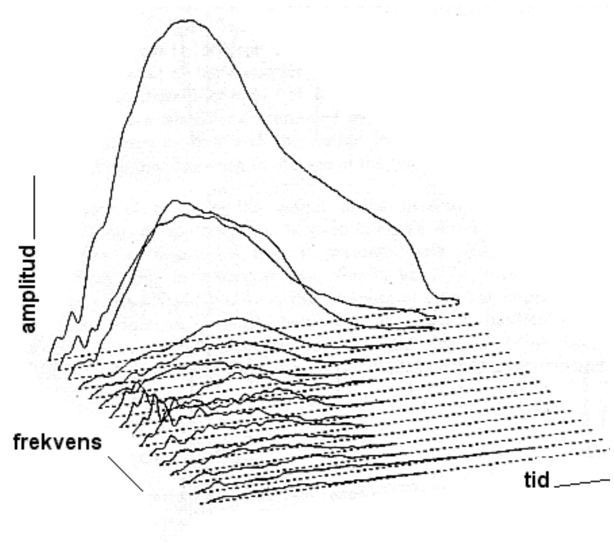
Only harmonic spectra - does not reproduce noise or transient components

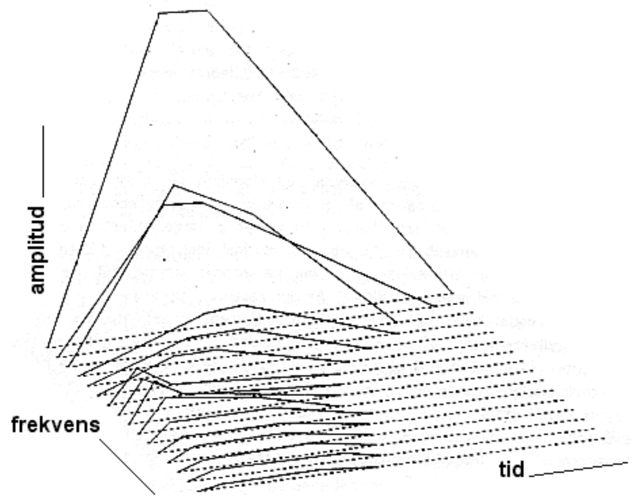
Additive synthesis

Build a desired spectrum by addition of sine waves



Additive synthesis





short violin tone

Simple in principle
Arbitrarily accurate
Many mathematical tools
Also inharmonic spectra
Easy to avoid aliasing distortion
Can exploit spectral masking

Cumbersome to specify the envelopes (piecewise linear)
Bad with stochastic signals (such as noise)
The parameters say little about how it sounds

Cordic's algorithm

for making sine waves

$$Y_{i+1} = Y_i + m \cdot X_i$$

$$X_{i+1} = X_i - m \cdot Y_{i+1}$$

(resembles a digital filter)

Amplitude is given by the initial value
Only two multiplies per sample
Generates sine and cosine terms (almost)

Max oscillation frequency is f_s / 6 .
High resolution in m is needed for musical precision

Sine wave generation by table lookup

also usable for other waves

Use precomputed tables of intermediate results
Use binary tricks such as 'fractional integers'
and integer-floating point unions

Get sin(φ) with only one FP multiply and add per sample,
other operations are integer

Additive synthesis (variation)

Use filters with $Q > 1$ as a sound source.

High Q => each resonator produces a damped sinusoid

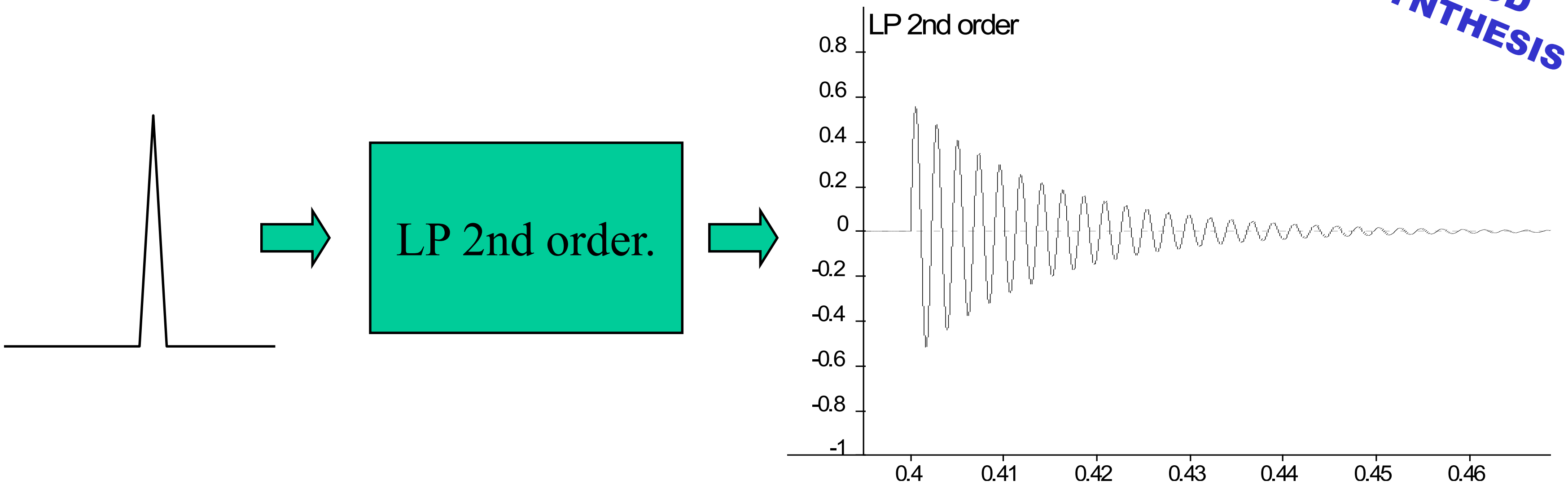
Extremely common in reality!

Special digital filter structures are needed
for very high Q resonators

(Mathews' sound examples)

Impulse responses as sources

LEGACY METHOD FOR VOICE SYNTHESIS



Minimal computations
Physically relevant
Can be excited with special transients such as glottal pulses

Envelopes are given
Poor for stochastic signals
The parameters are only vaguely perceptually relevant

Additive synthesis 2

Summation of signal packets, *wavelets*,
according to the formal theory for these.

Fourier series represent complicated waveshapes
as linear combinations of harmonic sines.

Wavelets represent complicated waveshapes
as linear combinations of wavelets at different *time scales*.

Arbitrarily close to the original
Mathematical tools exist
Also inharmonic spectra
Kan imitate noise

The maths are not so easy
The parameters are not descriptive of the sounds

Subtractive synthesis

Source-filter-method: A spectrally rich source is filtered

The foundation method for analogue synthesisers (Moog and followers)

Easy to understand

Linear circuit theory

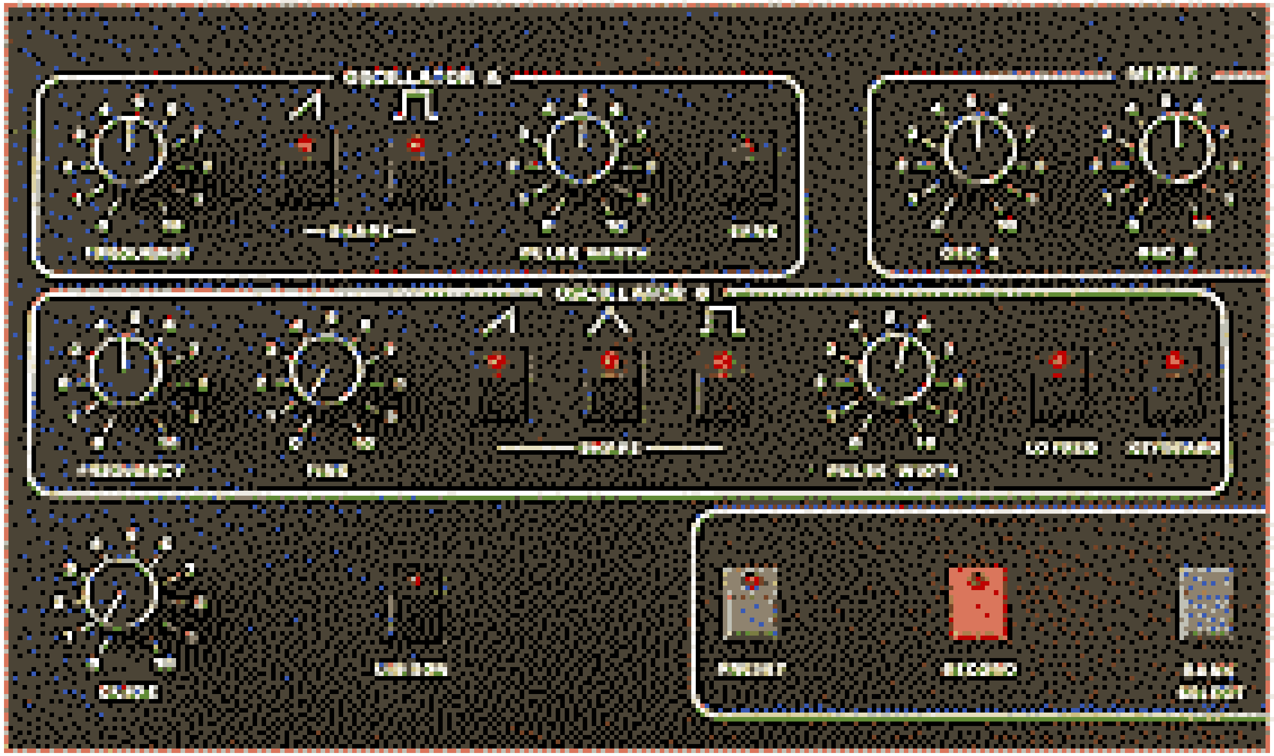
The filter parameters are perceptually relevant

The filter parameters are physically relevant

The source is usually either trivial, or sampled (=unspecified)

Tricky to avoid aliasing in digital implementations

Oscillator



An Electronic Circuit called an oscillator generates electronic waveforms of different shapes. Each note played is assigned two oscillators. These can be set at different octaves, or intervals, to create a rich, warm sound.

Filter

The Filter works like an advanced form of tone control to shape the sound produced by the oscillators.

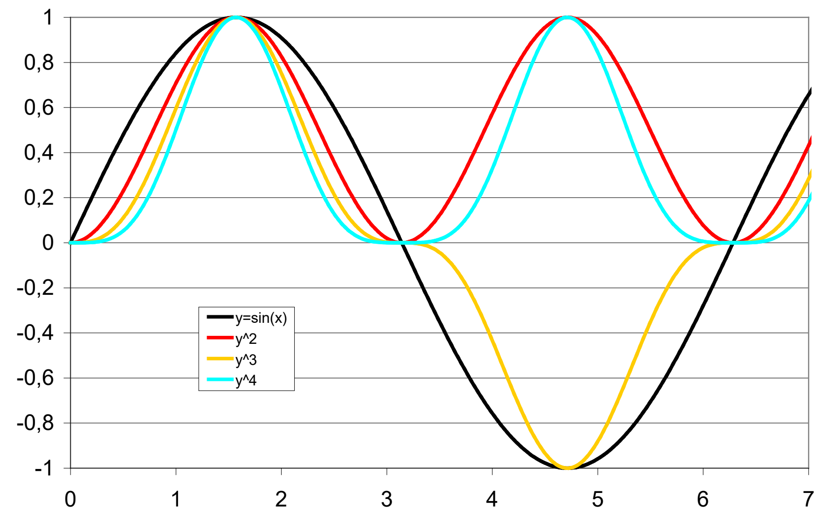
Wendy Carlos ljudexempel

Wave-shaping

LEAST COMMON METHOD TODAY

Controlled distortion, for example

$$\sin^2(\alpha) = \frac{1-\cos 2\alpha}{2}$$



Simple in principle
Computes quickly
Mathematically developed
Only harmonic spectra

Hard to control spectrum variation with amplitude
Not useful for stochastic signals (such as noise)
The parameters say nothing of what the sound is like

Wave-shaping

$$y = f(x) = d_0 + d_1 x + d_2 x^2 + d_3 x^3 \ldots d_N x^N$$

Tchebyschev polynomials:

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$T_3(x) = 4x^3 - 3x$$
$$T_4(x) = 8x^4 - 8x^2$$

$$T_{k+1}(x) = 2x T_k(x) - T_{k-1}(x)$$

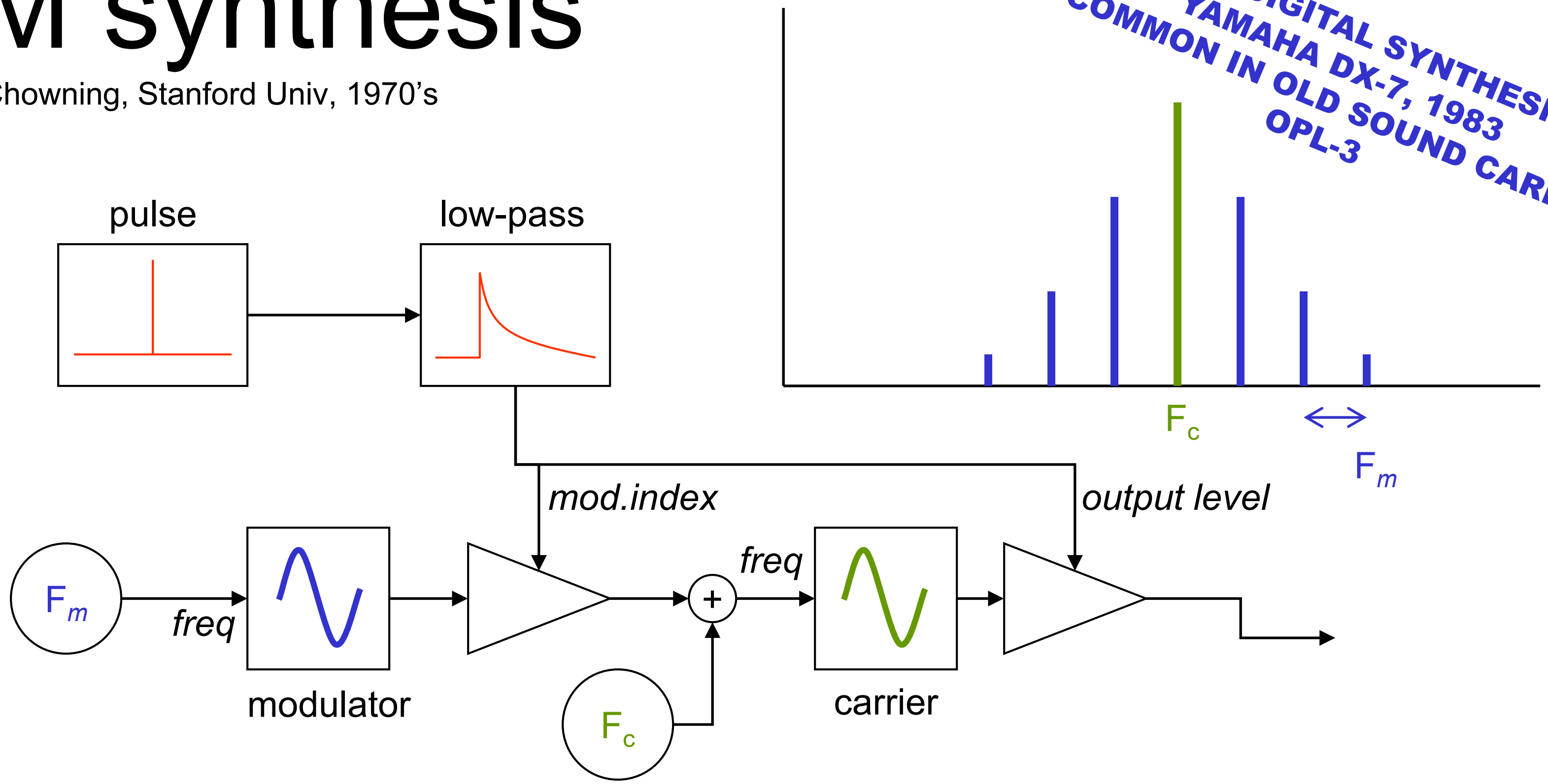
Waveshap.ald

Frequency multiplier, if the amplitude = 1

FM synthesis

John Chowning, Stanford Univ, 1970's

FIRST DIGITAL SYNTHESIS
YAMAHA DX-7, 1983
COMMON IN OLD SOUND CARDS
OPL-3



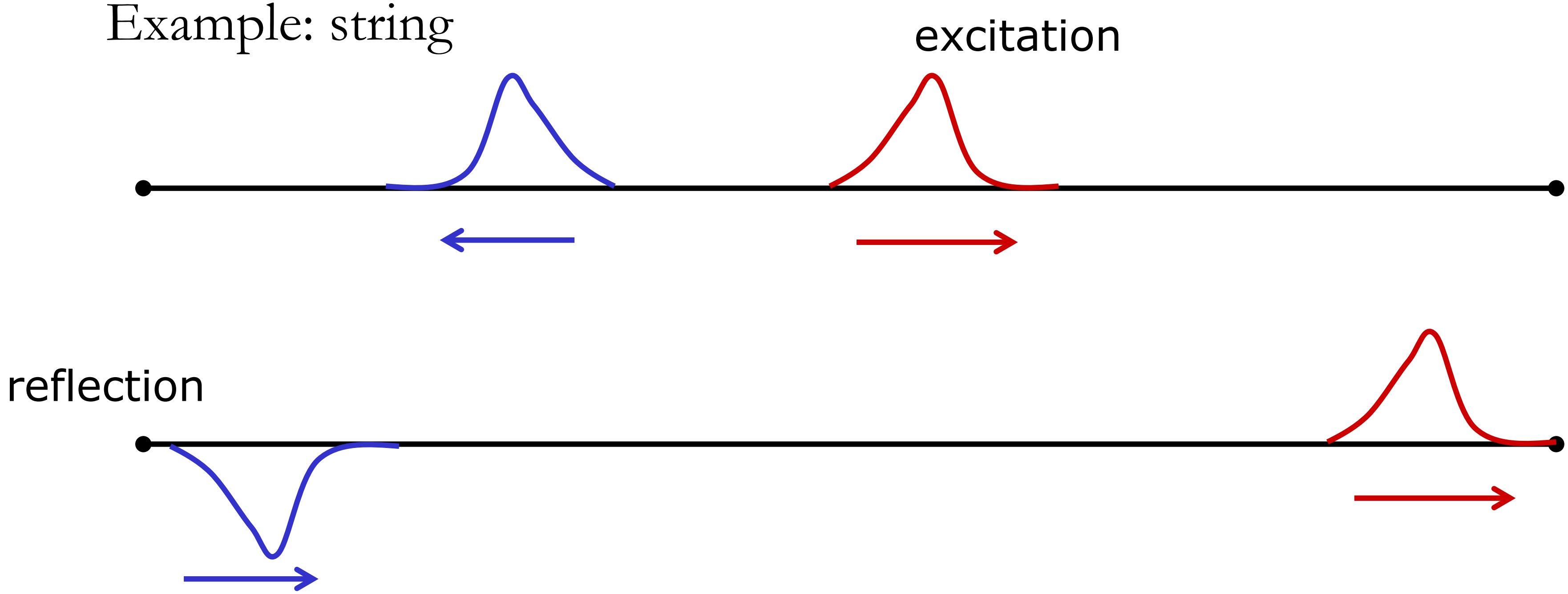
Produces complex spectra with little computation
New timbral space

Dense maths
The parameters are non-intuitive and unrelated to the sounds

Digital waveguide synthesis

J O Smith, Karjalainen & Välimäki

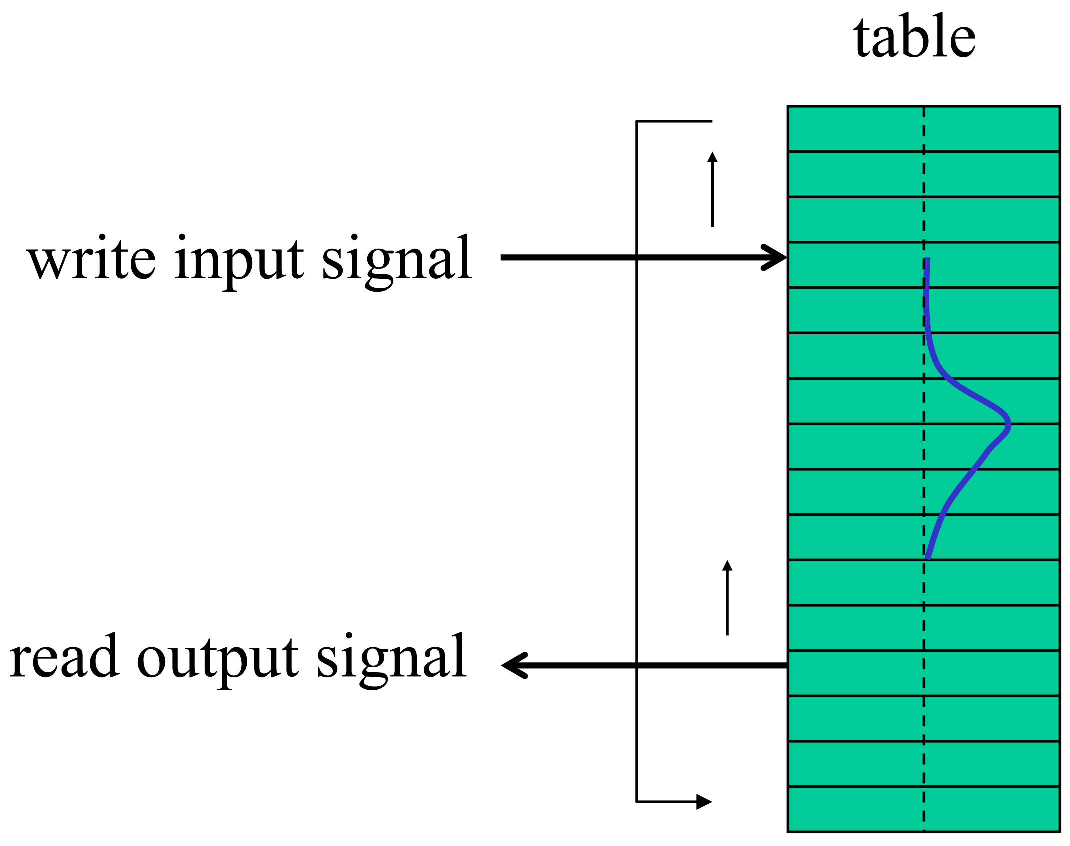
Example: string



Amplitude = sum of forward & backward wave

The string is a kind of **delay line**

Delays are easy to program

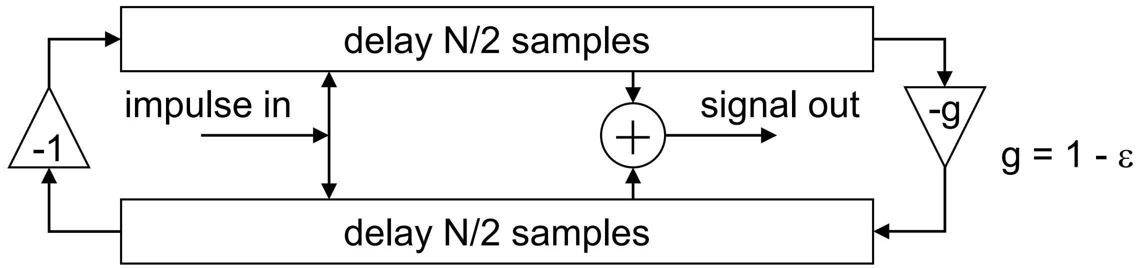


Pointers are incremented for each sample.
At the end of the table, wrap around.

Numerical waveguides

POPULAR METHOD IN RESEARCH

"physical modelling"



Direct analogy to real vibrating systems
Computationally lean
Sounds good with little effort

The time quantisation is tricky
Requires a lot of knowledge
of excitation and boundary conditions