SUBTRACTIVE SYNTHESIS

Introduction

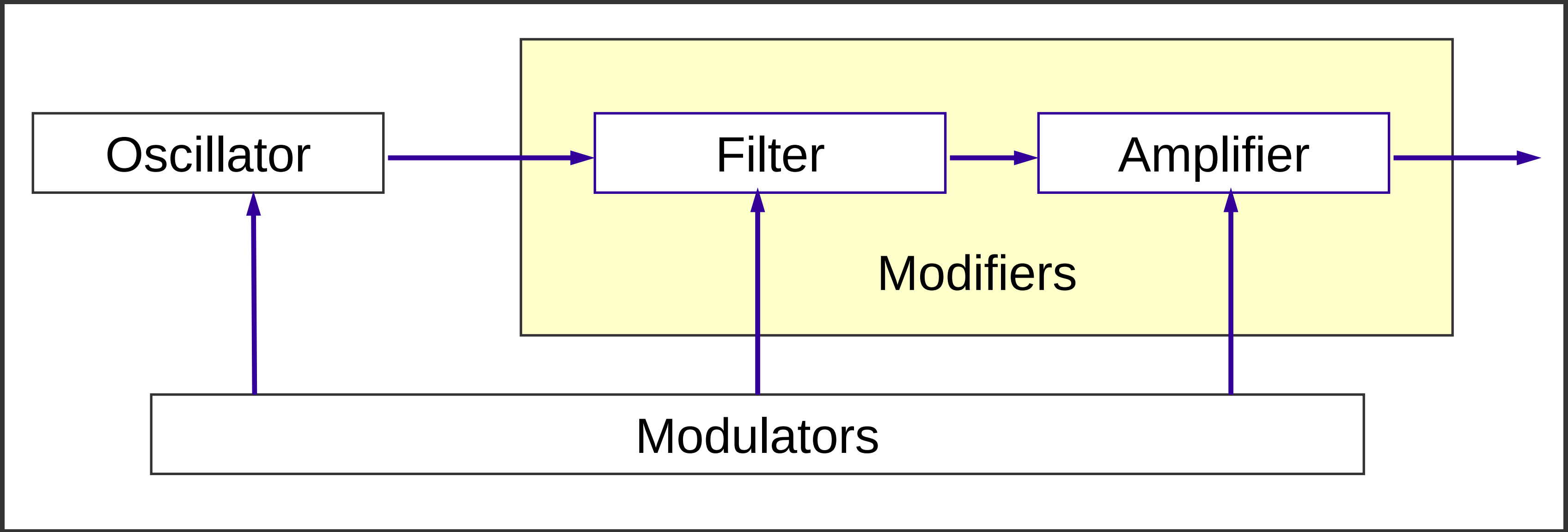
Subtractive synthesis

- From Latin *subtractio*
- First synthesis method.
- Also called analogue or modular synthesis.
- For many musicians, “*the* synthesis”.
- Originally analogue method, still used in digital instr.
- The main concept:
  - oscillators create rough harmonic signals,
  - filters shape the static spectrum,
  - modulators introduce dynamic changes to the sound.

Source and modifier

The subtractive synthesis works on a “source-modifier” basis:

- source - oscillators
- modifiers – filters and modulators



Source and modifiers

	Guitar	Synthesizer
Source	Vibrating string	Signals from oscillators
Modifier	Resonant body	Filters
Modulation	A way of picking and pressing strings	Modification of the module parameters

Oscillators - VCO

VCO – Voltage Controlled Oscillator

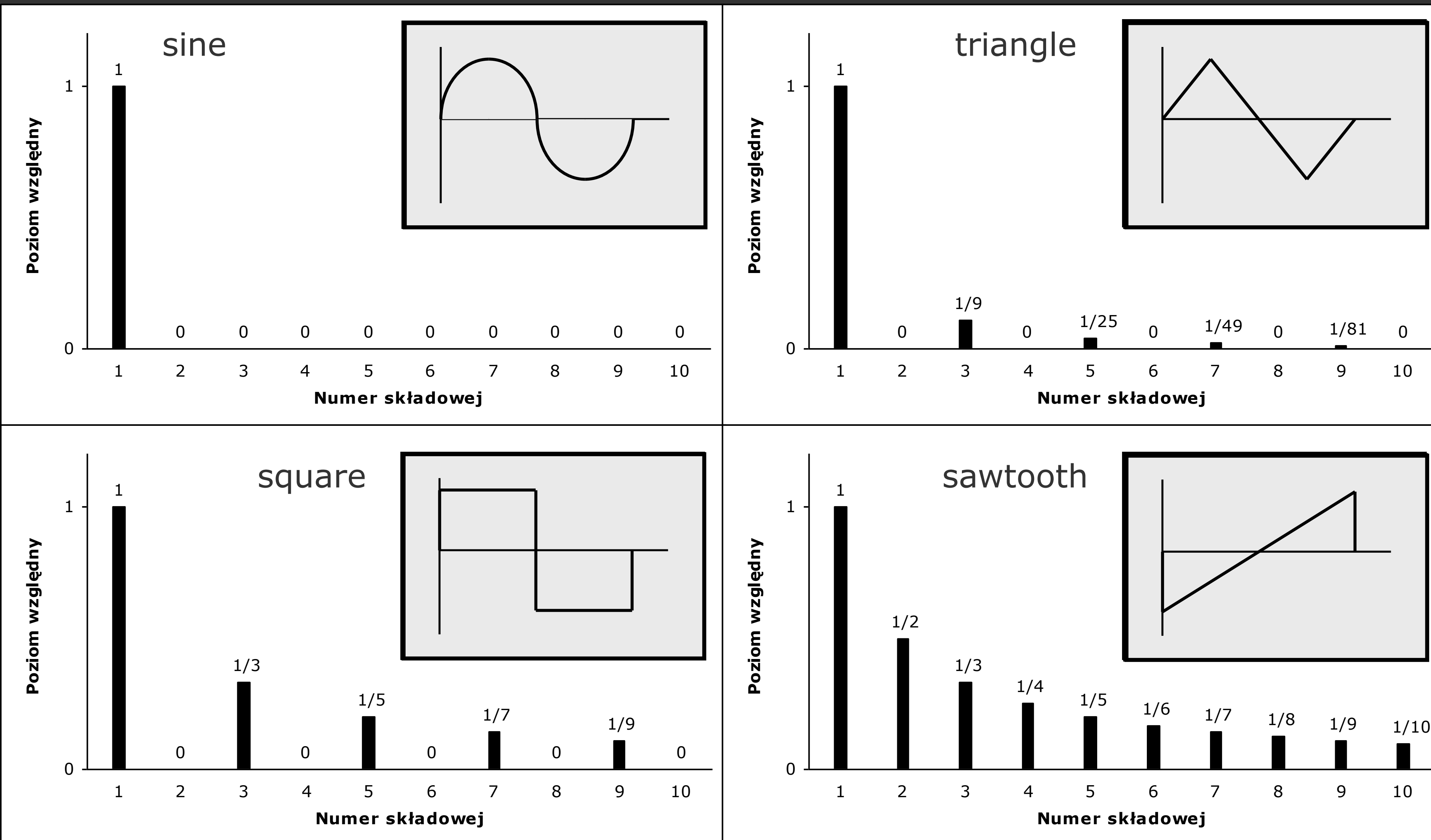
Generates harmonic signals.

A classic VCO generates the following signals (waves):

- sine wave
- triangle wave
- square (rectangular) wave
  - regulated pulse width
- sawtooth wave

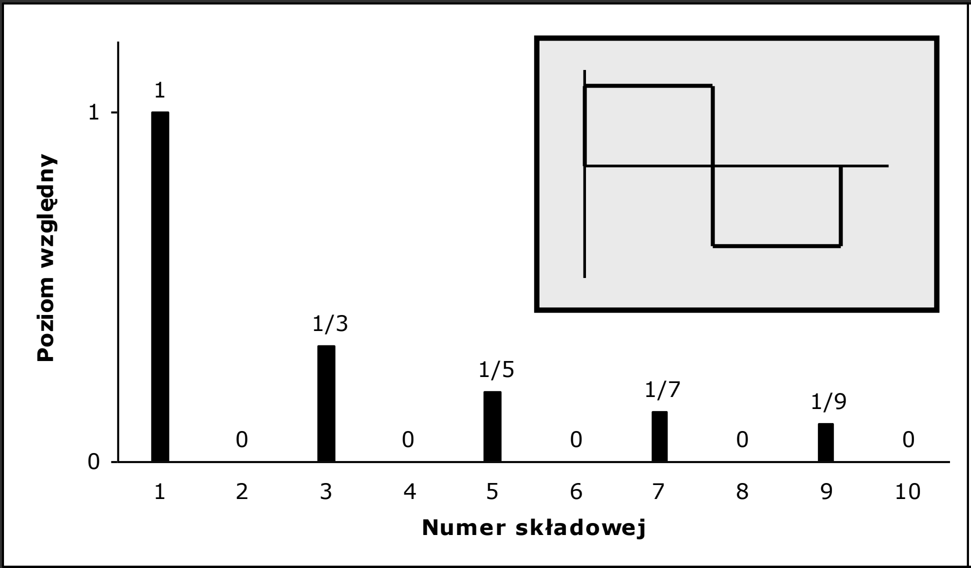
Modern VCOs can also generate more complex waves.

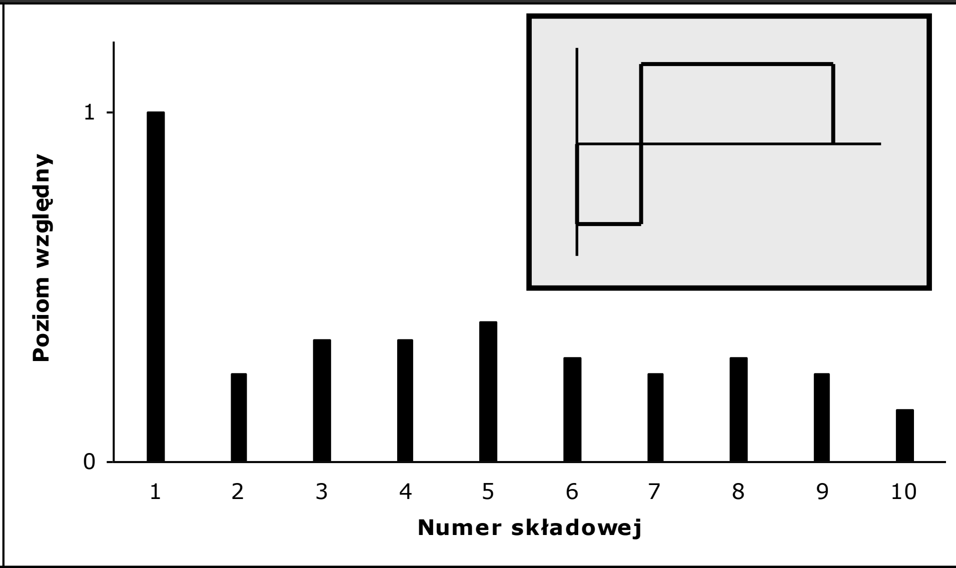
Simple waves from VCO



Simple waves from VCO

Square wave can have different shape according to the pulse width or fill rate parameter (PWM, p/m).



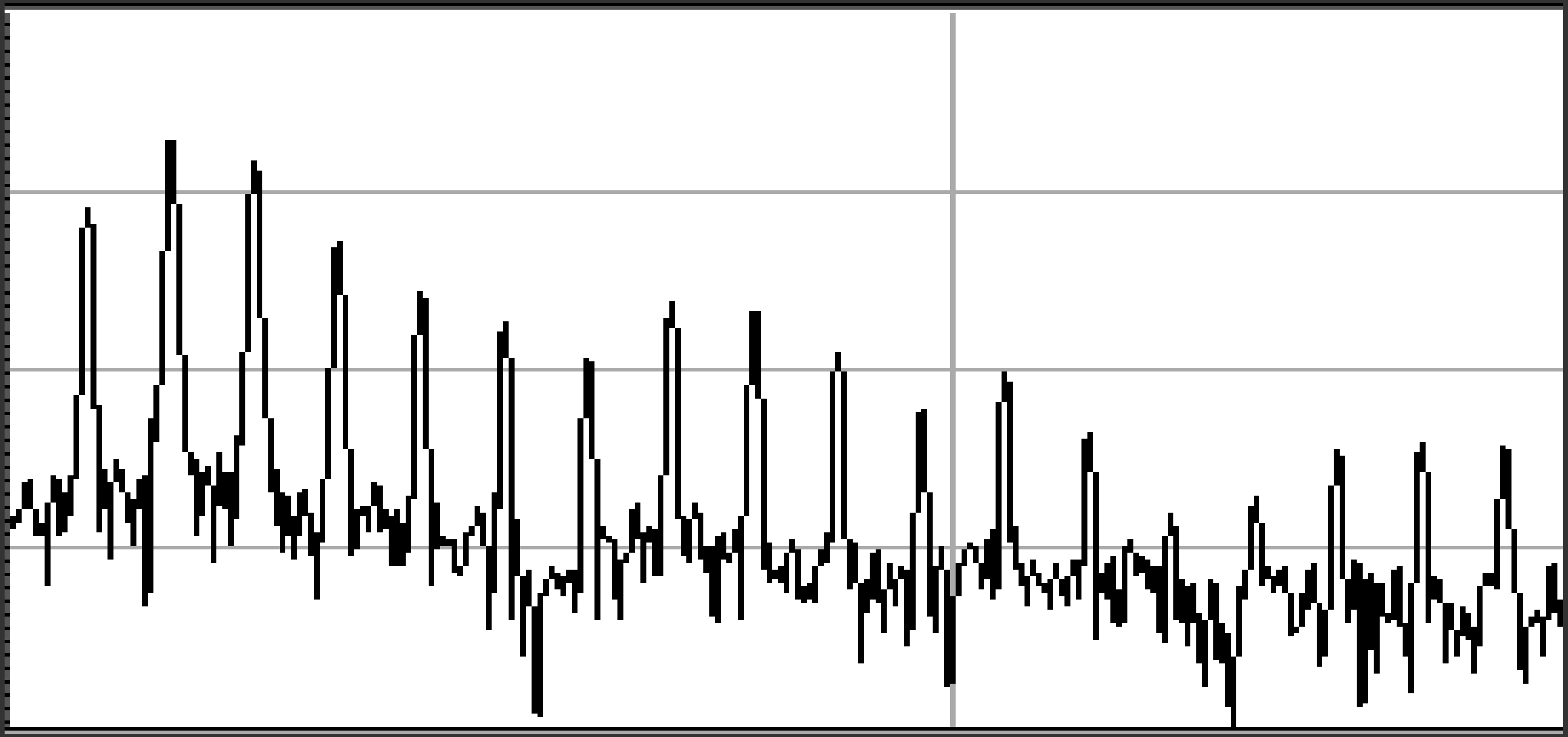


For fill rate 1:1, only odd numbered peaks are present.

Changing the fill rate from 1:1 increases level of even peaks and decreases level of odd peaks.

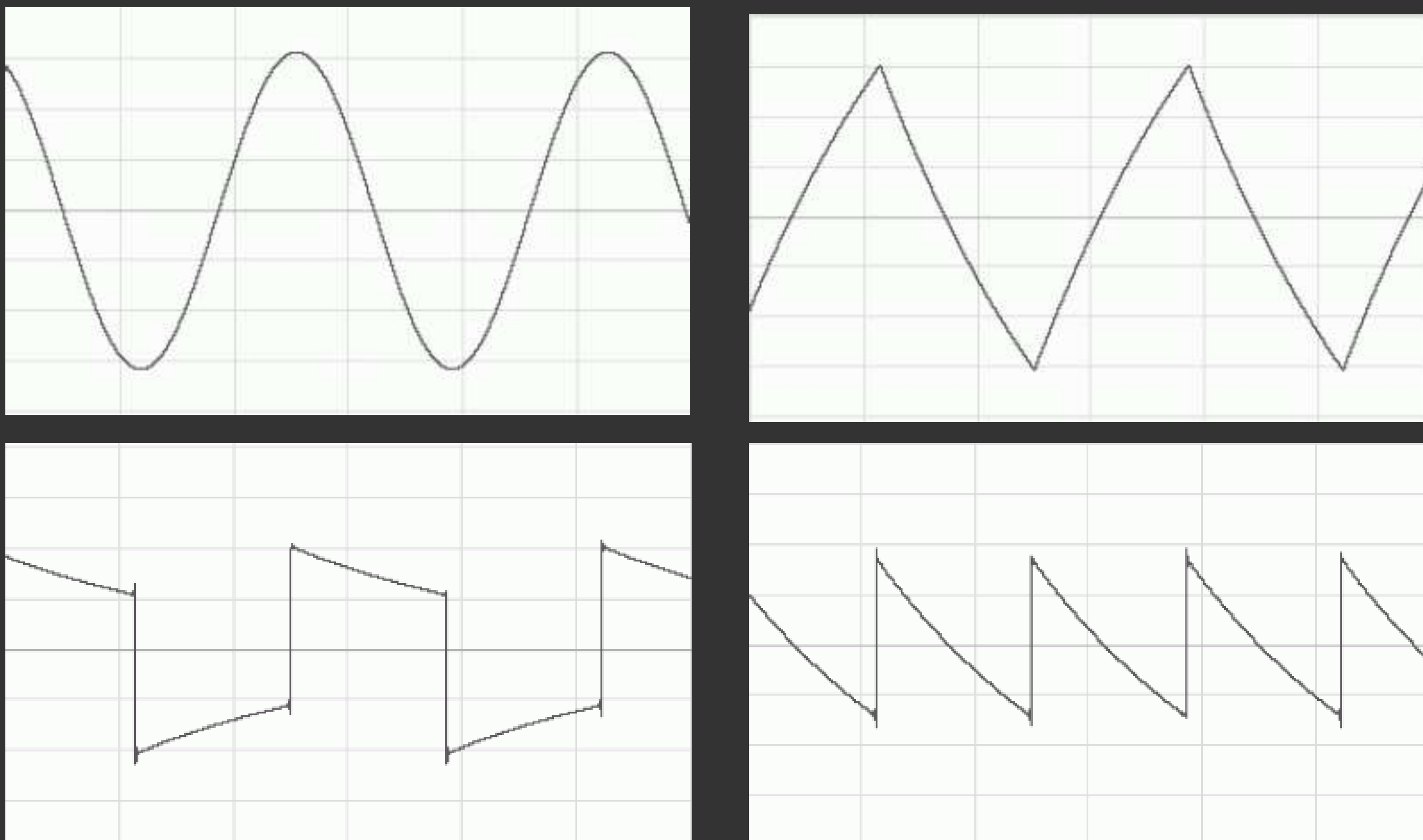
Spectrum of a musical sound

Haven't we seen such a spectrum shape before?



Waves generated by real analogue VCOs

Real waves from analogue *Moog Modular*



Voltage controlled modules

What does *„voltage controlled”* mean?

Voltage control (VC) means that the parameters (e.g. wave frequency, fill rate) depend on the voltage of a control signal.

Where does this control voltage come from?

- From keyboard (changing the sound pitch).
- From knobs on the front (e.g. detuning).
- From a signal generated by another module (the modulator), connected to the control input.

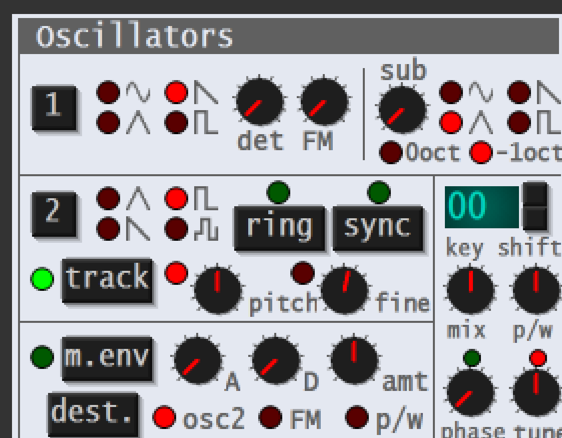
Oscillator VCO

Parameters of the VCO:

- wave shape (signal type)
- frequency (detuning)
  - – coarse – by octaves,
  - – fine – by cents
- fill rate (square wave only)

Modulation inputs:

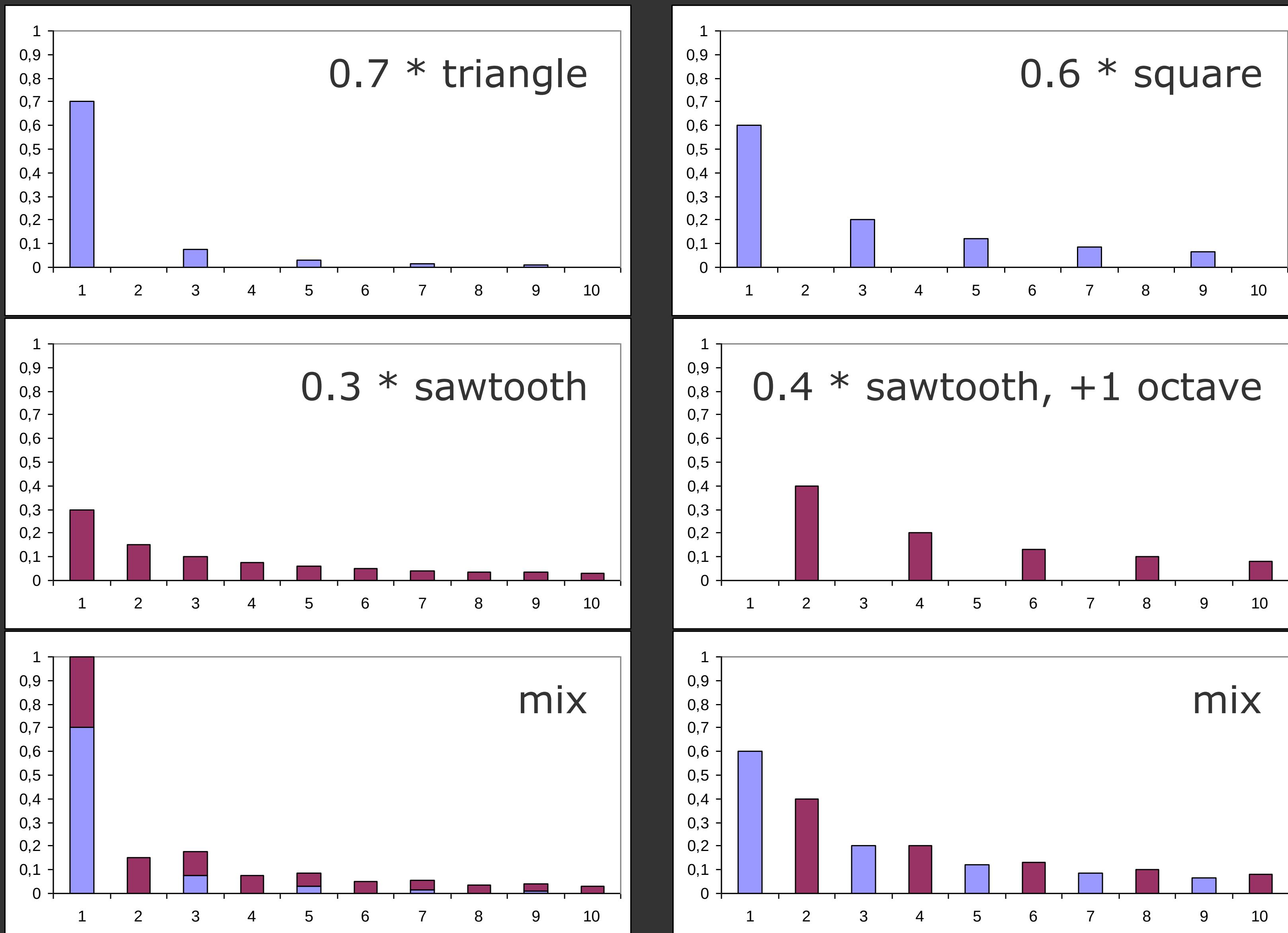
- frequency
- fill rate



Multiple oscillators

- One oscillator is not enough. In practice, waves generated by 2-3 oscillators are summed up (mixed).
- Proportion of the mix can be regulated.
- Some common examples:
  - different wave shapes, same frequency,
  - one wave detuned by one or more octaves, up or down,
  - one wave slightly detuned (the beating).
- With this method, we can shape the spectrum of the initial sound and make it less regular.

Multiple oscillators



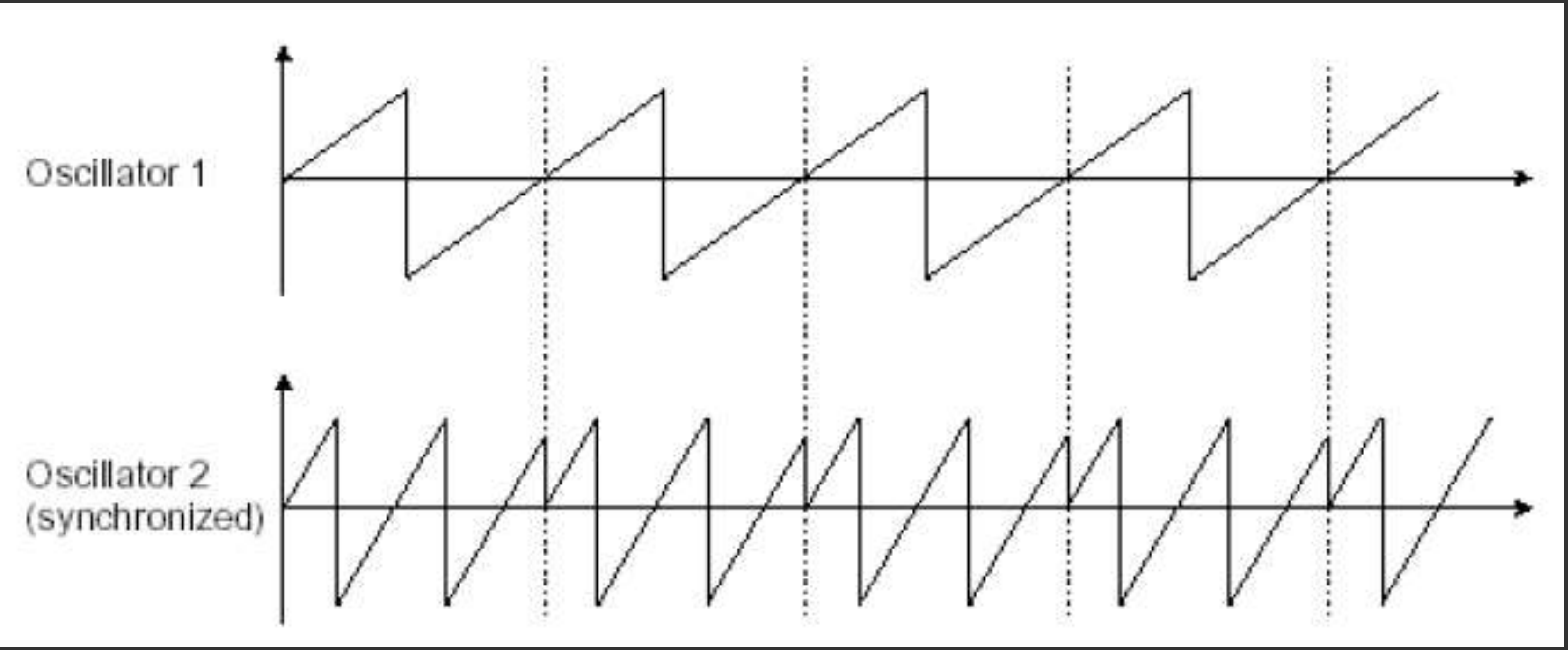
Multiple oscillators

More advanced examples:

- frequency modulation (FM) – frequency of VCO1 is modulated by output of VCO2; generates signals with complex spectrum;
- ring modulation – signals from VCO1 and VCO2 are multiplied, creating rich, inharmonic sounds,
- sync – each new period of wave from VCO1 resets the phase of VCO2, allowing for creation of new wave shapes.

Oscillator sync

VCO1 syncs VCO2: resets the phase of VCO2 at the start of each new period in VCO1 signal.



Filter - VCF

VCF – Voltage Controlled Filter

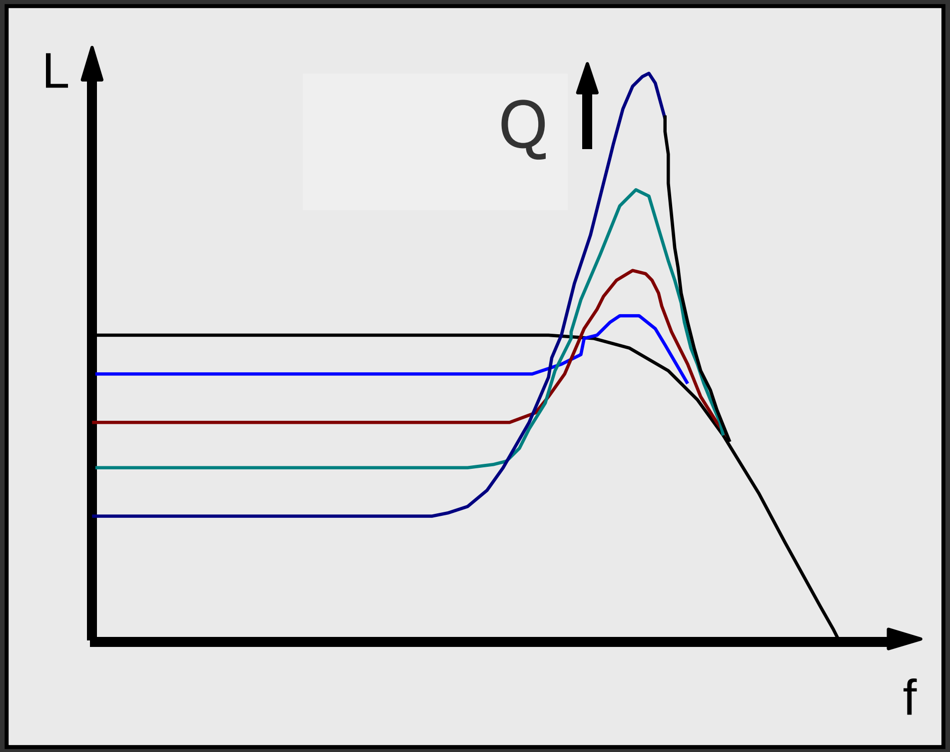
Modifies spectrum of the generated signal.

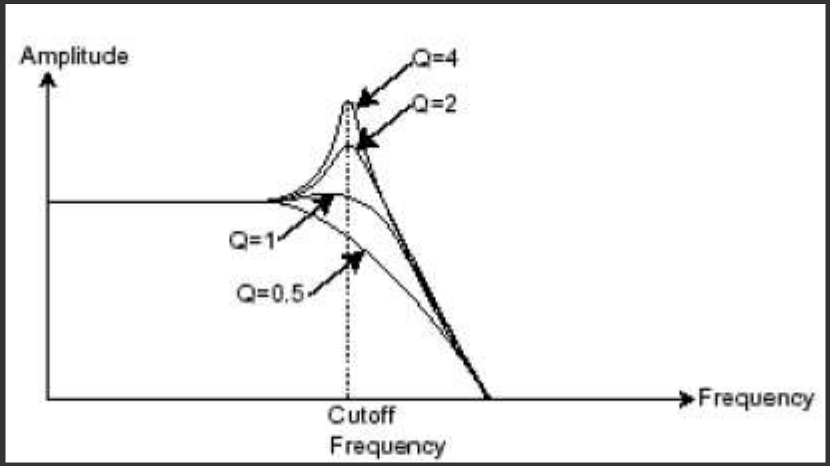
- Dampens selected frequency range, defined by a cut-off frequency.
- Filters may be: low-pass, high-pass, band-pass.
- Attenuation rate – how quickly the gain falls, usually: 12, 18 or 24 dB/octave.
- Resonance (emphasis, Q) – peak near the cut-off frequency, created by a feedback loop in the filter.

VCF – sample responses

Lowpass filter – the most common type used in synthesizers.

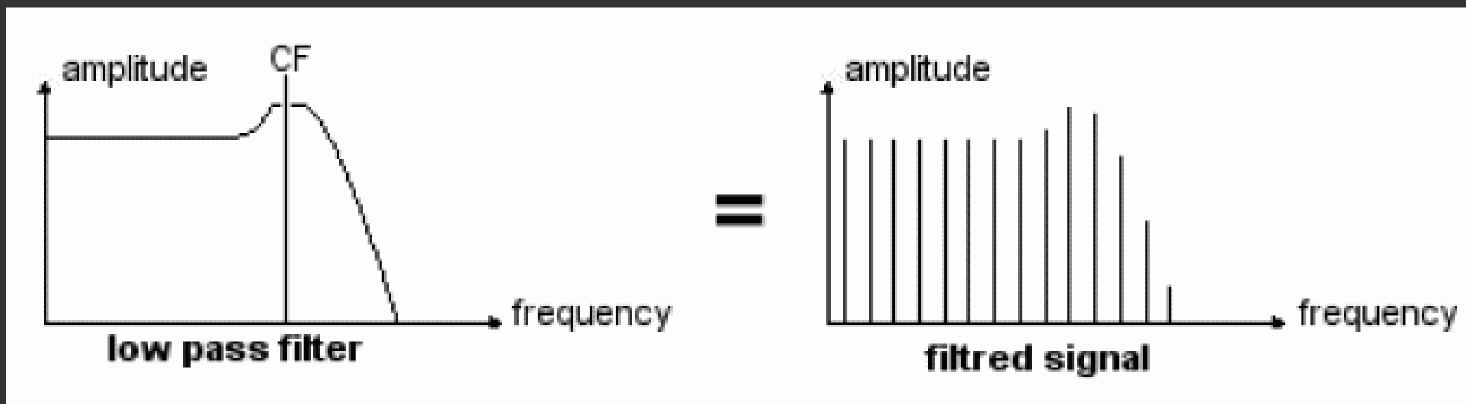
- Q – resonance
- *cutoff* – beginning of the stop band

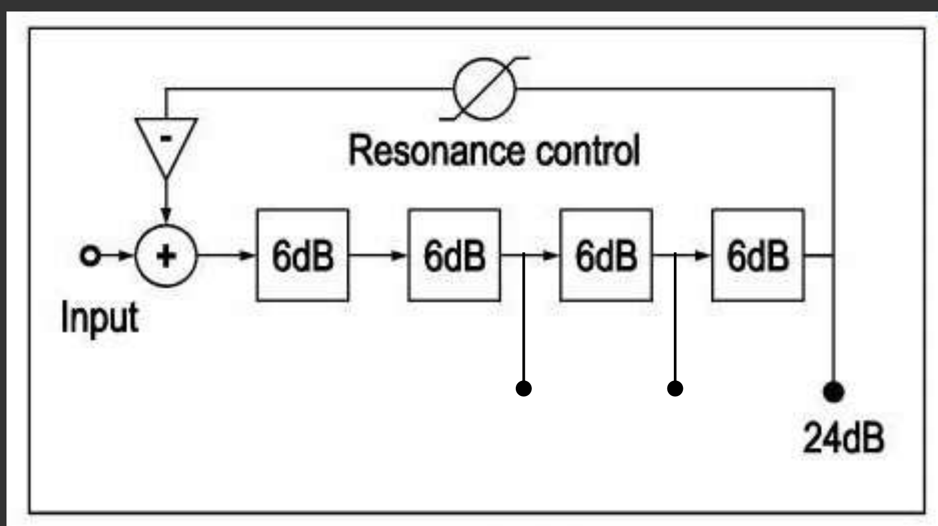


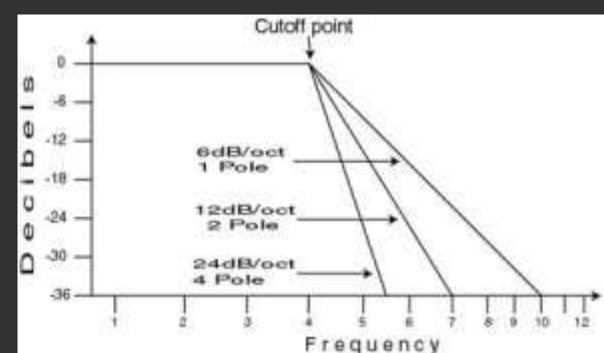


Attenuation rate

Attenuation rate defines the range of modified frequencies.



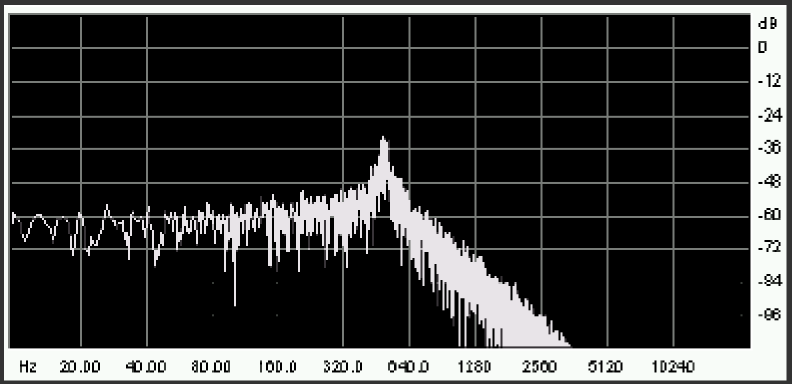




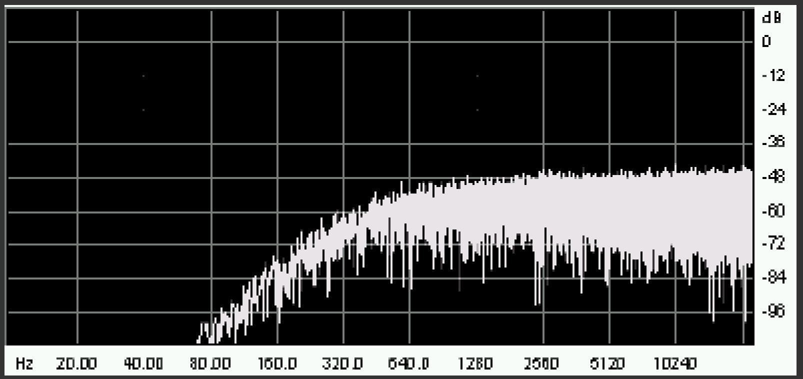
VCF – filtered signals

Spectra of filtered white noise (Moog Modular)

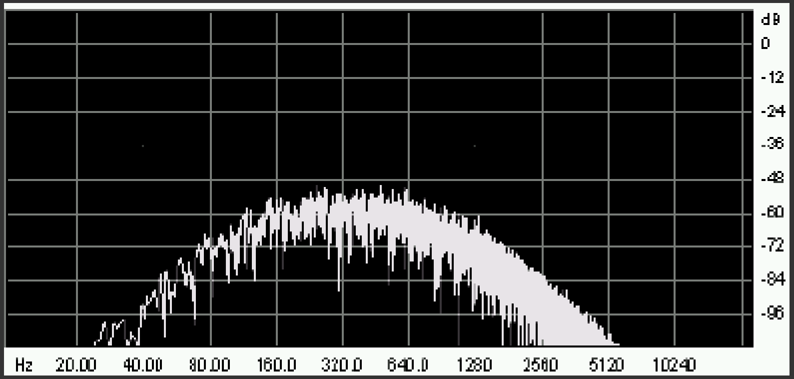
LP (low-pass)



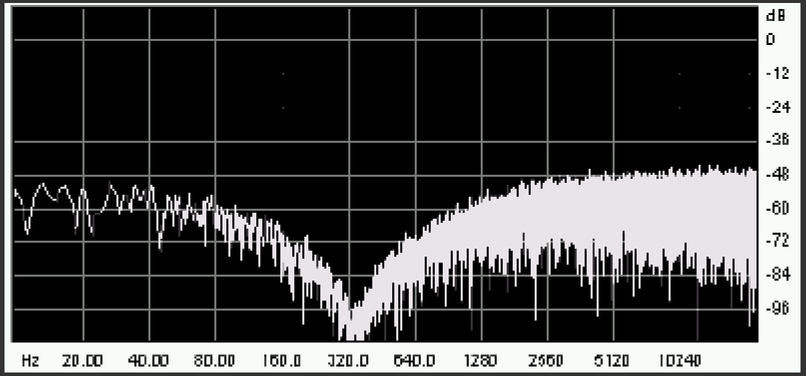
HP (high-pass)



BP (band-pass)



BR (band-stop)



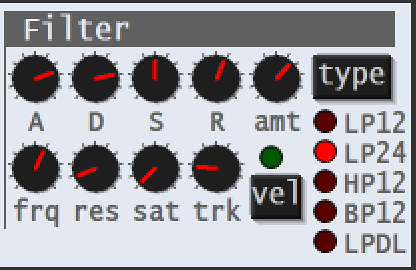
VCF - filter

Parameters of VCF:

- filter type
  – LP, HP, BP, *notch* (BS)
- cut-off frequency
- resonance (Q, *res*)
- attenuation rate

Modulation inputs:

- cut-off
- resonance (rarely)



Keyboard follow

Key follow allows controlling the module parameters with a musical keyboard. The effect depends on the key number.

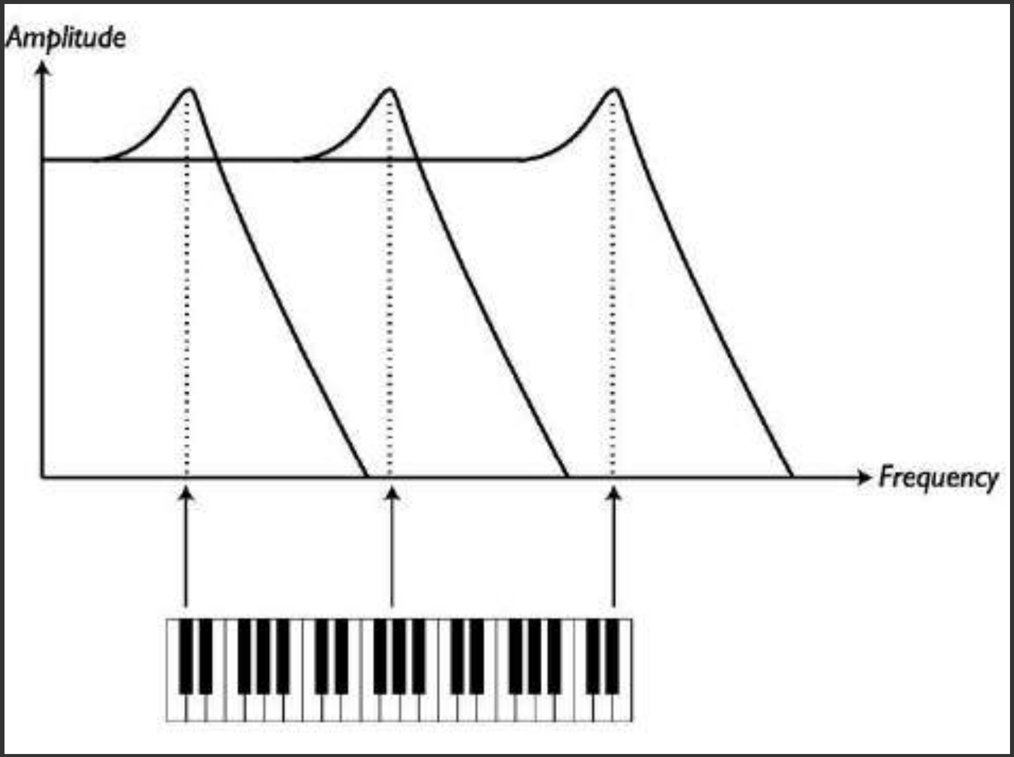
If we set a fixed cut-off frequency in VCF, e.g. 2.6 kHz in a low-pass filter, then:

- for a sound with frequency 500 Hz – first 5 partials will be passed through,
- but for a sound with frequency 4 kHz, all partials will be attenuated (they are in the stop band).

This is usually not what we need. We want to attenuate e.g. from 5th partial onwards, independently of the fundamental frequency of the signal.

Keyboard follow

- With key follow, the cut-off frequency follows the pressed keys. Strength of this effect can be regulated.
- As a result, the timbre of the sound remains constant.
- Similarly, we can apply key follow to other parameters.

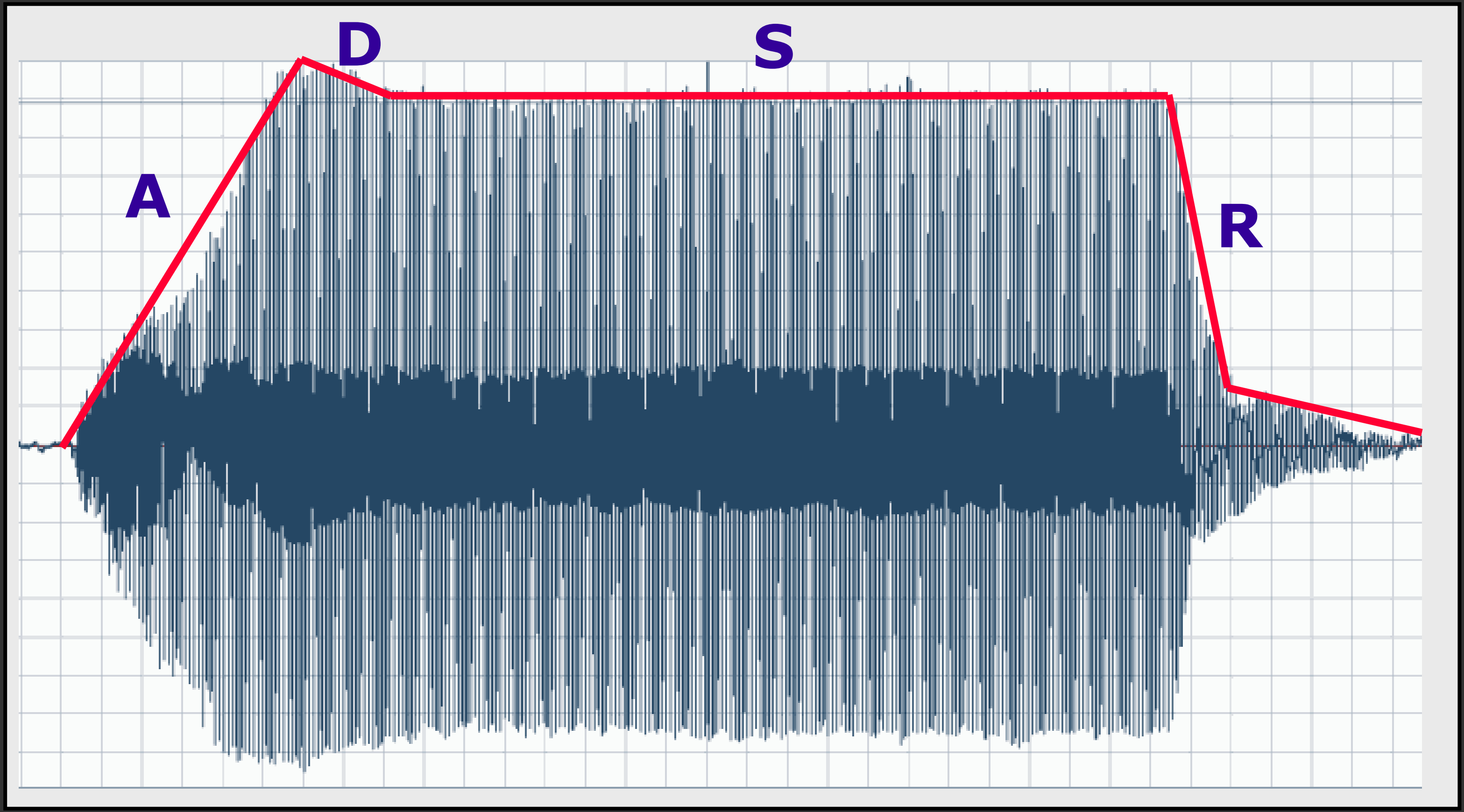


VCA – amplifier + envelope generator EG

VCA – Voltage Controlled Amplifier

- The output module of the synthesizer.
- In practice, VCA is always coupled with an envelope generator EG in order to shape the signal envelope.
- EG controls the gain of VCA, according to the envelope – a “gain vs. time” function.

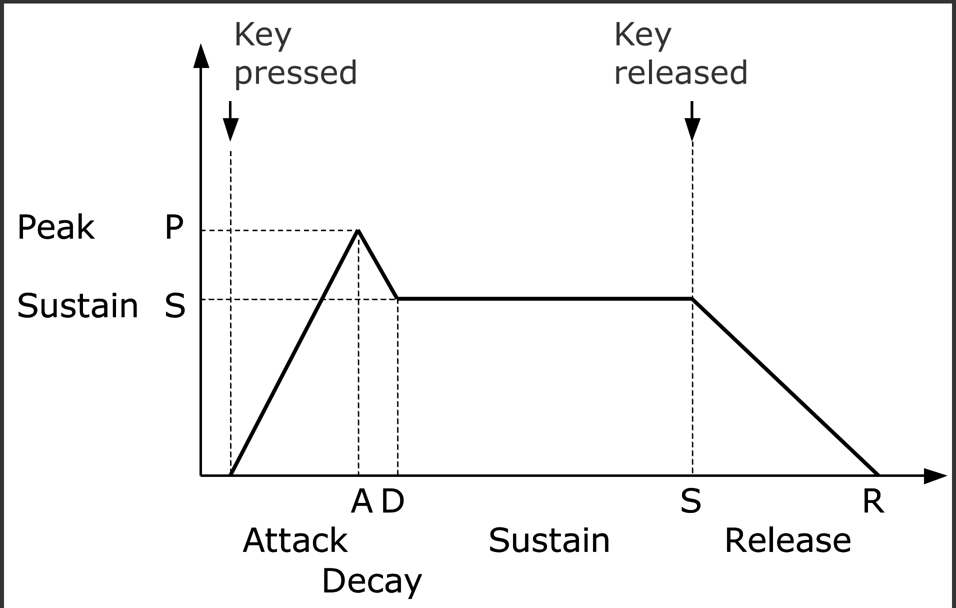
Envelope of a musical sound



ADSR envelope

Parameters of the ADSR envelope:

- A: duration of the attack phase
- D: duration of the decay phase
- S: level of the sustain phase (not duration!)
- R: duration of the release phase

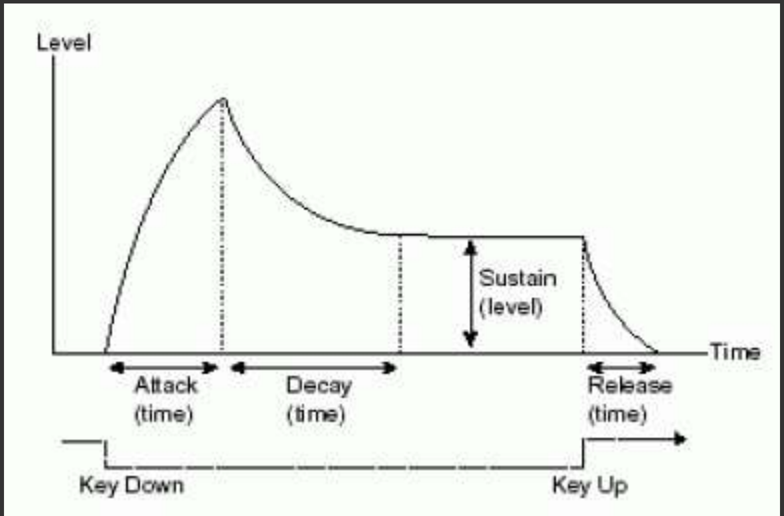


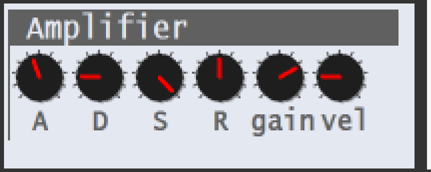
EG - envelope generator

EG – envelope generator in VCA

modifies changes of the signal loudness in time.

The ADSR envelope consists of four sections that change linearly or exponentially.





EG – practical envelope examples

Sound of a wind instrument (e.g. a trumpet):

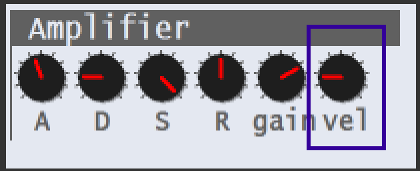
- A, R – sufficiently large
- D – is present, but it's short
- S – level slightly below the peak

Sound of a string instrument (e.g. a guitar):

- A – very short
- D – very long
- S – level at zero
- R – zero, or the same as D
- key release should not break the D phase

Velocity control

- All professional musical keyboards are dynamic, they have velocity sensors that measure the “strength” of key pressing.
- Usually, velocity value is used to control the gain of VCA (softer or louder sound for softer or harder key press).
- We can use the velocity to control other parameters, e.g. VCF cut-off (timbre changes according to the strength of key press).

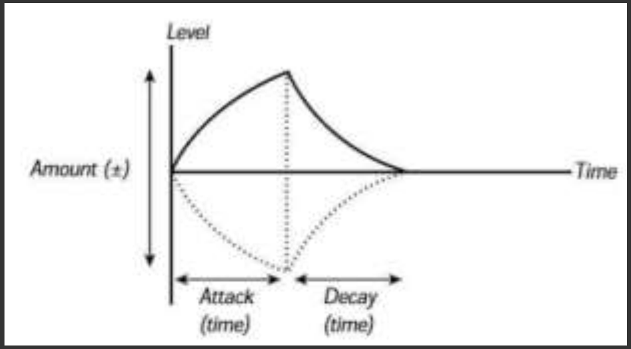


Modulation

- Synthetic sounds generated by VCO + VCF + VCA are static, their timbre is constant. Hence, they sound dull.
- If we want dynamic, alive sounds, we must modify the sound as it plays.
- Modulation in sound synthesis is achieved by changing the control parameters (voltage) with control signals, produced by:
  - envelope generators EG – linear changes,
  - LFO modules – cyclic changes
- Please remember: it is the modulation that makes the subtractive synthesis sound interesting!

EG is the modulator

- Envelope generator is an example of a modulator.
  It produces a control signal (not a sound).
- EG signal can control other modules.
  - VCO envelope – changes the produced frequency.
    It can be used to modify the attack phase or to create special effect sounds. VCO envelope often has a simplified AD shape.
  - VCF envelope – modifies the cut-off frequency.
    It may be used e.g. to alter the timbre during the attack phase.

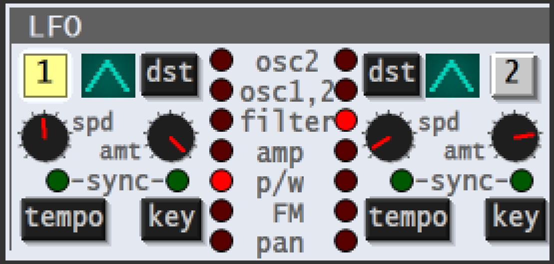


LFO – low frequency oscillator

LFO – Low Frequency Oscillator. Produces control (inaudible) signals with frequency below 20 Hz. Otherwise, it is a standard oscillator (similar to VCO).

LFO parameters:

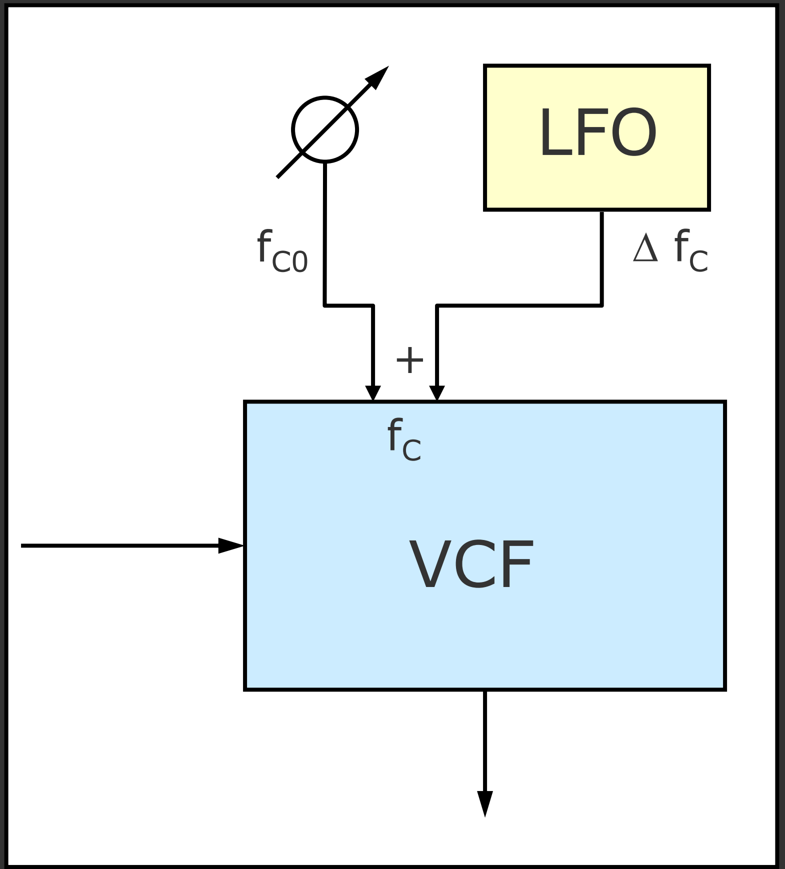
- wave shape
- frequency – modulation rate
- amplitude – modulation depth



LFO – examples

A typical example: LFO controls the cut-off frequency of VCF.

It produces cyclic timbre changes (dark-bright), often called a sweep.



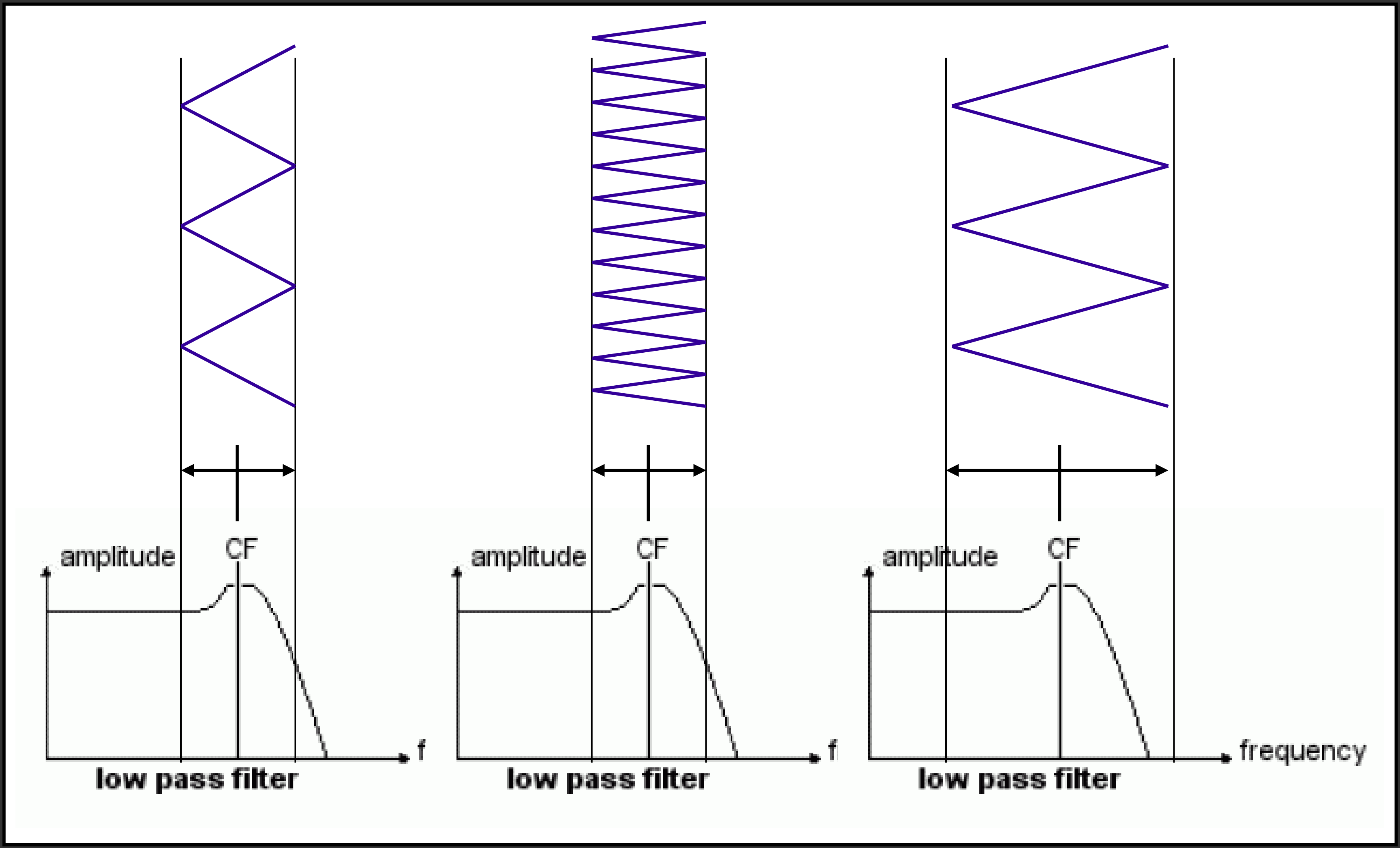
LFO – examples

Modulation parameters:

- LFO waveshape – type of changes (sine or triangle – smooth, square – step, sawtooth - mixed),
- LFO frequency – rate, how quickly the timbre changes,
- LFO amplitude – depth, range of timbre changes.

If the amplitude is set too high, a tremolo effect is produced. In extreme cases, the sound may periodically fade out completely (the cut-off reaches zero).

LFO – cut-off modulation



Higher rate
(LFO frequency)

Higher depth
(LFO amplitude)

Which parameters can LFO modulate?

VCO:

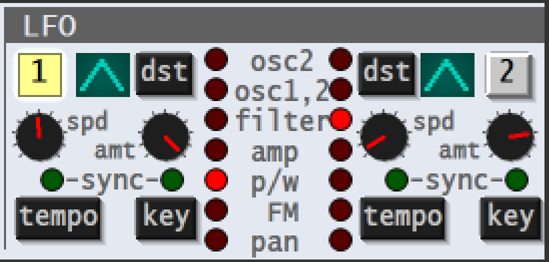
- signal frequency (vibrato)
- fill rate of a square wave (timbre modulation)

VCF:

- filter cut-off (timbre modulation)
- resonance (rarely available)

VCO:

- output gain (tremolo)
- stereo panning



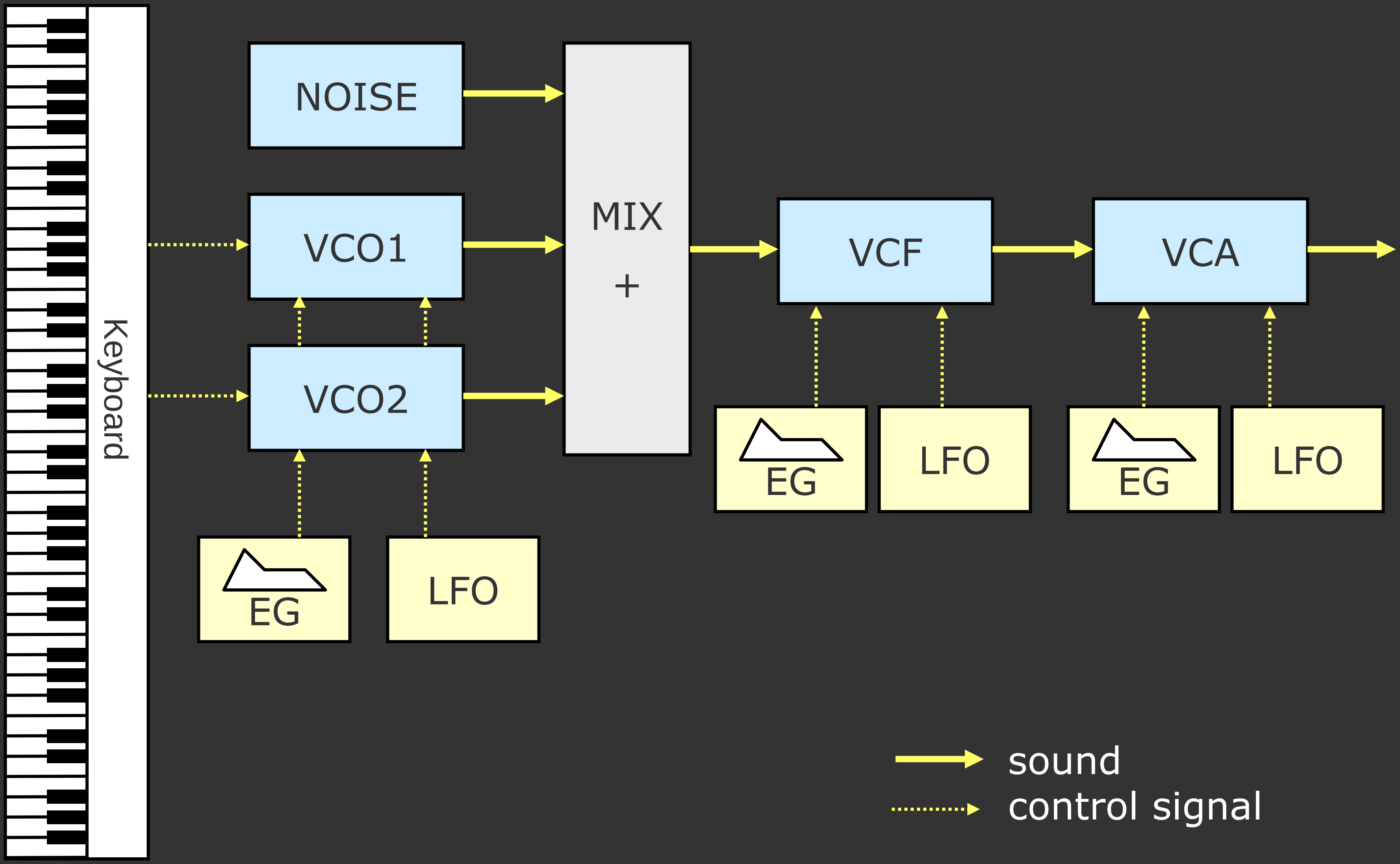
All module parameters that have control input may be modulated by LFO and EG.

Modular synthesizer

A hardware subtractive synthesizer may have two forms:

- modules connected with patches (cables) by a musician (Moog Modular, EuroRack) – more work needed, but much more flexible, a musician creates the synthesis algorithm by himself
- fixed connections between modules (MiniMoog, the majority of modern synthesizers) – easier to use, less flexible, but a standard setup (2-3×VCO, VCF, VCA, EGs, LFOs) is often sufficient.

General diagram of a subtractive synthesizer



Additional modules

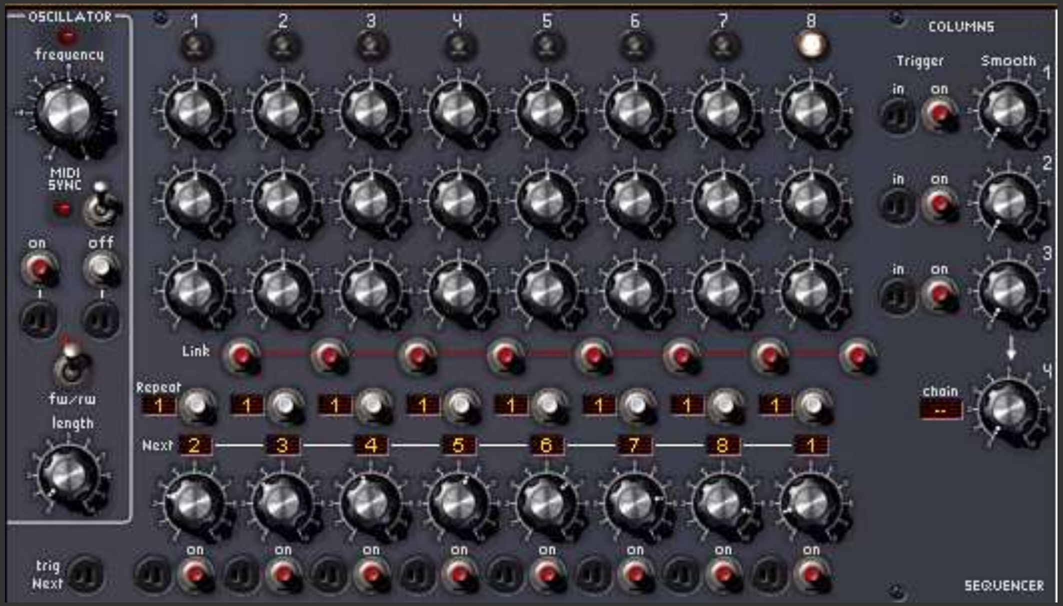
Other synthesizer modules (not present in some instruments):

- sound effects (delay, chorus, phaser, etc.)
- noise generators (RNG – Random Noise Generator)
- sequencer
- arpeggiator
- trigger modules
- sample and hold
- envelope follower
- and others

Sequencer

Step sequencer:

- generates programmed control sequences
- plays sounds automatically
- triggered by a keyboard or by a square wave generator



Controlling the synthesizer

- Musical keyboard – controls VCO frequency, triggers envelopes.
- Knobs, switches, control inputs – set the synthesis parameters, introduce modulation.
- Pitch bender – a wheel to modulate pitch.
- Modulation wheel – can be assigned to any parameter, modulation by hand.
- Foot controllers.
- Controlling with computers (MIDI, only digital instruments).

Types of subtractive synthesizers

- Monophonic – only one sound (voice) at a time (the last pressed key or the highest key). In order to compensate for monophony, a large number of VCOs (e.g. 16) have to be used. Example: Moog Modular.
- Polyphonic – duplicated synthesis pipelines allow for generating multiple voices at a time and playing chords. Two or three VCOs are usually sufficient.

All modern subtractive synthesizers are polyphonic
(but they usually can be switched to mono mode
if a musician whishes so).

Commercial subtractive instruments

- Robert Moog's synthesizers – Moog Modular, MiniMoog, PolyMoog and others.
- ARP, Buchla, Oberheim, Sequential Circuits Prophet, Yamaha CS, Roland, Korg MS & PS.
- Later models from 1980s were hybrid synthesizers with digital oscillators (e.g. Roland Juno).
- Digital instruments (emulators) – e.g. Clavia Nord Lead 2X), "virtual analog synthesis".
- Software synthesizers (VST) – a large number, including Arturia Moog Modular and free Synth1.

Robert Moog with his "children"

Digital implementation of subtractive s.

Subtractive synthesis may be implemented in digital as:

- hardware – instruments with keyboard, “virtual analog”, often combined with sampling and other methods,
- software – programs running on a computer; usually created in VSTi technology (need a VST host)
- modular software – a user builds the synthesis algorithm by connecting blocks (oscillators, modulators, etc.).

Digital subtractive synthesis

Synth1: a free and very capable software synthesizer

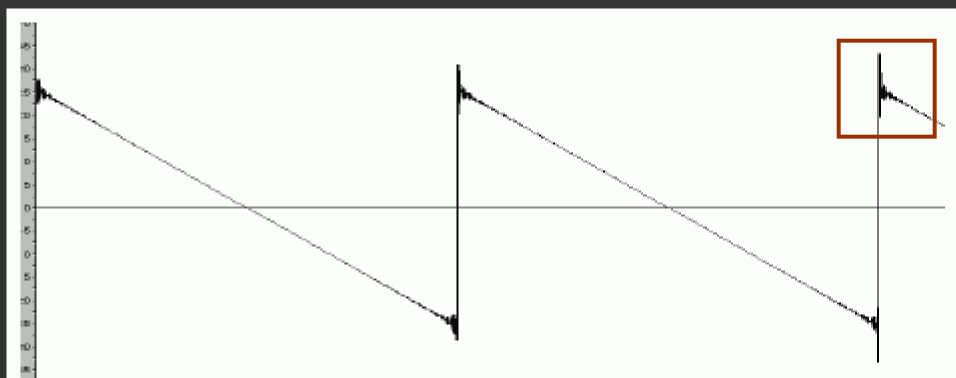
Problems of digital implementation

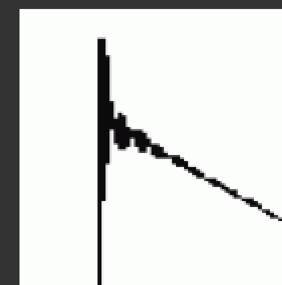
It’s easy to create a digital subtractive synthesizer.
But it’s very hard to make it sound good!
Digital devices are simply “too perfect”.

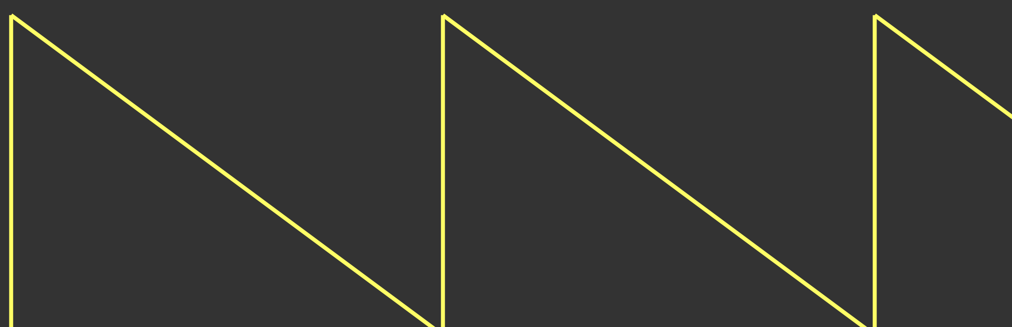
- Emulating imperfections of analogue synthesizers:
  - unstable wave shapes,
  - unstable parameters (but the frequency must be stable!)
- Digital oscillators – the aliasing problem.
- Differences in characteristics of analogue and digital filters.
- Level limiting (soft clipping).

Problems of digital implementation

A sawtooth wave produced by Moog Modular
vs. the ideal wave:

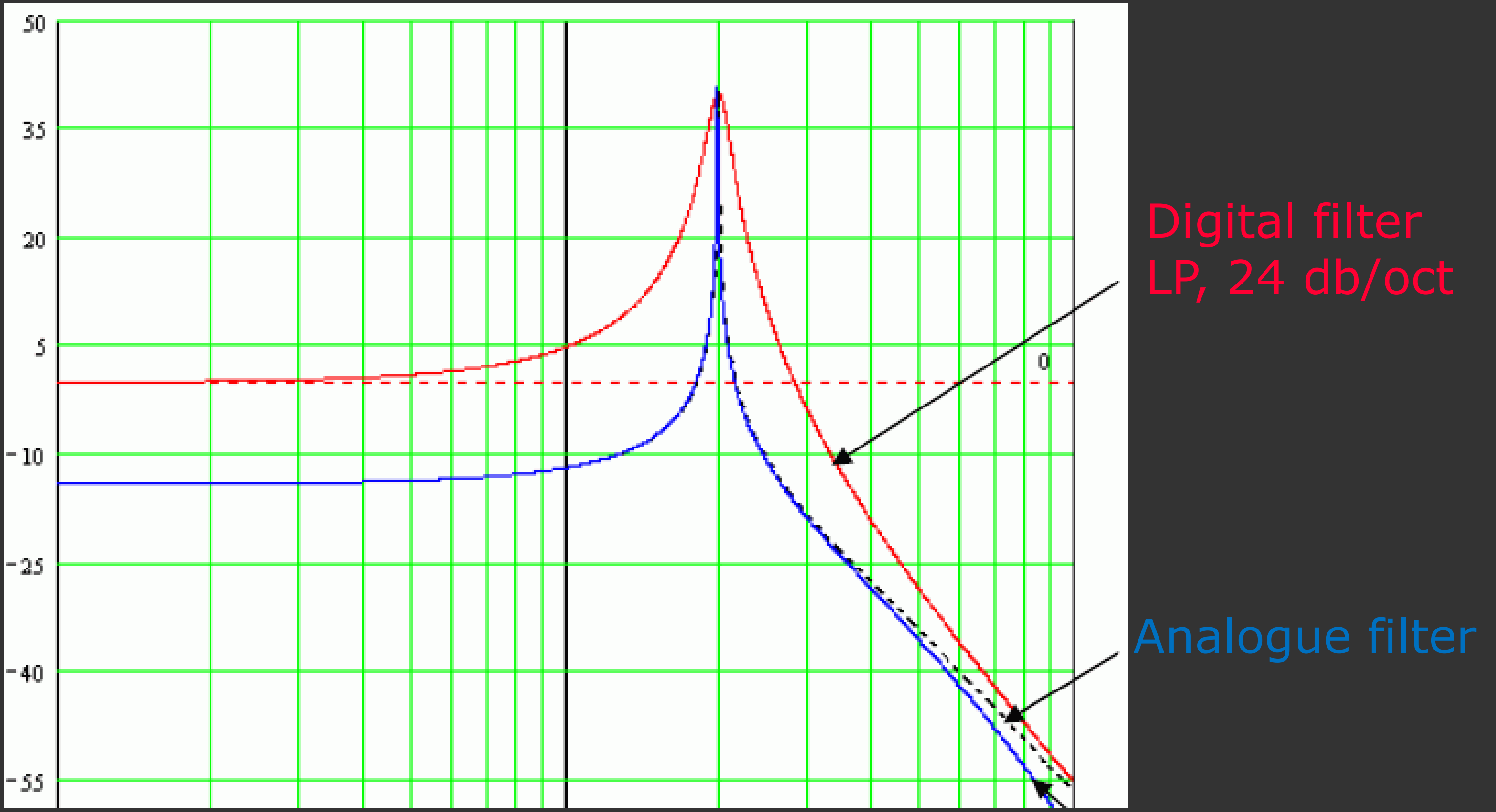






Problems of digital implementation

Transfer functions of resonant VCFs



Summary

Pros:

- ability to create new interesting sounds
- novel sounds (unlike all instruments before)
- easy method to implement

Cons:

- difficult to operate, many parameters to adjust
- it cannot replicate real instrument sounds
- problems with digital emulation
- analogue oscillators were unstable, they often detuned by themselves
- analogue instruments were expensive

Bibliography

- http://moogarchives.com
  Moog Archive – database of Robert Moog instruments
- http://daichilab.com/synth1/
  free software synthesizer Synth1
- https://multimed.org/student/eim/doc/Synth1.pdf
  Synth1 documentation
- http://www.xs4all.nl/~rhordijk/G2Pages/
  G2 Workshop - G2 synthesizer programming, subtractive synthesis theory
- https://www.youtube.com/user/DoKashiteru
  movies showing the work with Moog Modular