# Abbreviations

VCA Voltage-controlled amplifier

ADSR Attack, Decay, Sustain, Release

VCF Voltage-controller filter

VST Virtual studio technology

DAW Digital audio workstation

FM Frequency modulation

LUT Lookup table

LFO Low frequency oscillator

IR Impulse response

VCO Voltage-controlled oscillator

CV Control voltage

LPF Low-pass filter

HPF High-pass filter

BPF Band-pass filter

# A brief history of musical synthesisers

<https://www.thomann.de/blog/en/history-of-the-synthesizer/>

<https://en.wikipedia.org/wiki/Synthesizer>

An instrument usually described as a “synthesiser” or “synth” is any electronic device or software that can generate audio signals. This can be done through a variety of techniques that have been developed and have evolved during the 20th and 21st centuries.

One of the most well-known earlier synthesisers is the theremin, invented by Leon Theremin and patented in 1928. The theremin consists of an oscillator whose frequency and amplitude are controlled by two “antennas”.

The device operates through capacitive coupling with the “antennas” and the performer’s hands. The capacitance changes as the performer moves his/her hands, which subsequently controls the amplitude and frequency of the oscillator. Due to the environmental sensitivity, the theremin is notoriously difficult to play and to keep in tune.

The vacuum tube (or thermionic valve) triode was used before the silicon transistor to control currently flow with a separate control voltage. This formed the basis of many keyboard synthesisers which became popularised in the late 1930s. The Novachord built by the Hammond Organ Company is a prime example, which used 146 vacuum tubes for 72 VCAs.

<https://www.redbull.com/gb-en/electronic-music-early-history-of-the-synth>

Modular synthesis was popularised by the companies Moog and Buchla in the 1960s. Analogue electronics were used for synthesis where multiple modules generate control voltages in tandem to modulate parameters. Common building blocks were VCOs, envelope generators (ADSR), VCFs, VCAs, sequencers, wave-shapers, and noise generators. These are still the fundamental aspects of most synthesisers to date. Emulation or cloning of original Moog or Buchla hardware such as the 4-pole ladder VCF is still sought after in the current commercial market.

In contrast, modern eurorack modules offer a wide variety of complex options, which are often analogue or digital-analogue hybrid. An example is the Make Noise MATHS module which is very popular in the modular synth community. It provides features such as amplification, integration, summation, function generation, and is considered an essential module by many influencers. <https://www.musicradar.com/news/the-best-eurorack-modules-in-the-world>

<https://www.makenoisemusic.com/modules/maths>

<https://www.youtube.com/watch?v=UXEyEIo-WtA&ab_channel=ANDREWHUANG>

<https://ajhsynth.com/VCF.html>

<http://www.vintagesynth.com/yamaha/dx7.php>

Due to the complexity of analogue electronics, most synths were still monophonic in the 1960s and 1970s, or had very limited polyphony. Each extra note required duplication of electronics, which in turn require fine-tuning. The introduction of digital technology in the 1980s allowed for more flexible polyphony at more affordable prices. The Yamaha DX7 is an incredibly well-known early digital synthesiser released in 1983, which used FM-synthesis. The DX7 was used on records by U2, Toto, Queen, Elton John, and jazz virtuoso Chick Corea. Sampling synthesis, which is very similar to wavetable synthesis, was utilised in the late 1980s by other digital keyboard products such as the Roland D-50 and the Fairlight CMI, and drum machines used in the conception of the hip-hop genre.

The introduction of more powerful computation led to the development of software synths and VSTs for DAWs which use a variety of synthesis techniques such as FM, additive synthesis, subtractive synthesis, physical modelling, and wavetable synthesis. Wavetable synthesis is very popular in all music genres and sound design for film. Some of the most popular instrument VSTs used are Serum by Xfer Records, Massive by Native Instruments, and PIGMENTS by Arturia. The aforementioned VSTs focus on wavetable synthesis with sampling, filtering, parameter modulation and FM capabilities. Serum is extensively used in EDM genres by artists such as DeadMau5 and Virtual Riot.

<https://www.adsrsounds.com/product/software/serum/?gclid=CjwKCAjwjdOIBhA_EiwAHz8xm64omh9yLBlXYuwcY0uULQMfA1ZL5niC7qjhnhAE7iKlhgO9fy6CxhoCzBcQAvD_BwE>

<https://www.arturia.com/products/analog-classics/pigments/overview#en>

<https://www.native-instruments.com/en/products/komplete/synths/massive/>

<https://www.youtube.com/user/deadmau5>

<https://www.youtube.com/user/OfficialVirtualRiot>

VSTs not feasible for live performances (requires computer). Many amateur musicians own a basic MIDI controller. Keyboards are expensive. Simple, cheap alternative to keyboard.

# Basic modular synthesiser building blocks

This overview focuses on modular synthesiser building blocks directly but is relevant to all forms of synthesis since most standard modern synthesis is based on the principles popularised by Moog and Buchla. Example modules will be shown, discussed, and compared to features present in commercial wavetable synthesisers and features to be considered for design in this thesis.

It should be noted that modular synthesis is a niche market, with many commercial and boutique manufacturers along with hobbyists wanting to contribute. Hence, there are many modules with a wide variety of features that make them unique. Many modules fulfil multiple purposes instead of one. The examples chosen in this section are popular modules that are as simple as possible and serve only a single purpose.

## The VCO

<https://www.detroitmodular.com/eurorack/doepfer-a-111-3.html>

VCO modules commonly include 1V/octave CV inputs for frequency and provide the basic waveforms as outputs either separately via a switch or simultaneously. They can be analogue or digital in nature and can use a variety of synthesis techniques to generate their waveforms. They often come with the ability set the offset tuning voltage and can be used to create FM signals through control voltages. Extra features such as wave folding are sometimes also present.

The Doepfer A-111-3 Micro Precision VCO/LFO is an analogue VCO that can also operate in LFO configuration, either with a linear or exponential voltage control. Sync (for phase/frequency syncing) and PWM CV inputs are also available.

All the basic waveforms are present, except for the sinusoid which is notoriously difficult to generate with analogue electronics, which is commonly implemented by a high-Q unstable filter.

## The VCF

The VCF is an incredibly important module that forms the basis of subtractive synthesis techniques. Most synths also offer filtering capabilities, such as the widely used Nord Stage 3.

<https://www.nordkeyboards.com/products/nord-stage-3>

Filters can come in many types, often designed with unique characteristics. This can include special control voltage behaviour, feedback path saturation to limit resonance while adding additional harmonics, or the ability to achieve exceptionally high Q values that cause purposeful instability that allow filters to also function as a sinusoidal oscillator (which many VCOs do not generate).

Thus, filters for musical applications are usually not designed to be as “clean” and stable as possible. Instead, they focus on usability and uniqueness.

Filter types can include a switchable LPF, BPF or HPF mode, a ladder filter, 12dB/octave or 24dB/octave varieties and a state variable filter configuration.

<https://www.detroitmodular.com/eurorack/intellijel-uvcf.html>

The IntelliJel UVCF is popular state variable filter that simultaneously outputs a 2-pole low-passed, 2-pole high-passed and 1-pole band-passed signal which has a cut-off that can be modulated by 2 separate 1V/octave control voltages. It can also be set to have a high Q-value so that it can act as a sinusoidal VCO due to filter instability.

## The VCA

<https://www.detroitmodular.com/eurorack/mfb-vca.html>

The VCA has the primary purpose of performing the multiplication of signals for uses in AM and otherwise. It acts as an amplifier with a voltage controllable gain. It is often used in conjunction with an LFO to create a tremolo effect or with an ADSR envelope to shape the transient of signal to emulate bowing or plucking and removing clicks and pops that can occur with the immediate triggering of signal.

Many VCOs only output a continuous signal. Hence, a VCA is required to mute any oscillators that are not triggered.

The ring modulation effect can also be achieved by multiplying 2 signals in the audible frequency range together.

The MFB VCA is module that has 3 different inputs and 2 CV inputs that modulate the gain. The operation of the various inputs is specific to this module and out of the scope of this thesis.

## The ADSR envelope

The ADSR envelope is a critical component in synthesis used to achieve realistic sounds. It is often used to modulate filter cut-off to allow for dynamic subtractive synthesis. It is also used for AM to emulate the natural attack and decay characteristics of real instruments. It can emulate plucking, strumming, bowing, and blowing techniques found in real instruments. It can also be used in FM to recreate the typical pitch modulation found when striking percussive instruments \*REF?\*.

A close-up of a computer chip

Description automatically generated with low confidenceADSR envelopes are available in most wavetable synthesisers for parameter modulation, such as Serum, Massive and Ableton’s stock Wavetable VST instruments. Many keyboards also include this feature, such as the Nord Stage 3.

The ADSR envelope consists of 4 phases. The envelope curve is initiated with a gate “on” trigger after which a rising function is started. Once a threshold is reached, determined by the attack time, the decay state is activated. The decay is specified by a decay time parameter. The function decreases until a sustain level is reached, which is a parameter set by the performer. The sustain level is usually less than the peak achieved by the attack phase. The sustain phase remains constant until the gate signal changes state to indicate an “off” trigger, initiating the release phase. The release phase is a decreasing function that decreases until zero is reached (or close to zero in the case of an RC circuit), determined by a release time parameter.

There are thus 4 parameters that can be set by the performer: attack time, decay time, sustain level and release time. The A, D and R phases are usually exponential functions implemented by an RC circuit. This is well suited for AM and FM, since octaves are exponential in nature (doubling in frequency) and human hearing is logarithmic in nature \*REF?\* – an exponential volume change is perceived as linear.

ADSR state changes are often triggered by a comparator and other switching ciruitry when the exponential function reaches a fraction of its final charge value \*REF?\*. Reaching 0.67 of the final value is a common threshold \*REF?\*. The decay and sustain states are often a single RC circuit \*REF?\*. \*Doepfer schem?\*

The Doepfer A-140 ADSR Envelope Generator is a classic envelope generator with a gate CV input, an envelope output, and a negated envelope output. It also has a retrigger input that allows the “on” trigger to occur again, reinitiating the attack phase, independent of the current phase of the envelope.

Digitally, an ADSR envelope generator can be implemented by a 5-state state machine (off, A, D, S, R). It can be designed to provide retrigger functionality. Retriggers can often be required in monophonic synths where a note can be played before a previous note is released, thus requiring a retrigger without reaching the release phase. For computational efficiency, an exponential LUT can be used.

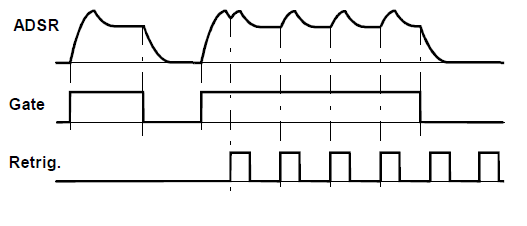
<https://www.detroitmodular.com/eurorack/doepfer-a-140-adsr-envelope-generator.html>

*Image obtained from A-140 manual.*

<http://www.doepfer.de/a100_man/A140_man.pdf>

Diagram

Description automatically generated



# A basic monophonic modular setupDiagram Description automatically generated

# An overview of synthesis techniques

<https://en.wikibooks.org/wiki/Sound_Synthesis_Theory>

Most techniques are often combined in commercial products and operate in a similar way. The similarities, differences and operation principles will be explored in this section. This is will also explore why wavetable synthesis can be considered the most flexible and computationally robust technique.

## Additive synthesis (Fourier synthesis)

The principle of operation is based on the harmonic series of a time signal:

Various sinusoids are added together with different amplitudes and phases to produce a signal. The amplitudes and phases and frequencies may be time varying as well, which ties into physical modelling techniques that accounts for the time dependent timbre of most instruments. Modulating frequency directly ties in with FM synthesis.

Computing and adding many sinusoids in real-time can be computationally expensive – which can be reduced with a sinusoid LUT, as is directly done in wavetable synthesis. If time-varying amplitudes and phases are not present, additive synthesis can be completely replaced by wavetables (LUTs). If enough memory is present, caching the resulting waveform in a LUT would require less computation and thus have more robust performance. Serum has some functionality for creating wavetables using the principles of additive synthesis.

## Subtractive synthesis

This technique is very simple and is possible in most synthesisers. It requires a harmonically rich source signal (generated by any means, such as direct computation, LUTs or analogue electronics) like a square wave:

It consists of odd harmonics with amplitudes:

The source signal is then passed through a filter to further shape the harmonics. Any filter can be used. Time varying filters with modulated parameters are usually prevalent.

This option is almost always present and/or possible to achieve in most synthesisers that offer filtering capabilities. Many products usually offer a selection of base waveforms which often includes most of or all the basic waveforms (sine, triangle, sawtooth and square).

## FM synthesis

This technique uses the same principles as FM for data communication, except in the audible frequency range. The resulting waveform is of the form:

where is a period function with time-dependent frequency .

This technique can produce unique and interesting results depending on the functions chosen for and . Emulation of drum-like sounds such as toms and growling sounds often occurring in EDM genres are easily possible with this technique.

The choices offered for chosen for and are product dependent but can often include the basic waveforms for and ADSR envelopes for . Multiple oscillators modulating each other’s frequency, often in a coupled or recursive manner, is common, as in the stock Ableton VST plugin Operator which is a FM-centric VST.

<https://www.ableton.com/en/shop/live/>

Many non-FM-centric synths also offer a vibrato feature, which requires the use of dedicated vibrato LFO that slightly modulates the source signal’s frequency. This is present in VSTs such as Omnisphere 2 by Spectrasonics, which is wavetable and sample-based.

<https://www.spectrasonics.net/products/omnisphere/>

FM synthesis is often combined with wavetable synths such as the Serum and Massive VSTs. It is also easily achievable in modular synth setups since most oscillator modules allow for controlling their frequency with a voltage signal.

## Physical modelling

<https://theproaudiofiles.com/physical-modeling-synthesis/>

This method involves simulating the sound source of interest. It is usually separated in continuous models for bowed or blown instrument or impulsive models such a struck or picked instruments.

A variety of methods can be used, such as IR modelling, analytical simulation (differential equations), frequency domain modelling as mentioned under additive synthesis, and waveguide synthesis such as the Karplus-Strong plucked string algorithm.

This type of synthesis is not relevant to the topic of this thesis.

## Sampling

<https://ccrma.stanford.edu/~jos/jnmr/Sampling_Synthesis.html>

Sampling synthesis is the technique of using pre-recorded audio samples to reproduce sounds. An example would be to record every key of a piano at different volumes and then assigning a sample to trigger when conditions are met. The Kontakt player by Native Instruments is a popular sample player plugin into which third-party sample libraries can be loaded into to reproduce high-quality and realistic audio. High quality samples often take enormous amounts of effort to make, which results in a high commercial price point as can be seen in Omnisphere and Spitfire Audio Kontakt libraries.

<https://www.spitfireaudio.com/shop/>

<https://www.native-instruments.com/en/products/komplete/samplers/kontakt-6-player/>

Recorded samples can also be manipulated to increase or decrease their pitch, allowing for a wide variety of options to the performer.

It is very similar to wavetable synthesis, where a predefined buffer (LUT) is used to generate sound. However, sampling often uses large buffers that are not necessarily intended to reproduce a periodic waveform (but sometimes do for continuous sound produced by instruments such as flutes), but instead a one-shot triggered signal, ideal for percussive instruments. Samples and wavetables can be manipulated and modulated in the same way.

This technique is computationally efficient but may require a large amount of memory to store the samples – often in the order of gigabytes, as for Kontakt libraries.

Another related synthesis technique is granular synthesis, where sampled audio is divided into “grains” which are treated like wavetables. They grains are looped, layered, and randomised to produce a soundscape often referred to as a “synth pad”.

## Wavetable synthesis

FOR PWM, SEE CARSON’S RULE

<https://itectec.com/electrical/electronic-coefficients-and-harmonics-of-a-pwm-signal/>

Dual Core

<https://predictabledesigns.com/introduction-to-the-ultra-high-performance-stm32h7-microcontroller/>

<https://wiki.st.com/stm32mpu/wiki/HSEM_internal_peripheral>

MIDI

<https://www.cs.cmu.edu/~music/cmsip/readings/MIDI%20tutorial%20for%20programmers.html>

Why MIDI – small, cheap, compact device for performers. Arbitrary controllers. Simplistic.

<https://ccrma.stanford.edu/~jos/pasp/Linear_Interpolation_Frequency_Response.html>

<https://en.wikipedia.org/wiki/Upsampling>

Quadratic interpolation

<https://zipcpu.com/dsp/2018/03/30/quadratic.html>