Electronic Sound Generation

Circuit design from A to Z — analog, hybrid, digital

Syntagma Forschung Wien

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A transdisciplinary main work · engineering level with a beginner's entry Syntagma Forschung Wien · CC BY 4.0 · PROVISIONAL FORSCH ≥0374 (slug `elektronische-klangerzeugung`)

> Trigger: Ray Wilson, *Make: Analog Synthesizers*. This work detaches the principles from the single teaching device and presents them systematically, bilingually and with interactive tools (T1–T7). **Note:** passages marked `[to be verified]` are to be checked against current primary sources before publication.

Part 0 — Orientation

> This part explains what the book wants, how to read it, and what to note before the soldering iron gets hot. If you want to build straight away, read 0.2 and 0.4 and then jump to Part 4.1.

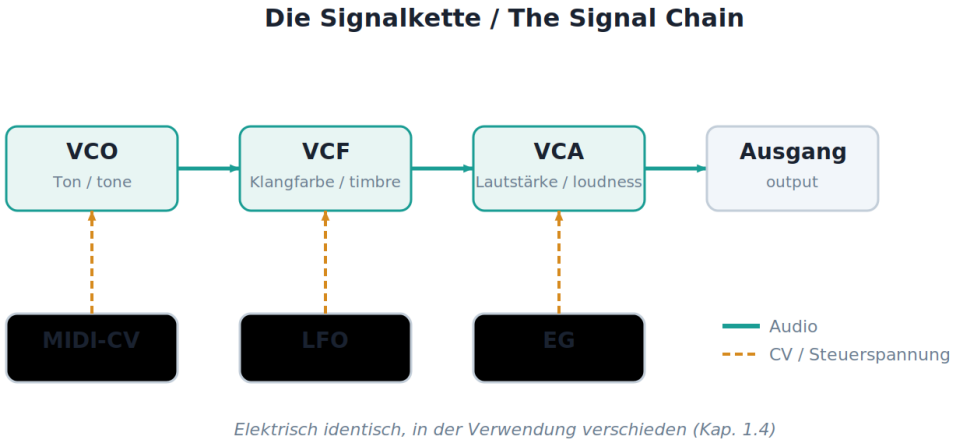


Fig. 1: The signal chain

Fig. 1: The signal chain

0.1 What electronic sound generation is

An acoustic instrument produces sound by making something physical vibrate: a string, a column of air, a drumhead. The electronic sound generator skips this step. It builds **the voltage curve directly** that a loudspeaker finally translates into moving air.

From this follows the freedom of the technique: because the curve is not dictated by a physical body, it can be **anything**. And from this follows the problem at the same time: because it can be anything, you must know which curve you want and how to produce it. That is precisely the subject of this book.

The core question throughout: how do you generate, shape and control a voltage so that a musically usable sound emerges at the end — and how do you build the circuit that does it?

0.1.1 What this book covers — and what it does not

The subject is the hardware axis: the circuit design of sound generation, from passive components through the basic circuits and modules to the finished instrument, the system formats and your own development.

Not the subject: - mixing, sound reinforcement and studio technique (a separate strand), - loudspeaker construction and room acoustics (a separate strand), - software synthesis and DSP implementation as a product (a separate strand; the points of contact are in Part 7), - music theory and composition.

The delimitation is deliberate: each of these fields carries its own book, and mixing them would dilute all four.

0.2 How to read this book

0.2.1 The dual track

Every chapter has two entry points, marked throughout the text:

- ▶️ **B — beginner track.** What happens, why it happens, with intuition, analogy and, where possible, a minimal build. Readable without higher mathematics.
- ▶️ **E — engineering track.** The calculation: formulas, dimensioning, limits, component choice.

Both tracks describe the same subject at different resolution. If you only want to build, ▶️ B and the calibration instructions get you far. If you want to develop, you need both.

0.2.2 Four reading paths

(A) "I want to hear something quickly." 0.4 (safety) → 4.1.1 (555 minimal build) → 2.6 (soldering) → 4.5 (LFO) → 4.7 (utilities)

(B) "I want to build a synthesizer." 0.4 → 1 (foundations) → 2 (components, instrumentation) → 3 (op-amp) → 4 (modules) → 5 (instrument) → 6.1 (format)

(C) "I want to develop my own modules." Path B → 8 (simulation, KiCad, manufacturing) → 8.5 (open hardware) → 9 (cookbook)

(D) "I want to understand how it works without building." 1 (foundations) → 3 (basic circuits) → 4 (modules) → 7 (hybrid/digital), with the tools alongside

0.2.3 The tools

Several chapters come with interactive calculators that use the same formulas as the text:

Tool	Topic	Chapter
T1	signal-chain visualizer	4.8, 5.1
T2	filter calculator (Bode plot)	4.2
T3	VCO tuning / exp-converter calculator	4.1, 3.3
T4	envelope simulator	4.4
T5	Eurorack power/HP calculator	6.1
T6	chip/component reference	2.3, Appendix B

They run in the browser, without installation and without an internet connection.

0.2.4 Conventions in the text

- **[to be verified]** marks statements to be checked against current primary sources before publication (availabilities, prices, project links). The book names them openly rather than concealing them.
- **Cross-references** appear as a chapter number in parentheses, e.g. (4.1.2).
- **Formulas** are in the engineering track; each is explained in the text before it is used.
- **Component values** are starting-point guide values; the reasoning for the choice accompanies each.

0.3 The three epochs — a map

An overview so the later chapters can be placed:

Epoch	Period	Defining features	Chapters
Analog	~1960–1980	voltage-controlled modules, Moog/Buchla, 1V/oct	1–6
Digital	from ~1980	FM, sampling, wavetables, presets	7
Hybrid / renaissance	from ~2000	analog signal path + digital control, the Eurorack DIY wave	6, 7, 8

The epochs do not replace one another but layer up. Analog technology is not obsolete — today it is used deliberately where its properties (saturation behavior, no aliasing, immediate response) are wanted. The structure of this book therefore follows the logic of the subject, not chronology: understand analog first, then add digital.

0.4 Safety

This section is the only one in the book that should not be skipped.

0.4.1 Mains voltage

The rule: anything connected directly to 230 V is life-threatening.

- **Use ready-made power supplies.** A certified PSU (plug-in supply or encapsulated module) safely isolates the mains. Building the primary circuit yourself — mains transformer, mains fuse, mains switch, protective earth — requires expertise and is the wrong place to learn as a beginner.
- **Never work on an opened device that is connected to the mains.** Not even "just briefly."
- **Electrolytics store charge**, even after switch-off. Discharge before touching (a defined bleed resistor, do not short) and check with the multimeter.
- **If in doubt:** the low-voltage section (±12 V) is harmless, the power supply is not. Take this boundary seriously.

0.4.2 Soldering

- **Ventilate.** Solder fumes (above all flux) are respiratory irritants. Open a window, better a fume extractor or a fan that draws the fumes away.
- **Safety glasses.** Clipping component leads sends wire pieces flying; desoldering can splash molten solder.
- **Wash hands** after handling leaded solder; do not eat or drink at the workbench.
- **The iron is hot** and stays so for minutes after switch-off. Use the stand, do not run cables over the tip.

0.4.3 ESD (electrostatic discharge)

CMOS components (the CD4000 series, microcontrollers, many modern ICs) can be destroyed by static charge — often **unnoticed**, with damage that only shows up later as a sporadic fault.

A practicable minimum: - Touch a grounded metal part before handling ICs (a radiator, the case of an earthed device). - Leave ICs in their conductive packaging until they are fitted. - No plastic surfaces and no wool sweaters at the workbench. - For regular work: an ESD mat and a wrist strap.

0.4.4 Hearing

The most frequently underestimated point in a book about sound generation.

- **Fault-finding produces unpredictable levels.** An oscillating circuit, a miswired VCA or a short can suddenly deliver full level to the headphones. **Turn the volume down before every power-up.**
- **Take the headphones off when testing**, or work over speakers at low volume while adjusting the circuit.
- **Hearing damage is irreversible** and cumulative. Long sessions at medium volume are more harmful than brief peaks — plan breaks.
- **Self-oscillating filters and high resonance** produce very high levels at narrow-band frequencies; be especially careful.

0.4.5 The ethics of the work

This work is published under a free licence and is designed for replication and further development. It contains **no** applications for military, weapons or surveillance purposes, and the methods described here are not intended for them either. Anyone using them that way acts against the declared intention of the work.

0.5 Prerequisites

What you should bring: - Basic arithmetic and a willingness to read a formula (the engineering track explains every one it uses). - Patience in fault-finding — the greater part of build time is fault-finding, and that is normal (5.4.2).

What you need not bring: - A degree in electrical engineering. - Existing equipment: Part 2.5 gives the order of acquisition; you can start with a multimeter and a soldering iron. - A modular system: the minimal build in 4.1.1 costs a few euros, and Part 7.6 shows how to play through all the concepts in software at no cost.

0.6 Cross-references

- **Straight on to the first tone:** Part 4.1.1 (555 minimal build).
- **A systematic start:** Part 1 (foundations).

- **Tools and components:** Part 2.
- **Safety during construction:** Part 5.2.4 (staged commissioning), Part 6.1.2 (reverse-polarity protection).

Part 1 — Physical and Signal-Theoretical Foundations

Dual track. ▶️ B builds the intuition: what sound is physically and how it becomes voltage. ▶️ E supplies the quantities used in later calculations. This part is the prerequisite for all module chapters — if you read 4.1 onward and stumble, the reasoning is usually here.

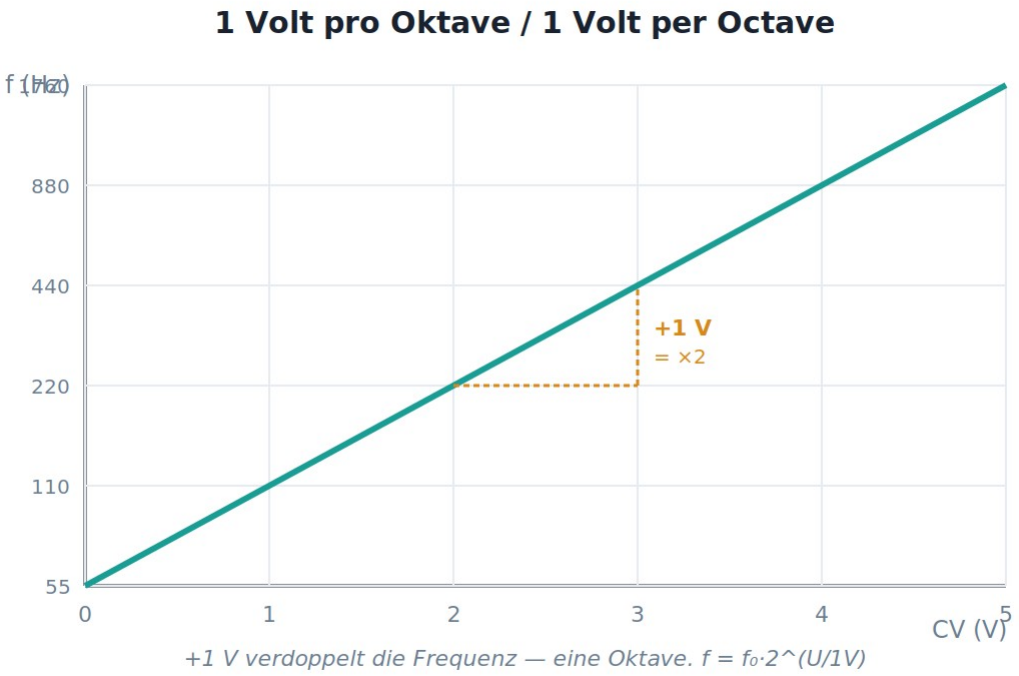


Fig. 2: 1V/octave transfer curve

Fig. 2: 1V/octave transfer curve

1.1 Oscillation, frequency, harmonics

1.1.1 ▶️ B — From air to voltage

Sound is a **pressure fluctuation in air**. A microphone converts it into an electrical voltage fluctuation; a loudspeaker turns it back into pressure. In between — in cables, circuits, modules — sound is simply a **voltage changing over time**.

This is the central change of perspective in this book: the synthesizer does not produce sound through vibrating strings or air columns, but by **building the voltage curve directly** that a

loudspeaker later translates into motion. Everything else is the question of how to shape that curve.

1.1.2 ▶️ B — The three basic quantities

- **Frequency** — how often the oscillation repeats per second, in hertz (Hz). Determines **pitch**. Human hearing range roughly 20 Hz to 20 kHz, declining at the top with age.
- **Amplitude** — how large the excursion is. Determines **loudness**.
- **Waveform** — what a single period looks like. Determines **timbre**.

1.1.3 ▶️ E — Fourier: why shape is timbre

Fourier's theorem states: **every periodic oscillation can be represented as a sum of sine waves** — a fundamental and integer multiples (the harmonics).

Timbre is therefore nothing other than the **distribution of harmonic amplitudes**. The canonical waveforms differ in exactly that:

Waveform	Harmonics	Amplitude falloff	Sound
Sine	only	—	pure, "whistling"
Triangle	odd only		soft, hollow
Square	odd only		hollow, clarinet-like
Sawtooth	all		bright, "cutting", string-like

Why this matters for building: the sawtooth contains *all* harmonics and is therefore the ideal raw material for **subtractive synthesis** — a filter can carve anything out of it. From a sine, by contrast, filtering cannot recover what is not already there. This explains why the sawtooth is the standard waveform of classic synthesizers (Part 4.1, Part 5.1).

Pulse wave and PWM: a square wave with variable duty cycle (pulse width) has a harmonic spectrum that changes with the width — at 50 % all even harmonics are absent; at other values they appear. Modulate the width slowly (PWM) and the spectrum drifts: the characteristically "floating," wide sound (Part 4.5).

1.2 Levels, dB and dealing with ratios

1.2.1 ▶️ B — Why decibels

Hearing works over an enormous range: from the just-audible to the pain threshold spans roughly a factor of **one million** in amplitude. Such spans are unwieldy linearly. The **decibel** is therefore a logarithmic **ratio measure** — it always describes a ratio, never an absolute value (unless the reference is named, as in dBu or dBV).

1.2.2 ▶️ E — The two formulas

For **voltages** (and all field quantities):

For **powers**:

The factor 20 vs. 10 is the most common confusion. Reason: power depends on the square of voltage (), and .

Values to remember (voltage):

Ratio	dB
×1	0 dB
×2 (double)	+6 dB
×10	+20 dB
×0.5 (half)	−6 dB
×0.1	−20 dB
×0.707	−3 dB (filter corner frequency!)

Practical consequence: the −3 dB mark at a filter's corner frequency (Part 4.2) is the point where *power* is halved — the voltage there is at .

1.2.3 ▶️ E — Levels in the synth vs. the studio

Context	typical level	Note
Eurorack audio	±5 V (10 Vpp)	Part 6.1.4
Line (professional)	+4 dBu ≈ 1.23 Vrms	studio
Line (consumer)	−10 dBV ≈ 0.316 Vrms	hi-fi
Microphone	~1–50 mV	preamp needed
Guitar (passive)	~100–500 mV	high impedance!

The order of magnitude: a Eurorack output delivers roughly **ten to twenty times** a line level. Hence the need for an output module (6.1.4) — fed straight into a mixer it overloads massively.

1.3 Impedance: why outputs are low and inputs high

1.3.1 ▶️ B — The principle

Impedance is the (frequency-dependent) resistance an input or output presents. The rule of audio engineering is **voltage bridging**:

> Outputs **low-impedance** (small), inputs **high-impedance** (large).

Intuition: the output should be able to deliver its voltage "stubbornly," without the attached load pulling it down. The input should draw as little current as possible, so as not to load the source.

1.3.2 ▶️ E — The calculation

A source with internal resistance into a load forms a voltage divider:

With , — no appreciable loss. Eurorack example: output resistance, input resistance:

Negligible. But hang **ten** inputs in parallel (passive multiple) and the load impedance drops to 10 kΩ:

Still acceptable for audio. **Not for pitch CV:** a 9.1 % voltage loss produces, at 1 V/octave, a pitch error that **grows with the control voltage**:

CV (nominal)	arriving	error
1 V	0.909 V	1.1 semitones (109 cents)
3 V	2.727 V	3.3 semitones (327 cents)
5 V	4.545 V	5.5 semitones (545 cents)

The instrument is thus not merely detuned but **increasingly wrong across the keyboard** — it plays intervals that are too small. This is the exact reasoning for buffered multiples (Part 6.1.4, 4.7.2).

1.4 The CV principle: voltage as a control quantity

1.4.1 ▶️ B — The central idea of the modular system

The breakthrough of modular technology (Moog, Buchla, 1960s) was the insight: **if every parameter is controlled by a voltage, then any voltage source can control any parameter.** An envelope can control loudness — or pitch, or the filter, or pulse width. The tangle of patch cables is the visible form of that universality.

There are two kinds of connection that must never be confused:

- **Audio** — swings fast (20 Hz–20 kHz), is heard.
- **CV (control voltage)** — changes slowly (or not at all), is not heard but *controls*.

Electrically the two are identical — same jacks, same cables. The difference lies only in speed and use. That is precisely why one *can* turn an LFO into the audio range and make modulation into synthesis (4.5.1).

1.4.2 ▶️ E — The standards

Standard	Law	Use
1 V/octave		Moog lineage, Eurorack, de-facto standard
Hz/V		Korg/Yamaha (historical), Buchla in part
Gate	high/low state	note on/off
Trigger	short pulse	event (attack)

Why 1 V/octave won: the law is **additive**. To transpose a played note up a fifth you simply add 0.583 V (= 7/12 V). With Hz/V you would have to *multiply* — considerably more involved in circuitry. Additivity makes mixers, offsets and sequencers trivial (Part 4.7.2). Implementing this exponential law is the subject of Part 3.3.

1.5 Noise, hum, grounding

1.5.1 ▶️ B — The four sources of interference

1. **Component self-noise** — thermally unavoidable, becomes audible at high gain (Part 4.3.2).
2. **Mains hum** — 50 Hz (Europe) or 60 Hz (USA) and multiples, coupled in from transformers and mains wiring.
3. **Digital interference** — clock and switching pulses from microcontrollers (Part 7).
4. **Ground loops** — several ground connections forming a conductive loop that acts as an antenna.

1.5.2 ▶️ E — Grounding in practice

Star ground. All ground connections run to **one** central point instead of being daisy-chained. Reason: in a chain, the currents of all stages flow through the same trace segments; their resistance produces voltage drops that couple into sensitive stages as interference.

Practical rules:

- **Separate analog and digital ground** and join them at only one point (typically at the PSU or the DAC).
- **Decoupling capacitors** (100 nF ceramic) directly at every IC supply pin, as close as possible. They supply fast current spikes locally instead of dragging them across the whole board.
- **Additionally an electrolytic** (10–100 µF) per assembly as an energy reservoir.
- **Keep sensitive traces short:** CV paths and OTA inputs are high-impedance and pick up interference.

- **Avoid ground loops between devices:** only one earth path; with several cases on their own PSUs, hum is typical (Part 6.1.5).

1.5.3 ▶️ E — Signal-to-noise ratio and gain structure

The **signal-to-noise ratio** (SNR) is the ratio of wanted signal to noise. It is determined by the **gain structure** — that is, where in the signal path you amplify and where you attenuate.

> **Basic rule:** amplify to the required level as early as possible, then avoid unnecessary attenuation followed by re-amplification.

Every attenuation followed by amplification also raises the noise of the stages in between. This is why an OTA VCA with a strong input divider and subsequent gain is noisier than a Blackmer VCA (Parts 4.3.2/4.3.3).

1.6 Cross-references

- **Waveforms in practice:** Part 4.1 (VCO). **Filtering the harmonics:** Part 4.2 (VCF).
- **Levels in the format:** Part 6.1.4. **Gain structure at the VCA:** Part 4.3.
- **The exponential law in circuitry:** Part 3.3.
- **Measurement of these quantities:** Part 2.5 (oscilloscope, multimeter, frequency counter).
- **Tools:** T2 (filter/Bode, dB axis), T3 (1V/oct transfer curve).
- **Corpus cross-reference:** level and sound-reinforcement practice in FORSCH-0288 (MISCHWERK).

Part 2 — Components, Instrumentation and Craft

> **Dual track.** ▶️ B: what you need, what it costs, where to start. ▶️ E: parameters, selection criteria and the failures you actually meet on real components. Section 2.3 (key ICs) precedes this as its own chapter.

2.1 Passive components

2.1.1 ▶️ B — Resistors

A resistor limits current and divides voltage. For synth building:

- **Metal film, 1 %, 1/4 W** is the standard. Carbon film (5 %) is cheaper but noisier and drifts more — noticeable in CV paths and filters.
- **The E24 series** (1.0 · 1.1 · 1.2 · 1.3 · 1.5 …) covers practically everything.
- **Buy an assortment**, not singles: an E24 kit from 10 Ω to 1 MΩ costs little and saves constant reordering.

▶️ E — Special cases that matter:

Type	Use	Why
Tempco +3300 ppm/K	exp converter (3.3.1)	compensates drift
Metal film 0.1 %	precision dividers, references	tracking accuracy
High value 10 M	integrator bleed (3.1.2f)	prevents saturation drift
Wirewound	power applications	rarely needed in a synth

Noise: every resistor produces thermal noise (Johnson–Nyquist). Noise grows with the square root of the resistance value — high-impedance parts of a signal path are measurably noisier. This is one reason for the impedance convention of Part 1.3.

2.1.2 ▶️ E — Capacitors: the type decides

Capacitors are the component where the wrong choice most often produces functional faults:

Type	Range	Properties	Use in a synth
Ceramic NP0/C0G	pF–nF	very stable, low loss	timing, RF filtering
Ceramic X7R/Y5V	nF–µF	**voltage-dependent!**, drifts	decoupling only
Film (PET/PP)	nF–µF	stable, low leakage	**timing, VCO, EG, S&H**
Electrolytic	µF–mF	polarized, high leakage, ages	PSU smoothing
Tantalum	µF	compact, polarized	digital supply

> **The most important rule:** for everything **timing-related** — VCO integrator, envelope, S&H hold element, LFO — use **film capacitors**. Electrolytics have leakage currents in the nA range that make long envelope times impossible (4.4.5) and let S&H voltages drift away (3.4.2). X7R ceramics change their capacitance under voltage by up to tens of percent — a VCO built with them never stays in tune.

2.1.3 ▶️ E — Potentiometers

- **Law: lin** (linear) for most CV and mixing applications; **log** (logarithmic, "A") for volume, because hearing is logarithmic (1.2.1); antilog rarely.
- **Form factor:** 9 mm for dense Eurorack panels, 16 mm for better feel. Shaft length and type (knurled/D-flat) must match the knobs — a common mis-order.
- ▶️ **E — Do not put high values in the signal path:** a 1 M pot in an audio path is noisy and picks up interference; 10–100 k with a suitable buffer is better.
- **Scratching** comes from DC across the wiper track — run pots DC-free or provide a coupling capacitor.

2.1.4 Diodes and small semiconductors

- **1N4148** — universal small-signal diode, standard for logic, clipping, protection.
- **1N4001…4007** — rectifiers, power supply.
- **1N5817/1N5819 (Schottky)** — low forward drop, **reverse-polarity protection** in Eurorack modules (6.1.2).

- **Zener diode** — voltage reference and noise source (4.6.2).
- **LED** — indication; **always** needs a series resistor: , typically 1–5 mA for panel indicators.

2.2 Active components: transistors

2.2.1 ▶️ B — The three families

- **Bipolar (BJT)** — current-controlled. NPN: **BC547/BC548**, 2N3904; PNP: BC557, 2N3906. In a synth: exp converter (3.3), ladder filter (4.2.3a), noise source (4.6.2), switching stages.
- **JFET** — voltage-controlled, high impedance. **J201, 2N5457**: as a controllable resistor (simple VCAs/filters), as an input stage.
- **MOSFET** — power switching, rare in analog synths; used as a switch in digital modules.

2.2.2 ▶️ E — Matched pairs

For the exponential converter (3.3.1) and the ladder filter you need **matched** transistors:

1. **Ready-made pairs/arrays:** THAT300/THAT320 (quad), historically CA3046/LM3046. Already on one die → thermally coupled, very well matched.
2. **Match your own:** measure several transistors from the same batch (at equal current) and take the two closest; then couple them mechanically with thermal paste and heat-shrink.
3. **Tolerance:** even 1 mV difference in shifts the scaling noticeably — matching is therefore not perfectionism but a functional prerequisite.

2.4 Power supply

2.4.1 ▶️ E — The ±12 V world

Analog synth circuits need a **bipolar** supply so signals can swing around 0 V (bipolar CV, audio). Eurorack standard: ±12 V, optionally +5 V (6.1.2).

Ways to generate it:

Path	Principle	Note
Transformer + rectifier + linear regulator	classic (7812/7912)	low hum, inefficient, runs warm
Switch-mode PSU (Meanwell etc.)	switched	efficient, compact; **HF interference** possible → good filtering needed
Charge pump/inverter	derive −12 V from +12 V	e.g. ICL7660/LT1054; small currents only
Bench supply	lab PSU	ideal for development (current limiting!)

▶️ **B — For the bench:** a **lab power supply with adjustable current limiting** is the most important purchase after the soldering iron. On a short circuit in a prototype it limits the current instead of vaporizing components. Ideal: two separate channels (for ±12 V) or a dual supply.

2.4.2 ▶️ E — Smoothing and decoupling

See also 1.5.2. Practical rules for every self-built module:

- **100 nF ceramic** directly at every IC supply pin (as short as possible).
- **10–47 µF electrolytic** per module as a local reservoir.
- **Reverse-polarity protection** (6.1.2) — not optional.
- **Ferrite bead or small inductor** in the supply of sensitive analog stages if digital modules in the same case cause interference.

2.5 Instrumentation

2.5.1 ▶️ B — The order of acquisition

1. **Digital multimeter (DMM)** — indispensable, from ~€20. Measures voltage, current, resistance, continuity.
2. **Lab supply with current limiting** (2.4.1).
3. **Oscilloscope** — the jump from "something is broken" to "I can see what happens."
4. **Tuner or frequency counter** — for VCO calibration (4.1.4).
5. *Nice to have:* function generator, capacitance meter, second DMM, logic probe.

2.5.2 ▶️ E — Multimeter: what matters

- **Continuity buzzer** — the most-used function in fault-finding (shorts, solder bridges).
- **Input impedance** typically 10 MΩ. At very high-impedance points (S&H hold element, integrator) even the meter loads the circuit and falsifies the reading — measure through a buffer there or judge the behavior indirectly.
- **True RMS** only needed when measuring non-sinusoidal AC — rare in a synth, where the oscilloscope is used instead.
- **Diode test** for checking transistors and for rough matching (2.2.2).

2.5.3 ▶️ E — Oscilloscope: the four parameters

Parameter	Meaning	For synth DIY
Bandwidth	max. frequency	20–50 MHz goes a long way; audio needs little, digital edges more
Channels	simultaneous signals	**2 channels minimum** (compare input vs. output), 4 comfortable
Sample rate	samples/s	rule of thumb ≥ 5–10× bandwidth

Parameter	Meaning	For synth DIY
Memory depth	length of the record	important for slow envelopes at fine resolution

▶️ **B — Do not forget DC coupling.** Control voltages are DC. If the probe input is set to **AC**, the DC component vanishes and envelopes look wrong. The most common beginner mistake when measuring CV.

Use a **10:1 probe**: less loading of the circuit, higher bandwidth; remember the ×10 reading and compensate the probe at the calibration output (trimmer in the connector).

2.5.4 What to measure with what

Question	Instrument	Approach
"Is power arriving?"	DMM	measure rails at several points
"Is the pitch right?"	frequency counter/tuner	VCO calibration (4.1.4)
"What does the wave look like?"	oscilloscope	waveform, reset cleanliness
"Where does the signal stop?"	oscilloscope	trace the signal stage by stage
"Is the solder joint good?"	DMM continuity	check before powering up
"Why does it hum?"	oscilloscope	make the 50 Hz component visible (1.5)

2.6 Craft: soldering, prototyping

2.6.1 ▶️ B — Soldering in five sentences

1. **Temperature-controlled station**, 320–350 °C for leaded, 350–370 °C for lead-free solder.
2. **Heat both parts** (pad and component lead), then feed the solder — do not put solder on the tip and smear it on.
3. **1–3 seconds** per joint; longer damages component and pad.
4. **A good joint:** shiny, concave ("volcano"), pad fully wetted. **Bad:** blobby, dull, lead visibly unwetted (a "cold joint").
5. **Flux is your friend** — it removes oxides; the rosin core in the solder usually suffices, extra flux helps on difficult spots.

Lead-free vs. leaded: leaded solder (Sn60Pb40/Sn63Pb37) is considerably easier to work with and permitted in the EU for hobby/repair use (RoHS concerns placing devices on the market, not personal use) [to be verified: current EU/AT legal position for hobby use]. Anyone selling must build lead-free.

2.6.2 ▶️ E — Desoldering

- **Solder sucker** — for individual pads.
- **Desoldering braid** — for flat residues and SMD.

- **The key trick:** add fresh solder to the old joint before removing it. The flux in the new solder makes the old, oxidized joint flow again.
- **Plated-through boards** hold solder in the hole; only thorough reflow with sufficient heat helps, otherwise the pad tears off.

2.6.3 ▶️ B — From breadboard to PCB

1. **Breadboard** — fast, ideal for learning and low-frequency circuits. **Limits:** contact resistance, stray capacitance, wobbly connections. Usually fine for audio, marginal for precision CV.
2. **Perfboard/stripboard** — permanent, but wiring-intensive; good for one-offs.
3. **Etched or manufactured PCB** — reproducible, clean, with a ground plane. From the second unit onward, or wherever precision matters, the right path (Part 8.2).

In practice: precision analog circuits (exp converters) often behave noticeably worse on a breadboard than on a PCB — stray capacitance and contact noise. Failing there does not necessarily mean a conceptual mistake (2.7 fault-finding).

2.7 Sourcing and stock

▶️ B — A sensible base stock:

Category	Recommendation
Resistors	E24 assortment 10 Ω–1 MΩ, metal film 1 %
Capacitors	film 1 nF–1 µF, ceramic 100 nF (decoupling), electrolytics 10/47/100 µF
Op-amps	10× TL072, 5× TL074
Timer/logic	5× TL555/NE555, 3× CD40106, 3× CD4066
OTA	3× LM13700
Transistors	20× BC547, 20× BC557, 1× THAT300 or similar
Diodes	50× 1N4148, 10× 1N5817
Jacks/pots	3.5 mm jack sockets, 9 mm pots lin 100 k

Sources (Europe): Reichelt, Mouser, Digikey, TME, Farnell; for synth-specific parts Thonk (UK), Befaco (ES), Modular Addict (US) [to be verified: current availability, shipping terms to AT].

Surplus/old stock: cheap, but beware of "NOS" classic chips (counterfeit risk, 2.3.7).

2.8 Cross-references

- **Key ICs in detail:** Part 2.3 (its own chapter).
- **Basic circuits using these parts:** Part 3.

- **Which capacitor type where:** VCO 4.1, EG 4.4, S&H 3.4.2/4.7.2f.
- **Reverse-polarity protection and rails:** Part 6.1.2. **Ground/hum:** Part 1.5.2.
- **From prototype to your own PCB:** Part 8.2. **Simulation before soldering:** Part 8.1.
- **[to be verified]** before publication: legal position on leaded solder (hobby, EU/AT); current distributors, prices and shipping terms. Web audit per the textbook-relationship rule.

Part 2.3 — The Key ICs of Sound Generation

Dual track. ▶️ B explains *what* each chip is for and *when* to reach for it. ▶️ E gives the internals, limits and dimensioning rules. This chapter is both reference and map — the chip profiles in Appendix B go deeper on each.

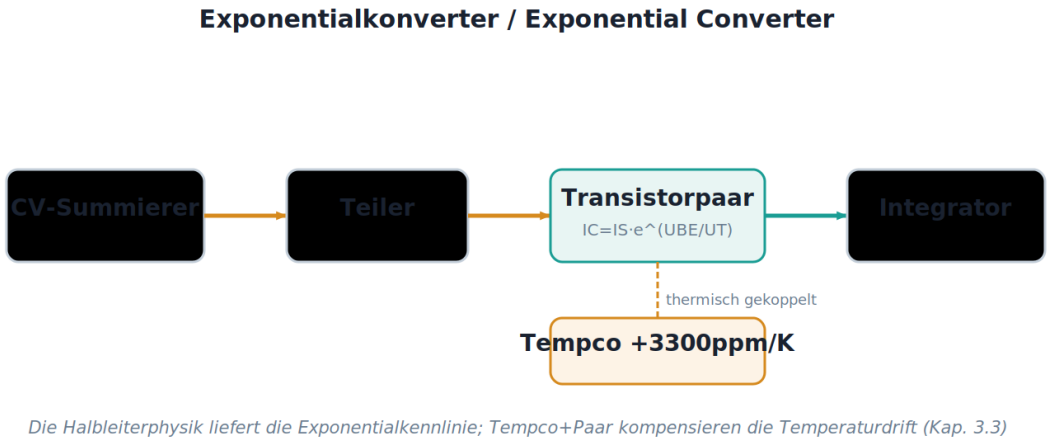


Fig. 5: Exponential converter

Fig. 5: Exponential converter

2.3.0 Why a dozen chips cover almost everything

The analog synthesizer looks complex but rests on a small set of recurring building blocks. Five functional classes suffice for practically every classic module:

Class	Job	Lead chip
Timer/clock	square wave, clock, simple LFO/VCO	NE555
CMOS logic	count, divide, switch, digital waveform	CD4000 series
Op-amp	amplify, compute, buffer, filter	TL07x, TL08x
OTA	voltage control of	LM13700

Class	Job	Lead chip
	gain/filter	
Dedicated	a whole VCO/VCF/VCA/EG on one chip	CEM/SSI family

Add two specialists: the **BBD** (bucket brigades for analog delay/chorus) and the **4046 PLL** (frequency multiplication, sync). Know these and you read 90 % of all DIY schematics fluently.

2.3.1 NE555 — the timer

▶️ **B.** The 555 is the entry chip par excellence: eight pins, since 1972, available everywhere for cents. It produces square waves (astable) or single pulses (monostable). In a synth it serves for clock, a simple clock-LFO, noise triggers and the first audible tone (Part 4.1). Too imprecise for pitch-accurate music — but unbeatable for learning and utility tasks.

▶️ **E.** Astable frequency:

Limits: supply-dependent thresholds (1/3 and 2/3 Vcc), temperature drift in the percent range, output current up to ~200 mA (the bipolar version pulls current spikes on the rail — for sensitive synth circuits use the **CMOS variant 7555/TLC555**: less interference, higher frequency, µA consumption). Exactly 50 % duty only with a diode across R2 or special wiring.

2.3.2 CD4000 CMOS series — logic as a sound source

▶️ **B.** The CD4000 family are digital logic chips that, repurposed, become sound building blocks in a synth. They run from 3–15 V (ideal for the ±12 V world), draw almost no current and are cheap. Key members:

- **CD4040 / CD4024** — binary dividers/counters. From one oscillator you get whole octave rows by division by two (top-octave principle of early organs and drums).
- **CD4046** — PLL (its own section 2.3.6).
- **CD4051 / CD4052** — analog multiplexers, as sequencer step switches and waveform selectors.
- **CD4066** — four analog switches (bilateral switch), the standard reset/routing switch in the VCO and for S&H.
- **CD40106** — six Schmitt-trigger inverters. **The** DIY favorite: each inverter plus one R and one C becomes a standalone oscillator (the Lunetta / Nicolas Collins world). Six per chip = six voices for a few cents.

▶️ **E.** Schmitt oscillator (40106): $ f $ (hysteresis-dependent approximation). Note: CMOS inputs are high-impedance and static-sensitive (ESD protection, Part 0.4); **always** tie unused inputs to a defined level, or you get oscillation and current draw. The 4066 switch has an on-

resistance of ~80–300 Ω (voltage-dependent) — account for it as an error source in audio paths with low load impedance.

2.3.3 TL07x / TL08x & relatives — the workhorse op-amp

▶️ **B.** The op-amp is the universal calculator of analog electronics: amplify, mix, buffer, filter, compare. The **TL072** (dual) / **TL074** (quad) is the de-facto standard in synth DIY: JFET input (high-impedance, good for CV), quiet enough, cheap, good-natured. For starting out, a stock of TL072/TL074 is enough.

▶️ **E.** Selection criteria when the TL07x is not enough:

Criterion	TL07x	Alternative
Offset/precision (exp converter, reference)	moderate	OP07, TL051, MCP6xx
Rail-to-rail (single-supply digital modules)	no	MCP600x, TLV23xx
very low noise (studio audio path)	ok	NE5532, OPA2134, LM4562
slew rate (fast waveforms)	13 V/µs	OPA series

Rule of thumb: TL07x as default, swap deliberately only where one figure of merit actually limits you. The basic circuits are in Part 3.

2.3.4 LM13700 — the OTA (operational transconductance amplifier)

▶️ **B.** The OTA is the chip that makes *voltage control* possible in the first place. A normal op-amp has fixed gain (set by resistors). In an OTA a **current** (, amplifier bias current) sets the gain — and that current can be generated from a control voltage. With it you build **VCAs** (voltage-controlled loudness) and **VCFs** (voltage-controlled filters). The **LM13700** (dual, with Darlington buffers) is the accessible classic; predecessor LM13600, relative CA3080 (single).

▶️ **E.** Transconductance is current-controlled:

Key dimensioning points: - **Linear input range** only ~±20–30 mV (differential pair). Larger signals must be **divided down** (input divider ~1/100) and re-amplified at the output, or you get distortion. The built-in **linearizing diodes** (diode-bias pins) extend the range. - typ. 0–2 mA; controlled via a series resistor to the CV or via an exp converter (for 1V/oct filter tracking). - The Darlington buffers in the 13700 act as impedance converters at the current output.

Use: VCA (4.3), OTA filter / state-variable (4.2), also usable as a controllable LFO/VCO. Reissues: **AS3280/V3280** (Alfa RPAR) as CA3080 replacement; the LM13700 itself is still in production [to be verified].

2.3.5 Dedicated synth ICs — CEM / SSM / SSI / AS

▶️ **B.** In the late 1970s firms like **Curtis (CEM)** and **SSM** integrated whole modules onto one chip: a complete VCO, VCF or VCA with internal temperature compensation. They sit in the classics (Prophet-5, SH-101, Juno, Oberheim). Long available only used and expensive — today **Alfa RPAR (AS series)** and **Cool Audio (V series)** supply pin-compatible reissues new.

Original	Function	Current reissue
CEM3340	VCO	AS3340 / V3340
CEM3320	VCF	AS3320 / V3320
CEM3360 / SSM2164	dual VCA	AS3360 / V3360, THAT2180
CEM3310 / SSM2056	EG (envelope)	AS3310 / V3310
SSM2044	VCF (4-pole LP)	V2044

▶️ **E.** Advantage: few external parts, stable tracking, compact layout. Disadvantage: less learning depth ("black box"), reissue-batch availability/price fluctuates, datasheet subtleties (trim points, reference currents) must be right. Chip-vs-discrete decision as in 4.1.3: reissue/stability → CEM/AS; understanding/modding → discrete or OTA-based.

2.3.6 Specialists: BBD & PLL 4046

▶️ **B — BBD (bucket-brigade device).** Bucket-chain memory: the analog signal is "scooped" from capacitor to capacitor and thereby delayed. This is the soul of analog **delays, chorus, flanger** before digital (MN3005/MN3007/MN3207, Reticon). Warm, slightly dark sound, because each stage adds a little noise and treble loss. Control the clock rate and the delay time changes — the basis of chorus/flanger.

▶️ **E.** Delay $ t_d = $ (N = number of stages). Needs an anti-aliasing filter before and a reconstruction low-pass after the chain, plus a companding IC (NE570/571) against the high noise floor. Clock chip formerly MN3101; reissues of the Panasonic BBDs from **Cool Audio (V3205 etc.)** and Xvive [to be verified].

▶️ **B — PLL 4046.** Phase-locked loop: keeps an internal VCO on a multiple/ratio of a reference clock. In a synth: frequency multiplication, sub-octaves, hard sync effects and clock recovery.

▶️ **E.** Core blocks: phase comparator (PC1 XOR / PC2 edge-triggered), internal VCO (R/C-set), loop filter. The PC1-vs-PC2 choice sets lock behavior and noise rejection; the loop filter sets settling time vs. jitter.

2.3.7 Sourcing, fakes, stock

- **Reissue chips** (AS/V series): via Thonk, Befaco, Reichelt, Mouser/Digikey [to be verified: current distributors/prices].
- **Fake risk** with "NOS" original chips (CEM/SSM) on marketplaces — relabeled chips are common; for new builds prefer the reissue series.
- **Sensible stock:** TL072/TL074, NE555/TLC555, CD40106, CD4066, LM13700, one VCO and one VCF reissue chip to experiment with.

2.3.8 Cross-references

- **Basic circuits** for these chips: Part 3 (op-amp/OTA in detail).
- **Modules:** VCO (4.1, CEM3340/discrete), VCF (4.2, OTA/CEM3320), VCA (4.3, OTA/CEM3360), EG (4.4).
- **Profiles:** Appendix B. **Tool:** T6 chip/component reference (searchable).
- **[to be verified]** before publication: current production/supply of LM13700, AS/V series, BBD reissues; distributors/prices. Web audit per the textbook-relationship rule.

Part 3 — The Operational Amplifier and the Basic Circuits

Dual track. ▶️ B: the two rules with which you can read 90 % of all op-amp circuits. ▶️ E: the dimensioning, the limits of the idealization, and the synthesis-specific circuits (exponential converter, OTA). This chapter is the computational foundation for Part 4.

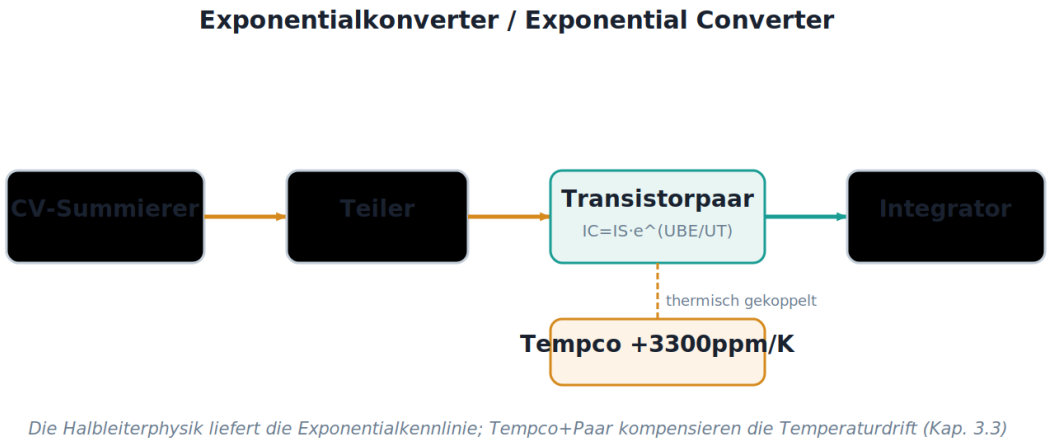


Fig. 5: Exponential converter

Fig. 5: Exponential converter

3.1 The operational amplifier

3.1.1 ▶️ B — The two golden rules

An op-amp has two inputs (+ and −) and one output. It amplifies the **difference** between the inputs — extremely strongly (open-loop gain typically 100,000×). In practice it is never used without **negative feedback**: part of the output is fed back to the − input.

With negative feedback, two rules apply that let you understand almost any circuit without calculation:

> **Rule 1:** The op-amp adjusts its output so that **both inputs are at the same voltage**.
> **Rule 2: No current** flows into the inputs.

Rule 1 is the core: the amplifier "does whatever it takes" to drive the difference to zero. Rule 2 follows from the very high input impedance.

3.1.2 ▶️ E — The basic circuits

(a) Impedance converter (voltage follower). Output tied directly to the − input. Gain = 1. Purpose: high-impedance in, low-impedance out. This is the **buffered multiple** of Part 4.7.2 and the output buffer of every envelope (4.4.3).

(b) Non-inverting amplifier.

Signal to the + input, divider from the output through to the − input, then to ground. Gain always ≥ 1, phase preserved.

(c) Inverting amplifier.

Signal through into the − input, back from the output, + input grounded. The − input thereby sits at **virtual ground** (Rule 1: it must be at 0 V because + is at 0 V). Gain can be less than 1; the signal is inverted.

(d) Summing amplifier (mixer). Several inputs, each through its own resistor, onto the virtual ground:

Because all inputs land on virtual ground, they do **not interact** — which is why the inverting summer is the standard mixer (Part 4.7.2). With equal resistors it becomes a simple sum. For DC-coupled CV mixers, fit no coupling capacitor (a common mistake, 4.7.2d).

(e) Difference amplifier. Amplifies the difference between two signals and rejects the common part. The basis of balanced inputs/outputs (Part 6.1.4, output modules).

(f) Integrator. A capacitor instead of in the feedback path:

With a constant input voltage this yields a **linear ramp**. That is the core of the VCO (4.1.2) and the LFO (4.5.2). **Practical note:** a pure integrator slowly saturates from the smallest offsets; a very large resistor (10 M) in parallel with the capacitor, or an active reset, is required.

(g) Differentiator. Capacitor in the input path — output proportional to the rate of change. Rarely used as a computing element in a synth, often as an **edge detector**: a gate becomes a trigger.

3.1.3 ▶️ E — Where the idealization ends

The golden rules hold approximately. For synth circuits four real limits matter:

Parameter	Meaning	Symptom when violated
Offset voltage	inputs not exactly equal	integrator drifts, VCA does not close fully
Input bias current	some current after all	envelope capacitor discharges, long times unreachable (4.4.5)
Slew rate	max. rate of change	steep square edges become sloped, treble missing
Output swing	output does not quite reach the rails	clipping before the expected voltage

The TL07x has FET inputs and therefore **very small bias currents** — precisely why it is the standard for envelopes and CV paths (Part 2.3.3).

3.2 Comparator and hysteresis

3.2.1 ▶️ B — Comparing instead of amplifying

Without negative feedback the op-amp becomes a **comparator**: it compares the inputs and slams the output to one of the supply rails. A continuous voltage becomes a switching state — the bridge between analog and digital.

Uses in a synth: generating a square from the sawtooth (4.1.2), a gate from CV (4.7.2g), the envelope's switch-over point (4.4.3), the VCO reset.

3.2.2 ▶️ E — Why hysteresis is indispensable

A plain comparator flips exactly at the threshold. If the input sits *near* the threshold and carries a little noise, the output flips **back and forth repeatedly** — the notorious chatter or oscillation at the switching point.

The solution is the **Schmitt trigger**: positive feedback from the output to the + input. This creates **two** thresholds — one to switch on, a lower one to switch off. The difference is the **hysteresis**.

Rule of thumb: the hysteresis must be clearly larger than the noise on the input signal. Too small → chatter; too large → the signal may never reach the second threshold and the output stops flipping altogether.

The **CD40106** (Part 2.3.2) is a Schmitt-trigger inverter with built-in hysteresis — which is why one R and one C there suffice for a complete oscillator.

3.3 The exponential converter (the heart of 1V/octave)

3.3.1 ▶️ E — The circuit

Part 4.1.2 derived the physics: a bipolar transistor's collector current follows the Shockley equation

The practical build turns this into a usable control circuit:

1. **Input divider.** The CV (1 V/oct) is divided down to ~17.9 mV/oct (gain ≈ 0.0179). Implemented as a voltage divider with a **trimmer** for the scale adjustment.
2. **Summing.** Ahead of the divider, all pitch sources are added (keyboard CV, sequencer, transposition, LFO vibrato) — an inverting summer (3.1.2d). Here the additivity of 1V/oct pays off (1.4.2).
3. **The transistor pair.** Two thermally coupled transistors as a differential pair. The second transistor provides the reference and cancels the sample-dependent term.
4. **Tempco.** The scaling resistor has +3300 ppm/K and is thermally coupled to the pair to compensate the drift (4.1.2).
5. **Current output.** The collector current charges the integrator capacitor (VCO, 4.1.2) or sets an OTA's (VCF/VCA).

3.3.2 ▶️ E — The log converter (the inverse)

Put the transistor in an op-amp's feedback path and you get the inverse function: a current becomes a logarithmic voltage. Applications: level metering (VU/dB display), compressors and envelope followers.

3.3.3 Calibration and typical faults

The calibration procedure is in 4.1.4. The three most common faults:

- **Pair not thermally coupled** → tracking drifts as things warm up.
- **Wrong tempco value** (e.g. an ordinary metal-film resistor instead of +3300 ppm/K) → drift remains.
- **Summing node too high-impedance** → noise and interference on the pitch CV (1.5.2).

3.4 Precision rectifier and the sample-and-hold core

3.4.1 ▶️ E — Precision rectifier

A plain diode only rectifies above its forward voltage (~0.6 V) — small signals disappear. Put the diode **inside the feedback loop** of an op-amp and the gain "regulates away" the forward voltage: the rectifier works from a few millivolts up.

Applications: envelope follower (audio becomes a control voltage), triangle-from-sawtooth (4.1.2), absolute value in a wave shaper.

3.4.2 ▶️ E — Sample & hold

The core (see 4.7.2f) consists of three parts:

1. **Analog switch** (CD4066) connects input and hold capacitor during the clock.
2. **Hold capacitor** stores the voltage. Film capacitor, not electrolytic (leakage).
3. **Buffer with very low bias current** (FET op-amp) reads the voltage without discharging the capacitor.

The droop calculation. The voltage decay per unit time follows from the total leakage current:

Example: (a good FET op-amp plus switch residuals), :

Negligible for musical purposes. At 1 V/octave, 1 mV/s corresponds to a drift of **1.2 cents per second** — practically inaudible.

With a cheap bipolar op-amp (bias current 100 nA instead of 100 pA), however, it would be **1 V/s**, i.e. **1200 cents/s — a full octave per second**. The held pitch would simply run away. This is why the component choice here is not optional but functionally decisive.

3.5 The OTA in detail

3.5.1 ▶️ E — From op-amp to OTA

The regular op-amp delivers a **voltage** at its output and has fixed gain set by resistors. The OTA (Part 2.3.4) delivers a **current** and has a gain that is **controllable by a current**:

This makes it the universal block for everything voltage-controlled: VCA (4.3.2), VCF (4.2.3b), controllable LFO.

3.5.2 ▶️ E — The wiring rules

1. **Input divider mandatory.** Linear range ~±20–30 mV; synth signals ±5 V. Division factor 100–200, then re-amplification (mind the gain structure, 1.5.3).

2. **Bias the LM13700's linearizing diodes** with a defined current — it widens the range considerably.
3. **Buffer the current output.** The OTA output is a current source; without a load resistor plus buffer (the Darlington stages in the LM13700 or an external op-amp) the voltage is undefined.
4. **Limit .** Typically 0–2 mA through a series resistor; without limiting, the chip is destroyed.
5. **Trim the offset** if control feedthrough (clicking) is a problem (4.3.2).

3.6 Cross-references

- **Chips for this chapter:** TL07x, LM13700, CD4066, CD40106 — Part 2.3, Appendix B.
- **Applications:** VCO (4.1), VCF (4.2), VCA (4.3), EG (4.4), utilities (4.7).
- **Formulas in brief:** Appendix A.
- **Physical justification of 1V/oct:** Part 1.4.2, Part 4.1.2.
- **Noise/gain structure:** Part 1.5.3.
- **Simulating these circuits:** Part 8.1 (LTspice/ngspice/Falstad).

Part 4.1 — The Voltage-Controlled Oscillator (VCO)

Dual track. This chapter has two entry points. The **beginner track** (▶️ B) explains *what* happens and *why*, with pictures and a minimal build. The **engineering track** (▶️ E) works through the dimensioning and states the limits. If you only want to build, follow B and skip the E blocks; if you want to design, read both.

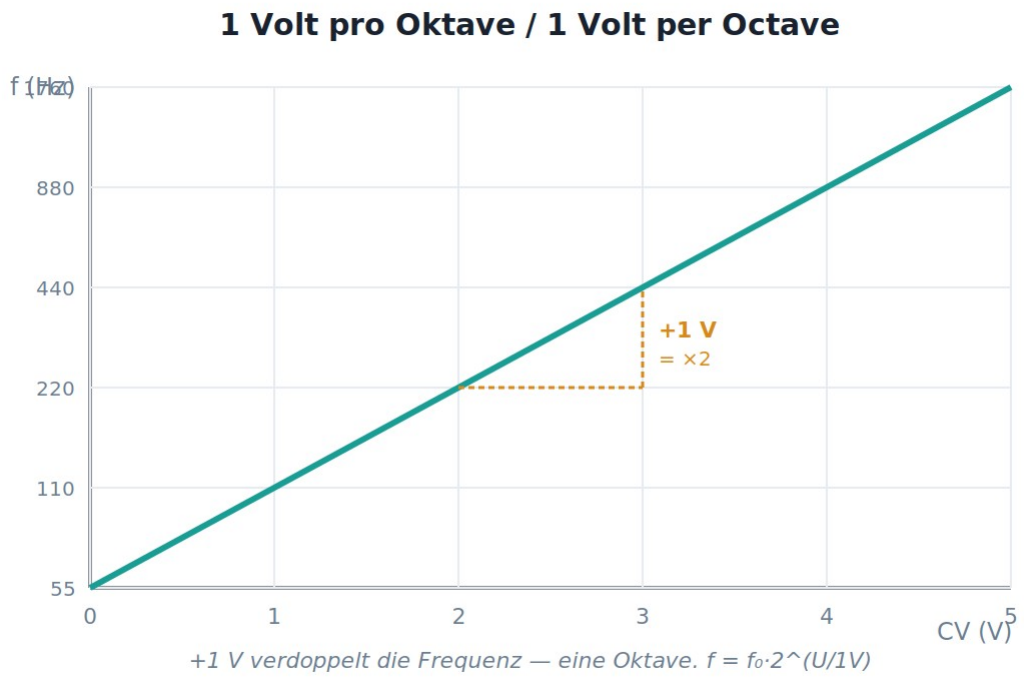


Fig. 2: 1V/octave transfer curve

Fig. 2: 1V/octave transfer curve

4.1.0 Position in the signal chain

The VCO is the **tone generator** of the analog synthesizer. It sits at the start of the signal chain:

```
[VCO] → [VCF] → [VCA] → output
   ↑        ↑       ↑
  CV       CV      CV / envelope
```

It converts a **control voltage** (CV) into a **frequency**. The convention of the Western modular world is **1 volt per octave** (1V/oct): raise the control voltage by exactly 1 V and the frequency doubles — the pitch jumps up one octave. This single convention is why modules from different makers work together. (Buchla and some Japanese systems use **Hz/V**; see Part 6.2.)

4.1.1 ▶️ B — What an oscillator does

An oscillator produces a periodic waveform: a voltage that repeats identically over and over. How often it repeats per second is the **frequency** (in hertz). 440 repetitions per second we hear as concert-pitch A′.

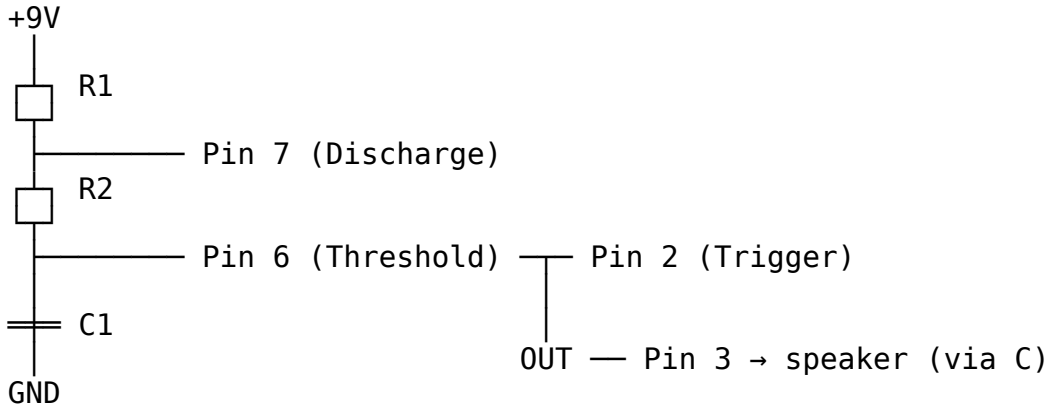
The **shape** of one period determines the timbre:

- **Sawtooth** — rises slowly, falls abruptly. Contains all harmonics. Bright, "cutting" sound; classic for strings and bass.
- **Square / pulse** — jumps between two values. Contains only odd harmonics (pure square), sounds "hollow." Shapeable via **pulse width** (PWM).
- **Triangle** — rises and falls linearly. Few, quickly decaying harmonics; soft sound.
- **Sine** — the fundamental only, no harmonics. A pure "whistle."

Core idea of the analog VCO: you charge a capacitor with a *constant current*. The capacitor voltage then rises **linearly** — which by itself gives a sawtooth/triangle ramp. Once a threshold is reached, a circuit discharges the capacitor abruptly and it starts over. **The larger the charging current, the sooner the threshold is reached, the higher the frequency.** Control that current with a voltage and you have a voltage-controlled oscillator.

Minimal build (▶ B): the square-wave VCO with the 555

The simplest audible entry needs a single chip, the **NE555** (timer IC, since 1972, a cent-part):



With R1 = 1 kΩ, R2 = 10 kΩ, C1 = 100 nF the 555 in *astable mode* produces a square-wave tone in the audible range. Swap R2 for a potentiometer and you can sweep pitch by hand. This is **not yet** a true VCO in the 1V/oct sense (the 555 does not respond exponentially to voltage), but it makes the principle "component value → frequency" audible in five minutes. Once you hear the tone, you have your foothold.

> **Why the 555 is not a good musical VCO:** its frequency depends *linearly* on resistance and capacitance ($f \approx 1.44 / ((R1+2 \cdot R2) \cdot C)$), not *exponentially* on a control voltage. For pitches that follow our octave hearing we need the exponential law — see the E track.

4.1.2 ▶ E — Why exponential? The 1V/octave condition

Our hearing is logarithmic: equal *musical* intervals correspond to equal *frequency ratios*, not equal frequency differences. An octave is always a factor of 2, independent of the starting frequency (110→220 Hz is an octave, and so is 4400→8800 Hz).

For a *linear* control voltage (convenient to generate and to add) to yield a *musically linear* pitch, the transfer curve must be exponential:

Each additional volt doubles f. That is the formal definition of 1V/octave. This exponential function is exactly what the circuit must physically produce.

The exponential converter

The lucky break of semiconductor physics: the collector current of a bipolar transistor depends **exponentially** on the base–emitter voltage (Shockley equation):

with thermal voltage at 300 K. Apply a linearly rising voltage to the base and the collector current rises exponentially — and that current charges the timing capacitor. The 1V/oct law is thereby produced.

Two problems, two canonical solutions:

1. **Scaling.** From mV: for a factor of 2 (one octave) the base needs only mV, not 1 V. An input divider (gain ≈ 0.0179) brings 1 V/oct down to that value. The divider is built with a trimmer as the **scale/tracking adjustment** (target: exactly 1.000 V/oct across several octaves).
2. **Temperature drift.** is proportional to absolute temperature . As the transistor warms, the scaling shifts — the VCO "runs away." Two countermeasures are standard:
   - **Matched pair:** two thermally coupled transistors (a differential pair, e.g. in the **THAT300/320** chip, formerly **CA3046/LM3046**, or a discrete pair bonded with thermal paste and mechanically matched) cancel the term against each other.
   - **Tempco resistor:** the scaling resistor is given a defined positive temperature coefficient of **+3300 ppm/K** (trade name "Tempco," e.g. from KOA or Vishay [to be verified: current sources/designation]) that compensates the drift. It must be thermally coupled to the transistor pair.

The integrator and the reset (sawtooth core)

The exponentially generated current charges a capacitor through an **op-amp integrator**. The output voltage is the ramp:

A **comparator** watches the ramp. When it reaches a fixed threshold, a switch (formerly a FET, often a **CD4066** or a discrete reset) discharges the capacitor abruptly — the ramp jumps back. The period is:

Since depends exponentially on the CV, so does . **The core trick of the whole chapter is in this line.**

Deriving the waveforms

The remaining shapes are derived from the sawtooth rather than generated separately:

- **Triangle:** instead of a hard reset, switch between up- and down-integration (bipolar integrator). Alternatively sawtooth → full-wave rectifier.
- **Square / pulse:** a comparator compares the sawtooth with a reference. Make the reference variable and you get **PWM** (pulse-width modulation).
- **Sine:** from the triangle via a **waveshaper** (diode network or a differential amplifier in its soft-limiting region, rounding the triangle peaks). Not a pure sine, but < 1 % THD is achievable.

4.1.3 Ready-made VCO chips vs. discrete

Historically there were dedicated VCO ICs that integrated the whole core:

Chip	Origin	Status	Note
CEM3340	Curtis, 1979	reissue available (AS3340 by Alfa RPAR, Cool Audio)	classic: saw/tri/pulse, sync, lin/exp FM, internal tempco
SSM2030 / SSM2033	SSM, 1980s	original scarce, concept in reissues	early Prophet/synth classics
AS3340	Alfa RPAR (LV)	currently in production [to be verified]	pin-compatible CEM3340 reissue, cent-to-euro range
XVCO / discrete	various DIY	open	full control, more trimming

Decision logic: for a build with stable tracking and little trimming → **AS3340**. For depth of learning and "understanding from the ground up" → discrete build with matched pair + tempco. Both paths are shown in Part 5.2 on a fully dimensioned reference VCO.

4.1.4 Practice: calibrating a 1V/oct VCO

No analog VCO is in tune without calibration. The procedure (order matters, because the steps interact):

1. **Scale/tracking:** apply 0 V, note the base pitch (e.g. with a tuner). Raise octave by octave (1 V, 2 V, 3 V …). Adjust the scale trimmer so each volt yields exactly one octave. Iterate over 3–5 octaves, because top and bottom drift differently.

2. **Tune/offset:** set the base frequency to the desired reference pitch with the tune control.
3. **Hi-freq trim (if present):** at very high frequencies the curve deviates (finite reset time, base current). A second trimmer corrects the top end.
4. **Temperature:** re-check after 10–15 min warm-up. If drift remains, check the thermal coupling of pair and tempco.

Instrumentation: frequency counter or tuner for tracking; oscilloscope for waveform and reset cleanliness; for PWM a second channel on the modulation source (Part 2.5).

4.1.5 Limits and typical faults

- **Poor tracking across the range:** usually a scale resistor without tempco, or a pair not thermally coupled.
- **"Running away" in use:** heating; tempco missing, misplaced, or wrong ppm value.
- **Unclean waveform / missing reset:** reset switch too slow or comparator oscillating; check hysteresis (Part 3.2).
- **Noise/hum coupling onto the CV:** high-impedance CV path; check grounding and shielding (Part 1.5).
- **Aliasing (relevant only for digital VCOs):** analog VCOs produce no alias artifacts — a point that matters in the hybrid part (7.3).

4.1.6 Cross-references

- **Prerequisites:** Part 3.3 (exp/log converter), Part 3.2 (comparator/hysteresis), Part 1.4 (the CV principle).
- **Downstream modules:** the VCF (4.2) processes the VCO signal; the VCA (4.3) shapes the loudness.
- **Tool: T3 VCO tuning / exp-converter calculator** (computes scaling, tempco, expected tracking; interactive transfer curve).
- **Chips in detail:** Appendix B (CEM3340/AS3340 profile).
- **Open-source projects with documented VCOs:** MFOS "Ultimate VCO," YuSynth VCO, Mutable Instruments (digital, as contrast), Music Thing Modular [to be verified: current repos/links].

[to be verified] before publication: current availability/designation of AS3340 & tempco resistors; concrete repo links of the DIY projects named; THAT300/320 currency. Web audit per the textbook-relationship rule.

Part 4.2 — The Voltage-Controlled Filter (VCF)

Dual track. ▶️ B: what a filter does to sound and an overview of the four topologies. ▶️ E: transfer function, pole order, resonance/self-oscillation, voltage-controlled cutoff tracking.

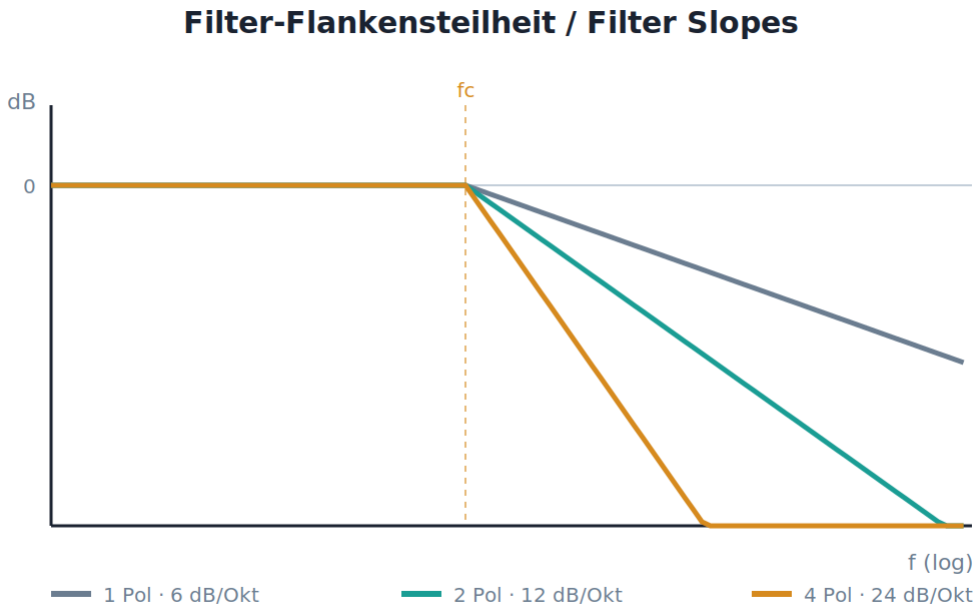


Fig. 4: Filter slopes

Fig. 4: Filter slopes

4.2.0 Position

The VCF sits after the VCO and shapes the timbre by removing or emphasizing harmonics:

```
[VCO] → [VCF] → [VCA]
          ↑
      cutoff CV (envelope, LFO, keyboard)
```

In the subtractive-synthesis paradigm the filter is the **decisive tone-shaping module**. The VCO delivers harmonically rich raw material (sawtooth, square); the filter carves the sound out of it.

4.2.1 ▶️ B — What a filter does

A filter lets certain frequencies through and attenuates others. Four basic types:

- **Low-pass (LP)** — passes low frequencies, attenuates high. By far the most important in a synth: takes away “edge,” makes sounds softer/darker.
- **High-pass (HP)** — the reverse: attenuates lows, passes highs. Removes “warmth”/bass.
- **Band-pass (BP)** — passes only one band of frequencies. “Telephone voice,” nasal.
- **Notch / band-reject** — attenuates exactly one band. For effects, phasers.

Two controls shape every filter sound:

1. **Cutoff (corner frequency)** — where the filter starts to act. For the LP: above it, attenuation begins.
2. **Resonance (Q / emphasis)** — boosts the region *around* the cutoff frequency. Little resonance = gentle; a lot = whistling, sharp; very much = the filter begins to **oscillate by itself** and becomes a sine oscillator.

Voltage control: put cutoff on a CV (instead of just a pot) and an envelope can open/close the sound over time (the "wah"/"chirping" filter sweep) or an LFO can modulate it periodically.

4.2.2 ▶️ E — Pole order and slope

The **slope** states how strongly frequencies above (LP) the cutoff are attenuated, measured in dB per octave:

- **1 pole = 6 dB/oct** — gentle (simple RC network).
- **2 poles = 12 dB/oct** — state-variable, Sallen-Key.
- **4 poles = 24 dB/oct** — the "fat" sound (Moog ladder, CEM3320). The standard for classic analog sound.

Transfer function of a first-order low-pass:

At the gain is −3 dB. For higher order, several such stages are cascaded; resonance arises from **feedback** from the output of the last stage back to the input.

4.2.3 The four classic filter topologies

(a) Transistor ladder — the Moog sound

▶️ **B.** Four low-pass stages in series (the "ladder" of transistor pairs) plus global feedback. The soft, rich, slightly compressing sound that defines "Moog." 24 dB/oct.

▶️ **E.** Cutoff is set via the control current through the transistor differential pairs (temperature-dependent → tempco/tracking as with the VCO, 4.1.2). Resonance via a feedback loop; at high resonance, self-oscillation. Characteristic: bass loss at high resonance (feedback removes fundamental energy) — part of the "Moog" signature. Buildable discretely; available as an IC reissue in various DIY modules.

(b) State-variable filter (SVF)

▶️ **B.** Delivers LP, HP and BP **simultaneously** from one circuit (separate outputs). Very flexible, clean, well controllable. 12 dB/oct per output. Basis of many "cleaner" synth filters (Oberheim SEM).

▶️ **E.** Two integrators in a loop plus a summer. Cutoff via both integrator time constants (voltage-controllable with OTAs), resonance via the damping path (). Advantage: cutoff and Q are largely independently adjustable. The SEM sound: less "aggressive" than the ladder, more "airy."

(c) Sallen-Key

▶️ **B.** Simple, robust 2-pole topology with one op-amp. Famous in the MS-20 (Korg) as a growly, aggressive filter (with a special resonance feedback there).

▶️ **E.** One op-amp with two Rs and two Cs; cutoff via the RC networks (voltage-controlled via OTA or LDR/Vactrol in MS-20 style). Resonance via positive feedback; the MS-20 filter clips characteristically at high resonance (distortion as a sonic feature).

(d) Diode ladder

▶️ **B.** A variant of the ladder with diodes instead of transistors as the control elements (EMS VCS3, TB-303, Roland classics). Grittier, more "liquid," idiosyncratic sound — the soul of the acid sound (303).

▶️ **E.** Diodes as voltage-controlled resistors in the ladder. More involved to calibrate, nonlinear behavior at resonance — which is exactly what gives the 303 character (screaming, "squelchy" resonance). The 303 filter is therefore the subject of many DIY clones.

4.2.4 Topology comparison

Topology	Slope	Sound	Outputs	Classic	Effort
Transistor ladder	24 dB/oct	rich, compressing, bass-loss@res	LP	Minimoog	medium
State-variable	12 dB/oct	clean, airy, flexible	LP/HP/BP	SEM	medium
Sallen-Key	12 dB/oct	growly, distorts@res	LP/HP	MS-20	low
Diode ladder	18–24 dB/oct	gritty, squelchy	LP	303, VCS3	high

4.2.5 Cutoff tracking (keyboard tracking)

▶️ **E.** For a resonant filter to "play along" with the keyboard (as a playable tone source when self-oscillating, or to keep the timbre constant per note), the cutoff must respond **exponentially** to the CV like the VCO. In practice this is the same 1V/oct problem as in 4.1 — exp converter + tempco at the filter's control input. Many filters offer a tracking control (0–100 %) that sets how strongly pitch drags the cutoff along.

4.2.6 Self-oscillation as a feature

At maximum resonance the filter tips into oscillation and delivers an (almost) pure sine at the cutoff frequency. With good tracking the filter becomes a **second, playable oscillator** — a common technique for adding a pure sine voice to a patch (e.g. kick drums from the self-oscillating filter).

4.2.7 Limits and typical faults

- **No/poor tracking:** exp converter/tempco at the cutoff missing or uncompensated.
- **Filter oscillates uncontrollably:** resonance feedback too strong / wrongly phased.
- **Level loss at high resonance:** topology-inherent (ladder) — add gain compensation in the feedback path if needed.
- **Unwanted distortion:** OTA input overdriven (check input divider, 2.3.4).
- **Noise in BP/HP:** high gain in the stopband; component noise becomes audible.

4.2.8 Cross-references

- **Prerequisites:** Part 2.3.4 (OTA), Part 3.1–3.2 (op-amp basics), Part 4.1.2 (exp converter for tracking).
- **Neighbor:** the VCA (4.3) follows in the chain; the EG (4.4) and LFO (4.5) modulate the cutoff.
- **Tool: T2 filter calculator** (cutoff/resonance/topology, frequency response/Bode plot, slope comparison).
- **Chips:** CEM3320/AS3320, SSM2044/V2044, LM13700 (OTA filter) — Appendix B.
- **Open-source filters:** MFOS VCF, YuSynth (various), Mutable Ripples/Blades (analog), various 303 clones [to be verified: repos].
- **[to be verified]** before publication: current chip/clone availability; DIY repo links. Web audit per the textbook-relationship rule.

Part 4.3 — The Voltage-Controlled Amplifier (VCA)

> **Dual track.** ▶️ B: why the most inconspicuous block is the most important one. ▶️
> E: OTA vs. Blackmer topology, linear/exponential, control feedthrough and distortion.

4.3.0 Position

The VCA sits at the end of the audio chain and determines **loudness over time**:

```
[VCO] → [VCF] → [VCA] → output
                  ↑
              envelope (EG)
```

Without a VCA a synthesizer sounds permanently — one endless tone. Only the VCA carves individual **notes** out of the continuous signal: attack, sustain, decay. It is at the same time the standard building block wherever a voltage should control an amplitude — including in the **CV path** ("a VCA for modulation").

4.3.1 ▶️ B — What a VCA does

A VCA is a volume control turned by a **voltage** instead of a finger. Control voltage 0 V → closed (silent); control voltage high → open (loud).

Two places of use that must be kept apart:

1. **Audio VCA** — shapes the loudness of an audible signal. Must close cleanly (no "bleeding") and must not click.
2. **CV VCA / attenuator** — controls the *depth of a modulation*. Example: an LFO should modulate the filter only "a bit," and how much should itself be determined by an envelope.

Linear or exponential? Two transfer curves, two purposes:

- **Linear:** double the control voltage = double the amplitude. Correct for **modulation control** and for envelopes whose shape you want reproduced exactly.
- **Exponential:** equal voltage steps = equal *loudness steps* in dB. Matches hearing (like 1V/oct for pitch) and produces more natural-sounding decays. Many VCAs offer both modes by switch.

4.3.2 ▶️ E — The OTA as a VCA

The most obvious implementation uses the OTA (Part 2.3.4). Transconductance is current-controlled:

The control current is generated from the control voltage (series resistor for linear, exp converter for exponential). Gain is thus proportional to — a VCA.

Dimensioning rules (the three traps):

1. **Limit the input level.** The linear input range of the OTA differential pair is ~±20–30 mV. A synth signal of ±5 V must therefore be divided down by a factor of ~100–200 and re-amplified after the OTA. Without the divider: audible distortion.
2. **Use the linearizing diodes.** The LM13700 has internal diodes that widen the linear range — bias them with a defined diode current, or you give away headroom.
3. **Compensate control feedthrough.** When changes abruptly (envelope attack), part of the control voltage couples into the audio path as a **DC step** — audible as a **click**. Countermeasures: offset trimmer at the OTA input, symmetrical layout, and envelopes without infinitely steep edges.

Noise and distortion: the OTA VCA is noticeably noisy when the signal is divided far down and amplified back up — signal-to-noise ratio is the price of simplicity. For audio paths with studio requirements, the next topology is often used instead.

4.3.3 ▶️ E — Blackmer / current-mode VCA (the studio class)

The second family comes from studio technology (David E. Blackmer, dbx): a **log–antilog transistor pair** in current mode, delivering an exactly exponential, dB-linear control law with very low distortion.

- Chips: **THAT2180/2181** (current), historically **dbx2150**, **SSM2164** / reissue **V2164** (quad, very common in Eurorack).
- Law: typically **−6 mV/dB**, i.e. a defined dB per volt — exact and temperature-compensated.
- Advantage: wide dynamic range, low distortion, clean closing.
- Disadvantage: more expensive, less "character" — which for sound design can also be a drawback.

Rule of thumb: OTA (LM13700) for DIY learning, modulation VCAs and characterful signal paths. V2164/THAT for polyphonic voices, mixer automation and anything with noise requirements.

4.3.4 Other implementations

Principle	Part	Character	Note
OTA	LM13700, CA3080	typical, slightly raw	DIY standard
Current-mode/ Blackmer	V2164, THAT2180	very clean, dB-linear	studio/poly
Dedicated	CEM3360/AS3360, CEM3330	classic, compact	synth classics
Vactrol (LDR+LED)	VTL5C3 etc.	soft, sluggish, "rubbery"	slow response as a sonic feature, part-to-part spread [to be verified: availability]
FET	J-FET as control resistor	simple, limited linearity	historical, high distortion
Discrete diff pair	transistors	full learning control	trimming effort

Vactrol note: the sluggish, exponentially soft response of an optocoupler is used deliberately as a sonic property (Buchla aesthetic, "low-pass gate," see 4.3.6). Original vactrols are hard to source; DIY substitutes from an LED + LDR in heat-shrink are common but vary widely.

4.3.5 The click — causes and cures

Clicking is the most common VCA problem and has three distinct causes that must be told apart:

1. **Control feedthrough** (see 4.3.2): a control-voltage step couples into the audio path → offset trimmer.
2. **Envelope edges too steep**: an attack/release of exactly 0 ms creates a step function → provide a minimum time constant (~1–2 ms) in the EG.
3. **DC offset in the audio signal**: a signal carrying DC jumps when the VCA opens → coupling capacitor at the input or a DC servo.

4.3.6 Related: the low-pass gate (LPG)

A West-Coast variant (Buchla): VCA and low-pass filter are controlled **together** by one vactrol. As the sound gets quieter it simultaneously gets darker — exactly as with acoustic instruments, whose harmonics decay faster than the fundamental. The result is the characteristic "plonk"/"bongo" behavior. Implementation: the vactrol controls a resistance in an RC low-pass *and* the attenuation; usually driven by a short trigger rather than a full ADSR envelope.

4.3.7 Limits and typical faults

- **VCA does not close fully** ("bleeding"): offset mistrimmed, or the control voltage never reaches 0 V.
- **Distortion on loud signals:** input divider dimensioned too small (OTA linear range exceeded).
- **Noise with the VCA closed:** gain after the OTA set too high; rethink the gain structure.
- **Modulation "lags":** normal with vactrol VCAs (inertia) — a component property, not a fault.
- **Exponential/linear confused:** envelopes feel "wrong" — check the mode (4.3.1).

4.3.8 Cross-references

- **Prerequisites:** Part 2.3.4 (OTA), Part 3.1 (op-amp basics).
- **Control source:** EG (4.4), LFO (4.5). **Predecessor** in the chain: VCF (4.2).
- **Tool:** T4 envelope simulator shows how the EG shape becomes audible at the VCA.
- **Chips:** LM13700, V2164/SSM2164, THAT2180, CEM3360/AS3360 — Appendix B.
- **Open source:** MFOS VCA, Befaco VCA modules, various LPG designs [to be verified: repos].
- **[to be verified]** before publication: availability of V2164/THAT2180, vactrol substitutes. Web audit per the textbook-relationship rule.

Part 4.4 — The Envelope Generator (EG)

Dual track. ▶️ B: the phases of an envelope and what they mean sonically. ▶️ E: RC time constants, the charging-curve mathematics, gate/trigger logic, and both discrete and integrated implementations.

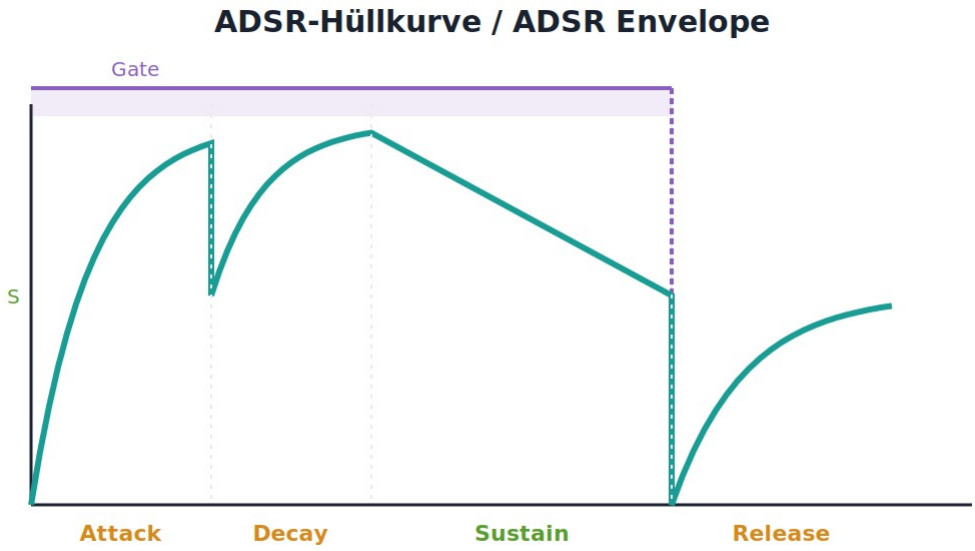


Fig. 3: ADSR envelope

Fig. 3: ADSR envelope

4.4.0 Position

The EG produces no audio signal but a **control voltage that changes over time**. It is the instrument's shaper of time:

```
gate/trigger → [EG] ──┬──→ VCA (loudness contour)
                      └──→ VCF (timbre contour)
```

Without an envelope every note sounds equally long and equally loud. The envelope turns a continuous tone into an **event**: attack, decay, tail.

4.4.1 ▶️ B — The phases

The standard is **ADSR** — four parameters that together describe the shape:

- **Attack (A)** — time from 0 to maximum after the key is pressed. Short = percussive (piano, drum); long = swelling (strings, pads).
- **Decay (D)** — time from the maximum down to the sustain level.

- **Sustain (S)** — **not a time but a level.** The height at which the envelope stays *as long as the key is held*. This is the point beginners most often misunderstand.
- **Release (R)** — time from the current level back to 0 after the key is released.

Shorter variants that often suffice in practice:

Type	Parameters	Use
AR	attack, release	simplest form; Noise Toaster, many DIY modules
AD	attack, decay	percussive, fires through once (drums, blips)
ADSR	all four	standard for playable instruments
DADSR	+ delay	delayed onset (layering, string swells)

Gate vs. trigger — the second common stumbling block:

- **Gate** is a *state*: the voltage stays high **as long as** the key is held. The EG needs this for sustain.
- **Trigger** is an *event*: a short pulse at the attack. An AD envelope needs only the pulse and then runs through on its own.

4.4.2 ▶️ E — The mathematics of the slopes

Analog envelopes charge and discharge a capacitor through a resistor. The slopes are therefore **exponential**, not linear:

Attack (charging toward the target voltage):

Decay/release (discharging):

The **time constant** is the core quantity. Values to remember:

Time	fraction reached (charging)
1 τ	63.2 %
2 τ	86.5 %
3 τ	95.0 %
5 τ	99.3 % (practically “done”)

Practical consequence: if “attack time” is defined as the time to full arrival, it corresponds to roughly **3–5 τ**. A module with “attack 1 ms to 10 s” therefore needs τ from about 0.2 ms to 2–3 s.

At that means from ~200 Ω to ~3 MΩ — precisely why EG circuits carry large pots (1 M) in series with a small protective resistor.

Why exponential sounds good: hearing perceives loudness logarithmically. An exponentially falling level is perceived as an *even* decay — exactly like a plucked string or a bell. Linear envelopes, by contrast, sound "cut off." (Some modules offer switchable linear slopes for special modulation tasks.)

4.4.3 ▶️ E — Circuit implementation

(a) The discrete classic (op-amp + switch + RC)

Basic structure of the classic analog ADSR:

1. **State logic** evaluates the gate and decides which phase the circuit is in (attack / decay+sustain / release). Realized with comparators, a flip-flop (CD4013) or discrete transistors.
2. **Charge-path switching:** depending on the phase, the timing capacitor is connected through the A, D or R resistor — typically with analog switches (CD4066) or diode steering.
3. **Buffering:** an op-amp impedance converter decouples the capacitor from the output so the load does not alter the times. **Important:** the buffer must be extremely high-impedance (FET input, TL07x), otherwise its input current discharges the capacitor and long times become unreachable.

The attack switch-over point: a comparator detects when the capacitor has (nearly) reached its maximum and switches to decay. Because charging is asymptotic, the switch usually happens at ~95 % — otherwise the attack phase would never end.

(b) Dedicated chips

- **CEM3310 / AS3310, V3310** — a complete ADSR on chip, voltage-controllable times.
- **SSM2056** — likewise classic, available in reissues [to be verified].
- Advantage: few parts, consistent times. Disadvantage: less intervention, availability risk.

(c) Digitally generated

Microcontrollers (Part 7.2) compute the curve and output it through a DAC. Advantage: arbitrary curve shapes, exact reproducibility, presets. Disadvantage: resolution/stepping on slow ramps (zipper noise) if DAC bit depth or update rate is too low.

4.4.4 Practice: envelopes for sound types

Sound type	A	D	S	R	Note
Percussive (drum, pluck)	0–5 ms	100–400 ms	0	short	sustain **0** is decisive
Organ/gate	0–5 ms	—	max	0–10 ms	rectangular, no decay
Strings/pad	0.3–1.5 s	medium	high	0.5–2 s	slow swell
Bass (plucked)	0–2 ms	150–300 ms	low	short	filter EG usually faster than amp EG
Wind/brass	30–120 ms	short	high	medium	filter EG with slight overshoot

The most important practical rule: set the VCA envelope and the VCF envelope **separately**. A classic brass sound arises because the filter opens and closes *faster* than the loudness does — the "blown attack" effect.

4.4.5 Limits and typical faults

- **Click on attack:** attack exactly 0 ms → step function. Provide a minimum τ (~1–2 ms) in the design (see 4.3.5).
- **Long times unreachable:** buffer op-amp with too much input current, or leakage in the timing capacitor. Use film capacitors instead of electrolytics.
- **"Sustain behaves like decay":** sustain misunderstood as a time — it is a level (4.4.1).
- **Retrigger behavior unclear:** with fast playing, the logic decides whether the envelope restarts from 0 (retrigger) or continues from its current value (legato). Both are legitimate — document which, per module.
- **Times change with the load:** output buffer missing.

4.4.6 Cross-references

- **Prerequisites:** Part 2.1 (RC network), Part 3.2 (comparator/hysteresis), Part 2.3.2 (CD4066/CD4013).
- **Target modules:** VCA (4.3), VCF (4.2). **Related:** LFO (4.5) as a cyclic modulation source.
- **Tool: T4 envelope simulator** (ADSR shape, τ computed from R·C, exponential/linear comparison).
- **Chips:** CEM3310/AS3310, SSM2056, CD4013/CD4066 — Appendix B.
- **Open source:** MFOS ADSR, YuSynth ADSR, Befaco Rampage (function generator) [to be verified: repos].

- **[to be verified]** before publication: availability of AS3310/V3310, SSM2056 reissues. Web audit per the textbook-relationship rule.

Parts 4.5–4.7 — LFO, Noise and the Utilities

> **Dual track.** These three module groups are treated together because they jointly form the **modulation layer** of a system. ▶️ B explains purpose and practice, ▶️ E the circuits.

Part 4.5 — The LFO (Low Frequency Oscillator)

4.5.1 ▶️ B — What an LFO does

An LFO is an oscillator that **swings too slowly to be heard** — typically 0.01 to 30 Hz. You do not hear it as a tone but as **movement**: it modulates other parameters.

Classic applications:

Target	Waveform	Result
VCO pitch	triangle/sine, slow	**vibrato**
VCA loudness	triangle/sine	**tremolo**
VCF cutoff	triangle	"wobbling" filter, dubstep wobble
Pulse width (PWM)	triangle, very slow	drifting, wide sound
Panorama	triangle	auto-pan
Sample & hold clock	square	stepped randomness

The fluid transition: turn an LFO up into the audible range (above ~20 Hz) and modulation becomes **sound synthesis** — vibrato becomes FM (frequency modulation), tremolo becomes ring-modulation-like sidebands. Many modules therefore offer an LFO/VCO range switch. This is not a footnote but the founding principle of FM synthesis.

4.5.2 ▶️ E — Circuit

Circuit-wise an LFO is a VCO with large time constants. Two common implementations:

(a) Integrator + comparator (triangle/square core). An op-amp integrator charges a capacitor linearly; a Schmitt trigger flips when the thresholds are reached and reverses the charging direction. Result: **triangle** at the integrator, **square** at the comparator, exactly phase-locked. Frequency:

(with as the Schmitt trigger's hysteresis divider).

(b) Schmitt-trigger inverter (CD40106). One inverter, one resistor, one capacitor — an LFO. . Six per chip. Gives a square plus (at the capacitor) an exponential sawtooth approximation.

Practical details: - **Large time constants** need film capacitors; electrolytics have leakage currents that distort the curve on very slow LFOs (minute range). - **Reset/sync input**: lets the LFO be synchronized to a clock — important for rhythmic modulation. - **Bipolar or unipolar?** An LFO for pitch vibrato should swing **bipolar** around 0 V (otherwise it detunes the base pitch). An LFO for loudness is often needed **unipolar**. Good modules offer both or an offset control.

Part 4.6 — Noise generators

4.6.1 ▶️ B — What noise is for

Noise is a signal without pitch — all frequencies at once, randomly distributed. Indispensable in a synthesizer for:

- **Percussion**: snare, hi-hat and cymbals are filtered noise.
- **Wind, sea, breath**: natural sounds.
- **Attack transient**: a pinch of noise in the attack makes winds/strings more realistic.
- **Random source**: through sample & hold, noise becomes random stepped voltages (4.7).

Noise colours (the analogy to the light spectrum):

Colour	Spectrum	Sound
White	all frequencies equally strong	bright, hissing (“TV snow”)
Pink	−3 dB/octave	balanced, “natural” — equal energy per octave
Red/brown	−6 dB/octave	dull, rushing sea
Blue/violet	+3/+6 dB/octave	very bright, sharp

Why pink noise sounds “more natural”: our hearing works in octaves. White noise has equal energy per *hertz* — so ten times as much in the 10–20 kHz octave as in 1–2 kHz. That is why it sounds shrill. Pink noise has equal energy per *octave* and is perceived as balanced. This is also why pink noise is the standard for sound-system alignment (cross-reference: FORSCH-0288, MISCHWERK).

4.6.2 ▶️ E — Circuit

(a) Zener/junction noise (analog). A transistor’s base–emitter junction operated in reverse (e.g. 2N3904) breaks down at ~6–9 V and produces strong noise. The signal is very small (µV–mV) and needs 2–3 amplifier stages (total gain 1000–10000).

- **Problem:** noise amplitude varies considerably between samples of the same type. In practice several transistors get tried — a well-known DIY annoyance.

- **Alternative:** purpose-specified noise diodes, or a high-value resistor as a source of thermal noise (very small, requiring much gain).

(b) Digital (LFSR). A linear feedback shift register generates a pseudo-random bit sequence. Classically with CD4006/CD4015 + XOR gates, today usually inside a microcontroller. Advantages: exactly reproducible, no part spread, definable period length. Disadvantage: strictly speaking periodic (though inaudibly so with sufficient register length).

(c) Pink filter. White noise becomes pink through a filter with −3 dB/octave. Since a true −3 dB/oct cannot be achieved with a simple RC network (which gives −6), a **cascade filter** of several staggered RC stages is used to approximate the −3 dB slope across the audio band.

Part 4.7 — The utilities (the underestimated backbone)

4.7.1 ▶️ B — Why utilities decide

A modular system is not only sound generators. The **connecting and shaping modules** determine whether a system is playable. They are cheap, unspectacular, and consistently bought too late by beginners (see 6.1.6).

4.7.2 The most important utilities

(a) Multiple (splitter) — distributes one signal to several destinations. - *Passive*: jacks soldered in parallel. Fine for gates/audio. - *Buffered*: with an op-amp impedance converter. **Mandatory for pitch CV** (reasoning in 6.1.4).

(b) Attenuator / attenuverter — reduces the strength of a signal. - *Attenuator*: 0 … 100 % (attenuation only, a potentiometer). - *Attenuverter*: −100 % … 0 … +100 % — can also **invert** the signal. An LFO that closes the filter instead of opening it. Indispensable for modulation work. - ▶️ E: an attenuverter is an op-amp with a pot between the inverting and non-inverting paths; at centre both cancel → the null point.

(c) Offset / bias — adds a constant DC voltage. Shifts a bipolar LFO into the unipolar range or tunes a VCO manually.

(d) Mixer (CV and audio) — sums signals. ▶️ E: an inverting summer (Part 3.2); for CV make sure it is **DC-coupled** — an AC-coupled audio mixer cannot mix control voltages. This is a common mis-purchase.

(e) Slew limiter / portamento — limits how fast a voltage may change. Pitch jumps become **glide/portamento**; a gate becomes an envelope shape. ▶️ E: an RC network with a buffered output; separate rise/fall times turn it into a versatile function generator.

(f) Sample & hold (S&H) — takes a snapshot of the input voltage on each clock and holds it until the next. - ▶️ B: noise + S&H = the classic “random melody” (the “computer” sound of the 1970s). - ▶️ E: an analog switch (CD4066) charges a hold capacitor, followed by a **very high-impedance** buffer (FET op-amp). Otherwise the capacitor discharges through the buffer input

→ the voltage "sags" (droop). Small capacitor = fast acquisition but more droop; large = stable but sluggish.

(g) Comparator / threshold switch — turns a control voltage into a gate once a threshold is crossed. An LFO becomes a rhythm generator.

(h) Ring modulator — multiplies two signals. Produces sum and difference frequencies without the original tones → metallic, bell-like, "unmusical" sounds. ▶️ E: classically with a transformer and diode ring, today with a four-quadrant multiplier (**AD633**, or the OTA principle). Known as the Dalek voice (Doctor Who) and in industrial/noise aesthetics.

4.7.3 The rule of thumb

> A sensibly built system has **at least as much utility HP as sound-generator HP**. Someone with three VCOs and no attenuverter can do less than someone with one VCO, two LFOs and four utilities.

Cross-references (4.5–4.7)

- **Prerequisites:** Part 3.1–3.2 (op-amp: summer, comparator, hysteresis), Part 2.3.2 (CD4066, CD40106).
- **Modulation targets:** VCO (4.1), VCF (4.2), VCA (4.3).
- **Tools:** T4 (envelopes, related time constants), T1 signal-chain visualizer (patch logic).
- **Chips:** CD40106, CD4066, CD4015, AD633, TL07x — Appendix B.
- **Pink noise in sound-system measurement:** cross-reference FORSCH-0288 (MISCHWERK).
- **Open source:** MFOS LFO/noise/S&H, Music Thing Modular Turing Machine (randomness), Befaco Rampage (slew/function) [to be verified: repos].
- **[to be verified]** before publication: AD633 availability, noise-transistor recommendations from current DIY practice. Web audit per the textbook-relationship rule.

Part 5 — From Module to Instrument

> **Dual track.** ▶️ B: how individual blocks become a playable instrument. ▶️ E: architectural decisions, a fully dimensioned reference build, mechanics and calibration. This part brings the module chapters (4.x) together.

5.1 Architectures of sound synthesis

5.1.1 ▶️ B — The basic paradigms

A synthesizer is not one technique but a **design attitude**. Four paradigms shape practice:

Paradigm	Principle	Typical examples
Subtractive	harmonically rich source → filter away	Minimoog, SH-101, almost everything classic
Additive	add many sines together	organs, Hammond, Kawai K5
FM/PM	oscillators modulate one another	DX7, the Yamaha lineage
Physical modeling	compute the acoustic process	digital (Part 7)

Subtractive is this book's paradigm because it is the most directly realizable in analog terms (Part 1.1.3 explains why the sawtooth is the ideal raw material for it).

5.1.2 ▶️ B — West Coast vs. East Coast

Two schools that developed in parallel historically and still shape the aesthetics today:

East Coast (Moog, New York). Keyboard-oriented, modeled on classical instruments. Signal chain **VCO → VCF → VCA**, driven by envelopes. Goal: playable, "musical" sounds. This is the chain Part 4 worked through.

West Coast (Buchla, California). Not keyboard-centric; sound arises from **complexity rather than subtraction**. Characteristic blocks: - **Complex oscillator** — two oscillators modulating each other (FM, AM). - **Wavefolder/waveshaper** — instead of filtering harmonics away, additional ones are *created* by "folding" the waveform. - **Low-pass gate** (4.3.6) instead of a separate VCA+VCF. - **Randomness and sequencers** as compositional tools instead of a keyboard.

▶️ **E — The wavefolder as a contrast.** A filter removes harmonic material; a wavefolder "flips" a triangle/sine wave at adjustable thresholds, creating new, partly inharmonic harmonics. Circuit-wise: diode networks or OTA chains driven into saturation. Sonically: metallic, glassy, dynamically responsive — audibly different from a resonant filter. The interactive **tool T7 (Wavefolder Visualizer)** shows the folding live and audibly: as the folding amount grows, more and more harmonics appear, visibly and audibly.

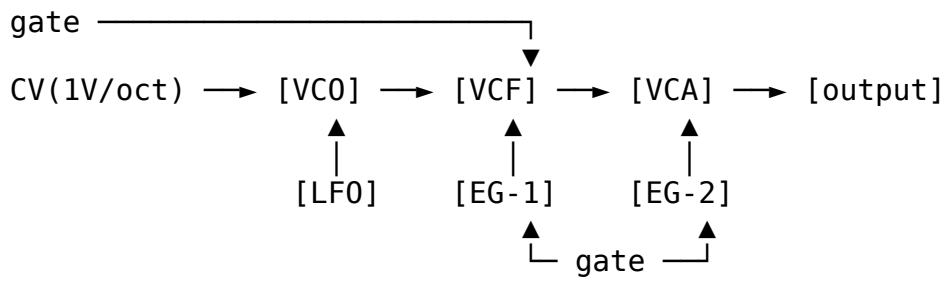
In practice most contemporary systems mix both schools — Eurorack is open enough for a Buchla-style complex oscillator to sit next to a Moog ladder filter.

5.2 The reference build: a complete minimal synth

5.2.1 ▶️ B — What gets built

A monophonic subtractive synthesizer using the modules from Part 4, as a self-contained instrument (not a modular system). Goal: **something you can actually play at the end**, with a manageable parts count.

Block diagram:



5.2.2 ▶ E — Module choice and reasoning

Block	Implementation	Chapter	Reasoning
VCO	AS3340 (or discrete + tempco)	4.1.3	stable tracking without elaborate calibration
VCF	LM13700 OTA, 12 dB SVF or 24 dB ladder	4.2.3	the OTA is obtainable and instructive
VCA	LM13700 (second half)	4.3.2	one chip for VCF+VCA saves parts
EG ×2	discrete, CD4066 + TL072	4.4.3a	two separate envelopes (amp/filter) are the core of sound design
LFO	CD40106 or TL072 integrator	4.5.2	triangle + square
Interface	MIDI-to-CV (MCU) or keyboard resistor ladder	4.9 / 7.2	
Output	level reduction + headphone driver	6.1.4	synth level is too hot for line

5.2.3 ▶ E — Current estimate

A rough calculation for sizing the PSU (method as in 6.1.3):

Block	+12 V	–12 V
VCO (AS3340 + buffers)	~25 mA	~20 mA
VCF (LM13700 + op-amps)	~20 mA	~20 mA
VCA (shared LM13700)	~10 mA	~10 mA
2× EG (TL072 + CD4066)	~12 mA	~10 mA
LFO	~8 mA	~8 mA
Output stage	~15 mA	~15 mA
Total	**~90 mA**	**~83 mA**

With 30 % headroom, a ±12 V supply from ~150 mA per rail suffices. With an additional microcontroller interface, budget +5 V separately (regulate locally from +12 V, 6.1.2).

5.2.4 ▶️ B — Build order (the order is half the battle)

Do not build everything at once. Stage by stage, testing each:

1. **Power supply** — measure the rails before any IC goes in. (The most common total loss: reversed or wrongly dimensioned supply.)
2. **VCO alone** — make the tone audible (oscilloscope + amplifier), then calibrate tracking (4.1.4).
3. **Add the VCF** — check filtering with a static cutoff, then resonance.
4. **Add the VCA** — with a fixed control voltage, then check for clicks (4.3.5).
5. **EG-1 to the VCA** — only now do individual notes emerge.
6. **EG-2 to the VCF** — the expressive power arises here.
7. **LFO** — last, as a modulation layer.
8. **Interface/keyboard** — make it playable.

▶️ **E — Why this order:** each stage has an **unambiguous test point** and builds on an already verified stage. Build everything and switch on, and a fault has N possible causes instead of one.

5.3 Enclosure, panel, wiring — SCHICHTWERK integration

5.3.1 ▶️ B — Why mechanics matter

An electrically perfect module with poor mechanics is unusable: canted pots snap off, wobbling jacks cause dropouts, unreadable labeling makes the instrument unplayable. The panel is also the user interface — this is where it is decided whether the device gets used.

5.3.2 ▶️ E — Fabrication routes for panels

Process	Material	Advantages	Limits
Laser (CO_2)	acrylic, wood, card	fast, precise, engravable labeling	no metal; acrylic snaps at thin webs
Laser (fiber)/CNC	aluminium	professional, sturdy, shielded	higher effort/cost
3D printing FDM	PLA/PETG/ASA	prototypes, special shapes, spacers	surface finish, dimensional accuracy, UV/heat
3D printing SLA	resin	fine detail, smooth surface	more brittle, UV-sensitive
External manufacture	anodized alu + screen print	production quality	minimum quantities, lead time
PCB as panel	FR4	ordered together	looks are a matter of

Process	Material	Advantages	Limits
		with the board, labeling in soldermask	taste; conductive where copper

Workshop context (SCHICHTWERK): for self-building, the combination **laser for acrylic/wood panels + FDM for internal mechanics (spacers, brackets, cable guides) + SLA for fine detail (knob caps, label carriers)** is practical. For aluminium panels, external manufacture pays off from small series upward.

5.3.3 ▶️ E — Design rules for Eurorack panels

Following from 6.1.1, here as fabrication specifications:

1. **Height 128.5 mm**, width = HP × 5.08 mm, minus ~0.3 mm clearance per side so neighboring modules do not jam.
2. **Slotted holes** for the M3 fixings — never rigid round holes (tolerance compensation, 6.1.1).
3. **Hole diameters** per component: 3.5 mm jacks typically 6 mm, 9 mm pots 7 mm, toggle switches 6 mm [check per manufacturer].
4. **Anti-rotation** for pots/jacks: either provide the locating hole or clip the lug off and rely on the nut.
5. **Material thickness:** 2 mm acrylic is marginal (snaps under load at jacks), 3 mm is practical; aluminium 1.5–2 mm.
6. **Labeling** on acrylic: engrave from the **back** and fill — then it cannot rub off.
7. **Control layout** should follow the signal flow: inputs bottom/left, outputs bottom/right, controls in flow order.

5.3.4 ▶️ E — Internal wiring

- **Jacks and pots on their own board** (panel PCB), connected to the main board via pin headers — this avoids wiring dozens of individual leads and is the standard in commercial modules.
- For **free wiring**: stranded wire (flexible), not solid; strain relief; colour-code by function.
- Do not ruin the **grounding scheme** (1.5.2) with the wiring: bring panel grounds to one star point rather than daisy-chaining jack to jack.
- Maximize the **distance between mains/transformer section and analog signal**; where unavoidable, cross rather than run parallel.

5.4 Calibration, test and fault-finding

5.4.1 Calibration order (complete instrument)

1. **Rails** checked (voltage, ripple on the oscilloscope).
2. **VCO tracking** (4.1.4) — scale, tune, hi-freq if present.
3. **VCF cutoff tracking** (4.2.5), if fitted.

4. **VCA offset** — trim for minimal bleed and freedom from clicks (4.3.5).
5. **EG times** checked against the specification (4.4.2) and attack clicks ruled out.
6. **Output level** set (6.1.4).
7. **After 15 min warm-up**, re-check VCO tracking (temperature drift, 4.1.2).

5.4.2 ▶️ E — Systematic fault-finding

> **Basic principle:** bisect the signal path. Instead of checking front to back, measure in the middle — each test then halves the search space.

Procedure:

1. **Power first.** Rails at several points, including directly at the IC pins (not just at the connector).
2. **Signal tracing.** Inject a known test signal and follow it stage by stage with the oscilloscope until it disappears or distorts.
3. **Visual inspection.** Solder bridges, cold joints, reversed electrolytics/ICs, forgotten parts. A large share of all faults is visible with a magnifier.
4. **Suspect components** checked individually (diode test, resistance measurement — powered down and discharged).
5. **Compare with simulation** (Part 8.1): where real behavior deviates from the simulation, the difference is the clue.

Most common causes in order of likelihood: soldering fault → wrong component value fitted → reversed/misoriented parts → wiring error → an actual circuit error → a defective component. The defective component is far rarer than assumed.

5.5 Cross-references

- **The modules in detail:** Parts 4.1–4.7. **Components and instruments:** Part 2.
- **Format requirements:** Part 6.1 (Eurorack dimensions, power, levels).
- **Designing your own boards and panels:** Part 8.2 (KiCad, manufacturing).
- **Digital extension (MIDI-CV, interface):** Part 7.2.
- **Tools:** T5 (power budget), T1 (signal-chain visualizer), T2/T3/T4 (dimensioning), T7 (Wavefolder Visualizer, ch. 5.1.2).
- **[to be verified]** before publication: concrete hole dimensions for common jack/pot brands; current fabrication services and terms. Web audit per the textbook-relationship rule.

Part 6.1 — Eurorack: Mechanics, Power, Levels

> **Dual track.** ▶️ B: what Eurorack is, what you need to start, and which traps get expensive. ▶️ E: the specification in detail — dimensions, bus board, power calculation, signal levels, impedances.

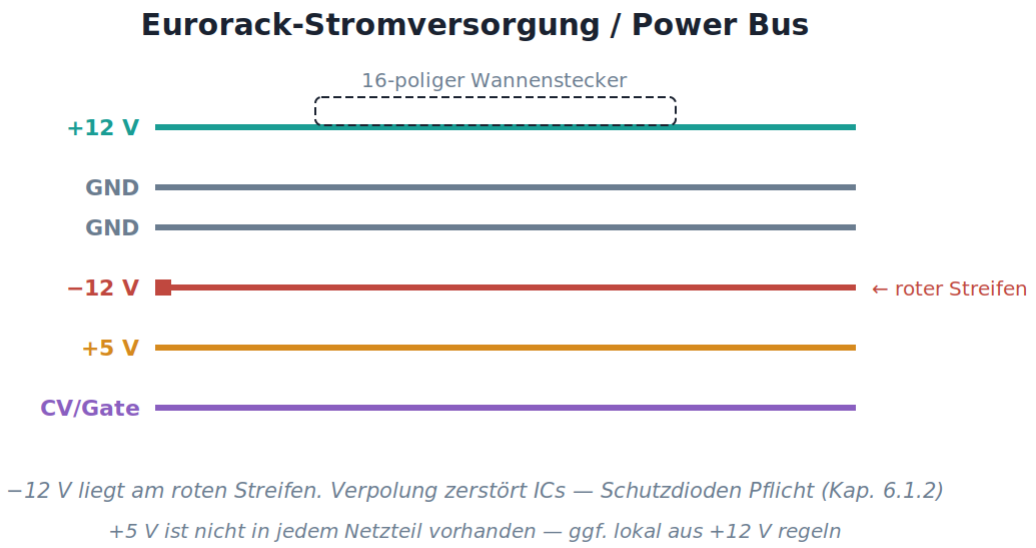


Fig. 6: Eurorack power bus

Fig. 6: Eurorack power bus

6.1.0 Why a format chapter

A module only becomes buildable once it fits a system **mechanically, electrically and in signal terms**. Eurorack is the de-facto standard of contemporary DIY modular building — not because it is technically the best format, but because it has the largest selection of modules, cases and kits. Anyone developing their own modules (Part 8) is in practice always developing against this specification.

Historical placement: Eurorack was introduced in 1995 by Doepfer (Dieter Doepfer) with the A-100 system. The format adopts the mechanics of the 19-inch industrial standard but defines its own conventions for power and signals. It is an **open standard** with no licensing fees — the reason for the explosion of manufacturers and DIY projects from roughly 2010 onward.

6.1.1 ▶️ B — Mechanics: HP, U, depth

Three dimensions you must know:

- **Height: 3U** — the front panel is **128.5 mm** tall. (Note: “3U” denotes the standard rack unit height; the actual panel height is slightly under the theoretical figure so the module fits the rails.)
- **Width: HP (horizontal pitch)** — **1 HP = 5.08 mm** (= 0.2 inch). Modules are integer multiples: 2 HP, 4 HP, 8 HP, 12 HP, etc. A typical case holds 84 HP or 104 HP per row.

- **Depth** — not standardized, but decisive in practice. Shallow cases often take only 25–40 mm; "skiff" enclosures are especially flat. **The most common beginner mistake:** ordering a deep module for a shallow case.

▶️ **E — Mounting.** The panel is fastened with M3 screws into threaded rails or sliding nuts. The holes are slotted so HP tolerances can be absorbed. For your own panels (Part 5.3, Schichtwerk fabrication) always provide slotted holes — rigid round holes cause stress and misalignment when several modules sit side by side.

6.1.2 ▶️ E — Power supply: ±12 V, +5 V

Eurorack distributes power over a **bus board** with 16-pin box headers:

Rail	Purpose	Note
+12 V	analog positive rail	main supply
−12 V	analog negative rail	for bipolar audio/CV signals
GND	ground	several pins
+5 V	digital rail	**not present in every PSU!**
CV / gate (2 pins)	optional bus	provided by Doepfer, rarely used

The notorious red stripe. The ribbon cable has a red stripe on one side — it marks **−12 V**. On the module, −12 V is on the side marked "−12" or with a dot at the box header.

> **Reverse-polarity protection — the most expensive trap in the hobby.** If the cable is plugged in rotated 180°, +12 V sits where −12 V is expected. Without protection this destroys ICs in seconds. Two measures belong in **every** DIY module: 1. **Series protection diodes** (Schottky, e.g. 1N5817) — simple, costs ~0.3 V drop per rail. 2. **Reverse-biased diodes to ground** plus a fuse — shorts on reverse polarity and blows the fuse.
>
> Better still: use **shrouded (keyed) box headers**. Costs cents, saves chips.

+5 V is not guaranteed. Many analog PSUs supply only ±12 V. A module expecting +5 V from the bus then fails. Well-designed digital modules therefore generate their 5 V **locally** from +12 V (LDO regulator, e.g. 7805 or the more modern LM1117/AMS1117) rather than relying on the bus.

6.1.3 ▶️ E — Calculating the power budget

Every module draws current on every rail. The sum must stay below the PSU rating — **with headroom**.

Calculation rule:

The rails are counted **separately**. A PSU rated "1500 mA" typically has 1500 mA on +12 V **and** 1500 mA on −12 V — not 1500 mA in total.

Headroom: plan at least **20–30 % reserve**. Reasons: - Inrush current peaks at power-up, especially with digital modules that have large bulk capacitors. - Manufacturer figures are often typical values, not maxima. - Expansion: the next module will come.

Typical current draw (order of magnitude):

Module type	+12 V	−12 V	Note
Passive (multiple, attenuator)	0	0	no connection needed
Simple analog VCA/mixer	20–40 mA	20–40 mA	op-amp based
Analog VCO	30–70 mA	30–70 mA	
Analog filter	20–50 mA	20–50 mA	
Digital module (ARM/DSP)	80–250 mA	10–30 mA	asymmetric!
Module with display/LEDs	+ 20–100 mA	—	LEDs add up

Mind the asymmetry: digital modules draw almost all their current on +12 V (where the 3.3/5 V regulator sits), while −12 V is barely loaded. A system with many digital modules can therefore exhaust the +12 V rail while −12 V stays half empty.

6.1.4 ▶️ E — Signal levels and impedances

Here lies the second major source of misunderstanding: Eurorack has **no** strictly normed levels, but clear conventions.

Signal type	usual range	Note
Audio	±5 V (10 Vpp)	some modules up to ±10 V; far hotter than line level
CV unipolar	0 … +8 V (or 0…+10 V)	envelopes, pitch
CV bipolar	−5 … +5 V	LFOs, modulation
Pitch CV	1 V/octave	Part 4.1
Gate	0 V / +5 V (up to +10 V)	switching threshold usually ~1–2.5 V
Trigger	short pulse, +5 V	typ. 1–10 ms

Impedance convention: outputs low-impedance (typically a **1 kΩ** protection resistor in series), inputs high-impedance (typically **100 kΩ**). This allows one output to feed several inputs through a passive multiple without a noticeable level drop.

▶️ **B — The practical consequence:** Eurorack audio is **much louder** than studio line level. A modular output fed straight into a mixer overloads it. You need an **output module** (output/line interface) that reduces the level by roughly 12–20 dB and often balances it. Conversely, external audio needs an **input module** that raises the level.

Passive vs. buffered multiples: a passive multiple (just jacks soldered together) is usually fine for gates and audio. For **pitch CV** to several destinations you should use **buffered multiples** — otherwise the output resistance divides with the input resistances, the voltage sags slightly, and VCO tracking becomes inaccurate (audible detuning).

6.1.5 The most common traps (short list)

1. **Ribbon cable rotated** → fit reverse-polarity protection, use keyed headers.
2. **Module depth not checked** → won't fit the skiff.
3. **+5 V expected but absent** → regulate locally.
4. **Power budget too tight** → 20–30 % reserve.
5. **Too many modules on one bus-board branch** → voltage drop across the board; measure the rails at full build.
6. **Pitch CV split passively** → tracking error; use a buffered multiple.
7. **Module output straight into a mixer** → overload; use an output module.
8. **Ground loops** across several cases/PSUs → hum (Part 1.5).

6.1.6 ▶️ B — What you need to start

The minimal playable configuration:

1. **Case + PSU** (with enough HP and current; mind the depth)
2. **Sound source** — VCO (or a module with several voices)
3. **Filter** — VCF
4. **Envelope + VCA** (often combined in one module)
5. **Modulation source** — LFO
6. **Control** — MIDI-to-CV interface or sequencer
7. **Output** — output module for connecting to a mixer/interface
8. **Utilities** — multiples, attenuators, mixers (consistently underestimated)

The classic beginner mistake: too many sound sources, too few **utilities**. A modular system lives on attenuators, mixers, multiples and offset modules — unspectacular, but without them the exciting modules cannot be patched together sensibly (Part 4.7).

6.1.7 Cross-references

- **Other formats** (Serge/banana, Buchla, MU, Kosmo, Frac): Part 6.2. **Interoperability/level matching:** Part 6.3.
- **Making your own panels and cases:** Part 5.3 (Schichtwerk fabrication: 3D printing, laser, aluminium).
- **Developing your own modules:** Part 8 (KiCad, PCB, panel).
- **Tool: T5 Eurorack power/HP calculator** (module list, rail sums, headroom warning, HP occupancy).
- **Utilities in detail:** Part 4.7. **Ground/hum:** Part 1.5.
- **[to be verified]** before publication: current Doepfer A-100 specification details and dimensions against the primary source (doepfer.de technical details); typical PSU sizes/prices. Web audit per the textbook-relationship rule.

Parts 6.2–6.4 — Other Formats, Interoperability, the Open-Hardware Landscape

> **Dual track.** ▶️ B: which systems exist besides Eurorack and how to translate between them. ▶️ E: the technical differences that matter at the crossover. Part 6.1 is the prerequisite.

Part 6.2 — Other formats

6.2.1 ▶️ B — Why there is more than Eurorack

Eurorack (6.1) is today's most widespread standard, but not the only one and not the oldest. Each format embodies a **design philosophy**: different jacks, different levels, different ergonomics — and thereby a different musical practice. Knowing the differences also explains why certain sounds and playing styles are bound to certain formats.

6.2.2 The main formats compared

Format	Height	Jack	Power	Signal level	Character
Eurorack	3U (128.5 mm)	3.5 mm jack	±12 V	±5 V audio, 1V/oct	largest selection, dense
Serge	4U	banana	±12 V	variable	patch-programmable, stackable
Buchla 200/200e	own	banana (CV) + jack (audio)	±15 V	10 Vpp, often Hz/V	West Coast, separate CV/audio worlds

Format	Height	Jack	Power	Signal level	Character
MU / Moog Unit (“5U”)	5.25″	1/4″ jack	±15 V	larger	large, “vintage”, expensive
Frac Rak	3U (smaller)	1/4″ jack	±15 V		older DIY format
Kosmo	200 mm	1/4″ jack	±12 V	electrically Eurorack-compatible	DIY, large panels, robust
Pedal/ desktop	—	6.3/3.5 mm	various	instrument/ line	standalone devices

6.2.3 ▶️ E — The three differences that matter technically

At the crossover between formats the dimensions are not the problem (an adapter cable solves that) but **three electrical quantities**:

1. **Jack type.** Phone jack (Eurorack, MU, Kosmo) vs. **banana** (Serge, Buchla CV). Bananas are stackable (several plugs on top of one another = a passive multiple) and have a **separate ground** — a conceptual difference, not a mere change of connector.
2. **Supply voltage.** ±12 V (Eurorack, Kosmo) vs. ±15 V (Buchla, MU, Frac). A ±12 V module on ±15 V can be damaged; the reverse lacks headroom. Do not simply re-patch.
3. **Pitch standard.** 1V/octave (most) vs. **Hz/V** (classic Buchla, old Korg/Yamaha). These two are **not compatible** — they need an active converter (6.3.2), not a cable.

Part 6.3 — Interoperability

6.3.1 ▶️ B — What connects easily

- **Same level standard, different jack** → a passive adapter cable (jack ↔ banana). Works for audio, gate and 1V/oct CV as long as the voltages are in the same range.
- **Audio between formats** is usually uncritical as long as the level fits — adjust via an attenuator (4.7.2b) or amplifier if needed.

6.3.2 ▶️ E — What needs an active converter

Crossover	Problem	Solution
1V/oct ↔ Hz/V	fundamentally different law	active converter (exp/log, Part 3.3)
±12 V ↔ ±15 V	supply/headroom	separate PSU per system; adjust signal level via attenuator
Gate 5 V ↔ 10 V / S-trig	switching threshold/polarity	level shifter; S-trigger (Moog, inverted) needs inversion

Crossover	Problem	Solution
Modular level ↔ line/instrument	level 10–20 dB too hot	output module (6.1.4)

S-trigger as a special case: older Moog gear uses "switch trigger" — a signal that *switches to ground* instead of a positive voltage. A modern V-trigger (positive gate voltage) must be inverted for it. A common stumbling block when connecting old and new gear.

6.3.3 ▶️ E — MIDI, USB and the digital bridge

- **MIDI-to-CV** translates note numbers into 1V/oct CV and gate (Part 4.9). The central bridge between the keyboard/sequencer world and the modular system.
- **CV-to-MIDI** for the reverse direction.
- **USB/class-compliant** interfaces tie the system to the computer (DAW, VCV Rack, Part 7.6).
- **Clock synchronization** (analog clock vs. MIDI clock vs. DIN sync) is a compatibility topic of its own — clock dividers/converters reconcile the standards.

Part 6.4 — The open-hardware landscape

6.4.1 ▶️ B — Why this landscape exists

DIY synthesizer building lives on an unusually open culture: schematics, layouts and build guides are shared, commented and developed further. This openness is not accidental but has concrete roots — educational projects, expiring patents on basic circuits, and a community that treats knowledge as a common good. For builders this means: almost every circuit covered here already exists as a documented, open project.

6.4.2 A curated project landscape

> **Note:** the overview below names established sources for orientation. Availability, activity and links change — every entry is to be checked against the current state before publication. **[to be verified: all projects, links, activity status]**

Project/source	Contribution	Character
MFOS (Music From Outer Space, Ray Wilson)	teaching projects, the "Noise Toaster", complete synths	educational, well documented, the starting point for many beginners
YuSynth (Yves Usson)	an extensive module collection, VCO/VCF/…	classic recreations, proven
Ken Stone / CGS (Cat Girl Synth)	unusual modules, close to West Coast	experimental
Music Thing Modular (Tom Whitwell)	Turing Machine (randomness), simple utilities	minimalist, open

Project/source	Contribution	Character
Mutable Instruments (Émilie Gillet)	open-source digital/hybrid modules, code free	formative for the hybrid wave; firmware open
Befaco	open kits, utilities	kit-oriented, community-close
Nonlinearcircuits (NLC)	idiosyncratic, chaos-adjacent circuits	avant-garde
Thonk	kits and components (distribution)	a source, not a developer
Lunetta / Nicolas Collins	CMOS-based sound tinkering (40106 etc.)	an entry without precision demands (2.3.2)

6.4.3 ▶️ E — How to judge a project

Not every open project is equally buildable. Criteria (cf. 8.5.1):

1. **Completeness** — schematic **and** layout **and** BOM **and** calibration instructions? If one is missing, the build gets difficult.
2. **Currency of the parts** — are the chips still obtainable, or does the project rest on long-discontinued ICs (2.3.7)?
3. **Documented successes** — have others built and confirmed it? A forum thread with successful builds is worth more than a glossy datasheet.
4. **Licence** — is reuse permitted and clarified (8.5.2)?
5. **Support/community** — is there a place where questions get answered?

6.4.4 ▶️ B — This book's place in the landscape

This work does not see itself as a competing project but as a **map and foundation**: it explains the principles on which the named projects rest and thereby makes them readable and assessable. Anyone who has understood Parts 3 and 4 can read an MFOS or YuSynth schematic, follow its dimensioning and modify it deliberately — rather than merely re-soldering it.

This book's trigger — Ray Wilson's *Make: Analog Synthesizers* with the "Noise Toaster" — itself stands in this tradition: a teaching device on which the principles can be experienced. This work carries the idea further by detaching the principles from the single teaching device and presenting them systematically, bilingually and with interactive tools.

Cross-references (6.2–6.4)

- **Eurorack fundamentals:** Part 6.1. **Level/impedance:** Parts 1.2–1.3.
- **Active converters (exp/log):** Part 3.3. **MIDI-CV:** Part 4.9.
- **Publishing a project yourself:** Part 8.5.
- **A software modular system to try out:** Part 7.6 (VCV Rack).

- **[to be verified]** before publication: all named projects, people, links and activity status against current primary sources; format specifications (Serge/Buchla/MU dimensions, voltages). Web audit per the textbook-relationship rule and the source-seriousness rule.

Part 7 — Hybrid and Digital

Dual track. ▶️ B: what digital does better, what stays analog, and why most modules today are hybrid. ▶️ E: microcontroller platforms, DAC/ADC dimensioning, DSP fundamentals and the aliasing question. This part presupposes Parts 1–6.

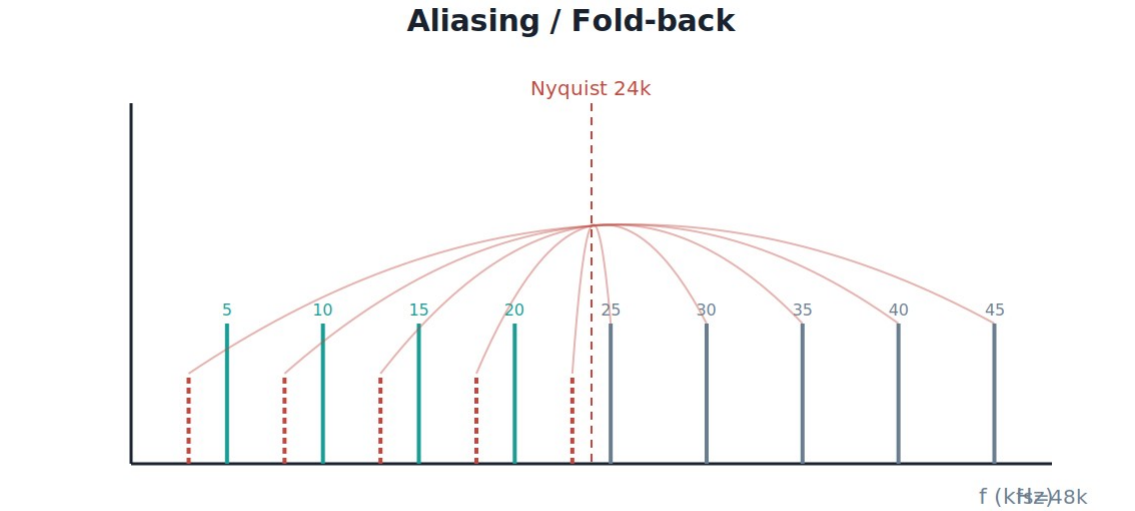


Fig. 7: Aliasing

Fig. 7: Aliasing

7.1 Why digital — and where analog stays

7.1.1 ▶️ B — The honest comparison

The “analog vs. digital” debate is often conducted ideologically. Factually, both have clearly nameable strengths:

Criterion	Analog	Digital
Reproducibility	part tolerances, drift	exact, preset-capable
Complexity per part	every voice costs hardware	polyphony in software
Memory/presets	difficult (needs VC pots)	trivial
Aliasing	does not exist	a central problem (7.3.3)
Saturation/overdrive	soft, often desirable	hard, usually undesirable

Criterion	Analog	Digital
Cost at high functional density	rises linearly	nearly constant
Latency	zero	buffering + conversion
Development cycle	solder, measure	compile, flash

The productive conclusion: not "which is better," but **which task belongs where**. In practice a clear division of labour has emerged:

- **Analog typically stays** in the **audio path** — filter, VCA, saturation. There the nonlinear behavior is part of the sound.
- **Digital typically takes** the **control layer** — sequencer, MIDI interface, modulation sources, presets, menus, randomness.

This is the **hybrid architecture** (7.5) and describes the majority of today's Eurorack modules.

7.1.2 ▶️ E — What is genuinely harder digitally

Two points rarely found in marketing copy:

1. **Aliasing** (7.3.3) — a digitally generated sawtooth is, without countermeasures, *wrong*: harmonics above half the sample rate fold back into the audible range and produce inharmonic artifacts. The analog VCO does not have this problem in principle (4.1.5). Good digital oscillators require considerable effort (band-limited methods).
2. **CV quantization** — a 12-bit DAC across a 10 V range gives a 2.44 mV step. At 1 V/octave that is about **2.9 cents** per step — audible as stepping on slow glissandi. Clean pitch CV needs 16 bits or more (7.3.1).

7.2 Microcontrollers in a module

7.2.1 ▶️ B — The platforms

Platform	Core	Strength	Typical use
Arduino (AVR)	8-bit, 16 MHz	simplest entry, huge community	sequencers, MIDI-CV, logic
Teensy 4.x	ARM Cortex-M7, 600 MHz	very fast, audio library	audio DSP, samplers
Daisy Seed	ARM Cortex-M7 + codec	**built for audio**: codec, SDRAM on board	effects, digital oscillators
RP2040 (Pico)	dual Cortex-M0+, PIO	cheap, **PIO** for exact timing	CV generation, gate logic, utilities
STM32	ARM, wide family	industrial standard, much peripheral	commercial modules

Platform	Core	Strength	Typical use
ESP32	Xtensa + WiFi/BT	radio on board	networked/ experimental modules

▶️ **B — Entry recommendation:** for **CV/gate tasks** (sequencer, quantizer, LFO, randomness) the **RP2040** is currently the cheapest and most flexible choice. For **audio DSP** (delay, reverb, digital oscillators) **Daisy Seed** is the most direct route because codec and memory are already on board [to be verified: current availability/prices].

7.2.2 ▶️ E — The RP2040 PIO argument

The RP2040 has **PIO** (programmable I/O) — small state machines that generate cycle-accurate signals independently of the main processor. For synth applications this means **jitter-free gates and clocks**, regardless of what the CPU is doing. On classic microcontrollers every interrupt collision produces timing jitter that becomes audible in rhythmic applications.

7.2.3 ▶️ E — Integrating with the analog world

A microcontroller runs at 3.3 V (or 5 V), the modular world at ±12 V with bipolar signals. Four adaptations are mandatory:

1. **Supply:** regulate 3.3/5 V locally from +12 V (6.1.2); do not rely on +5 V from the bus.
2. **Scale the CV input:** map ±5 V (or −10…+10 V) to 0…3.3 V — a voltage divider plus offset, usually with an op-amp as a summer (3.1.2d). Do not forget **protection diodes** to the rails; an accidentally patched 12 V output otherwise destroys the ADC pin.
3. **Scale the CV output:** amplify/shift the DAC output of 0…3.3 V to the desired range (op-amp).
4. **Interference decoupling:** digital switching edges couple into analog stages (1.5.1). Separate ground planes, decoupling, a ferrite bead if needed (2.4.2).

7.3 DAC, ADC and digital CV

7.3.1 ▶️ E — Resolution: the cent calculation

For pitch CV, resolution is decisive. With a 10 V output range and 1 V/octave:

Bit depth	Steps	Step size	Pitch resolution
8 bit	256	39.1 mV	46.9 cents
10 bit	1,024	9.77 mV	11.7 cents
12 bit	4,096	2.44 mV	2.9 cents
14 bit	16,384	0.61 mV	0.73 cents
16 bit	65,536	0.15 mV	0.18 cents

Assessment: human hearing distinguishes, at best, about **5–6 cents**. 12 bits (2.9 cents) is therefore just adequate for played notes, but audibly stepped on slow glissandi. **16 bits** is the practical standard for pitch CV. For modulation CV (filter, amplitude) 12 bits often suffice.

▶️ **E — PWM as a DAC substitute.** Many microcontrollers have no true DAC but do have PWM outputs. An RC low-pass smooths the PWM into a DC voltage. The trade-off: the more smoothing (better resolution, less ripple), the **slower** the response. For pitch CV this is marginal; for slow modulation it is usable. Real DACs (MCP4728, DAC8565 and similar) are the clean route.

7.3.2 ▶️ E — Sampling and the Nyquist criterion

A digital system samples the signal at the **sample rate** . The sampling theorem (Nyquist–Shannon) states:

Only frequencies **below half the sample rate** (, the Nyquist frequency) are reconstructible. At a 48 kHz sample rate, then, everything up to 24 kHz — which covers the audible range.

7.3.3 ▶️ E — Aliasing: the core problem of digital oscillators

What happens to frequencies **above** the Nyquist limit? They do not disappear but **fold back** into the audible range:

Example: sample rate 48 kHz, Nyquist 24 kHz. A sawtooth with a 5 kHz fundamental has harmonics at 10, 15, 20, 25, 30 kHz … The first four are correct. After that everything folds back:

Harmonic	true frequency	appears as
4th	20 kHz	20 kHz (correct)
5th	25 kHz	23 kHz
6th	30 kHz	18 kHz
7th	35 kHz	13 kHz
8th	40 kHz	**8 kHz**
9th	45 kHz	**3 kHz**

The folded tones bear **no harmonic relation** to the fundamental — and when a melody is played they move in the *wrong* direction (as the fundamental rises, the aliases fall). The result sounds shrill, “digital,” metallically wrong.

Countermeasures (the art of digital oscillator design):

Method	Principle	Effort
Oversampling	compute internally at 4–16× rate, then filter	high (compute time)
BLIT/BLEP	“repair” discontinuities in a	medium, the standard

Method	Principle	Effort
	band-limited way	
Wavetable	precomputed tables, band-limited per octave	memory instead of compute time
Additive	generate only harmonics below Nyquist	expensive but exact

The **analog** VCO does not have this class of problem — a frequently overlooked, factual advantage of analog sound generation (4.1.5).

7.3.4 ▶️ E — Reconstruction and anti-aliasing filters

- **Before** the ADC: a low-pass removing everything above (otherwise input noise folds back).
- **After** the DAC: a reconstruction low-pass smoothing the staircase and removing image frequencies.

Both are analog filters (Part 4.2, Part 3) — the digital world needs the analog one at its edges.

7.4 DSP fundamentals in a module

7.4.1 ▶️ B — What gets computed in a module

The three most common digital effects and their core idea:

- **Delay** — a ring buffer in memory. Write pointer and read pointer at a defined distance; the distance is the delay time. Feedback creates repeats. The direct digital counterpart to the BBD (2.3.6).
- **Reverb** — networks of delays and all-pass filters (the Schroeder/Moorer approach) or convolution with a measured room response.
- **Filter** — digital biquads; the same mathematics as in Part 4.2, only in difference equations instead of R and C.

7.4.2 ▶️ E — The digital filter in one line

A biquad (two-pole filter) is a difference equation:

The coefficients are computed from cutoff and Q (the analogy to the analog transfer function of 4.2.2 is direct). **Practical note:** at very low cutoff frequencies relative to the sample rate, biquads become numerically unstable (coefficients close to 1); then use state-variable topologies or higher computational precision.

7.4.3 ▶️ E — Fixed point vs. floating point

- **Floating point (float)** — convenient, wide dynamic range, fast enough on modern ARM cores with an FPU. Today's default choice.

- **Fixed point (int)** — necessary on small controllers without an FPU; requires manual scaling and overflow control.

7.5 Hybrid architectures

7.5.1 ▶️ B — The three proven patterns

(a) Analog signal path, digital control. The sound runs entirely analog (VCO/VCF/VCA); a microcontroller generates CV, manages presets and provides the user interface. Examples: many modern desktop synths. **Advantage:** analog sound with preset capability.

(b) Digital source, analog shaping. A digital oscillator (wavetable, sample) feeds an analog filter and an analog VCA. **Advantage:** arbitrary sound sources with analog saturation and filter behavior. Very common in current Eurorack modules.

(c) Analog source, digital processing. Analog oscillators followed by digital effects (delay, reverb). **Advantage:** an analog core voice plus effects that would be costly in analog.

7.5.2 ▶️ E — Keeping the interfaces clean

Three points are critical in every hybrid design:

1. **Minimize conversion points.** Every A/D and D/A conversion costs signal-to-noise ratio and latency. Do not convert back and forth repeatedly.
2. **Separate ground and supply** (1.5.2, 7.2.3) — the most common reason for “digital chirping” in the audio signal.
3. **Budget the latency.** Buffer sizes determine the delay: . At 64 samples and 48 kHz that is 1.33 ms per buffer — uncritical for modulation, but noticeable when cascaded several times.

7.6 The bridge to software

7.6.1 ▶️ B — VCV Rack and virtual modular systems

VCV Rack is an open-source software modular system that reproduces Eurorack logic on a computer. It is relevant to this book for three reasons:

1. **A learning tool at no cost** — patch logic, signal chains and module behavior can be worked through without buying a single part. Anyone who has read Part 4 can try every concept there immediately.
2. **A design tool** — an architecture (Part 5.2) can be built and judged virtually before components are ordered.
3. **A hardware bridge** — with suitable interfaces, virtual and physical modules can be connected [to be verified: current feature set/licensing model].

Limits: the software models behavior, not component tolerances; the aliasing question (7.3.3) and the saturation behavior of analog stages are reproduced with varying fidelity depending on the module.

7.6.2 Relation to the separate software strand

The software side of sound synthesis — DSP implementation, wavetable engines, WASM/Rust realization — is developed separately in the corpus as **SignalWerk/SW-Synth** and is not duplicated here. This book treats the **hardware axis**; the points of contact are this Part 7 and the toolchain (Part 8).

7.7 Cross-references

- **Analog counterparts:** VCO (4.1), VCF (4.2), BBD delay (2.3.6).
- **Powering digital modules:** Part 6.1.2 (regulate +5 V locally), Part 2.4.
- **Interference decoupling:** Part 1.5.2, Part 2.4.2.
- **Firmware toolchains:** Part 8.3.
- **Corpus:** the software DSP strand SignalWerk/SW-Synth (kept separate).
- **[to be verified]** before publication: current availability/prices of Daisy Seed, Teensy 4.x, RP2040 boards; VCV Rack feature set and licensing; DAC types and sources. Web audit per the textbook-relationship rule.

Part 8 — Development and Toolchain

> **Dual track.** ▶️ B: the tools that take you from an idea to a finished board — all available in free versions. ▶️ E: simulation methodology, layout rules for analog circuits, manufacturing parameters, and what "publishing open hardware" concretely means.

8.1 Simulation: computing before soldering

8.1.1 ▶️ B — The three tool classes

Tool	Type	Strength	Cost
Falstad Circuit Simulator	browser, interactive	immediate, vivid, ideal for **learning**	free
LTspice	desktop, SPICE	industry standard, very accurate, large model library	free (proprietary)
ngspice / KiCad simulator	desktop, SPICE	fully open source, integrated in KiCad	free (OSS)
QSPICE	desktop, SPICE	newer, fast	free [to be verified]

▶️ **B — Recommendation by purpose:** for **understanding** a basic circuit (Part 3), Falstad is unbeatable because you see current flow animated and change component values live. For **dimensioning** a real module, LTspice or ngspice is right, because there real device models compute with tolerances and temperature behavior.

8.1.2 ▶️ E — The four analyses you need

Analysis	Question	Use in a synth
DC operating point	Where do the quiescent voltages sit?	operating points, checking offsets
Transient (.tran)	What does the signal look like over time?	waveform, envelope, reset behavior
AC sweep (.ac)	What is the frequency response?	**filter curves** (Part 4.2), Bode plot
Parameter sweep (.step)	How does a component value affect things?	dimensioning, tolerance analysis

▶️ **E — The analysis that saves the most:** `.step` across component tolerances. Instead of checking a circuit with ideal values, let resistors and capacitors vary across their tolerance bands. If a filter only works with exactly 10.00 nF but not with 9.5 or 10.5 nF, the design is unusable — something you see in simulation in seconds rather than after populating ten boards.

8.1.3 ▶️ E — Limits of simulation

Simulation is a model, not a substitute for measurement. Four systematic deviations:

1. **Model quality.** SPICE models of special chips (OTA, CEM/AS) are often simplified or unavailable; an LM13700 model reproduces saturation and distortion only approximately.
2. **Parasitic effects.** Trace capacitance, crosstalk and ground impedance are not in the schematic — they arise only in the layout (8.2.3).
3. **Temperature.** The exp converter's drift (3.3) can be simulated if set explicitly — default runs compute at 27 °C.
4. **Noise.** SPICE can do noise analysis, but real interference (1.5) is a layout and construction matter.

Consequence: simulate to settle the dimensioning; measure to confirm it (Part 5.4).

8.2 From schematic to printed circuit board

8.2.1 ▶️ B — KiCad as a continuous chain

KiCad is a fully open-source EDA suite (schematic, layout, 3D view, manufacturing output) with no restrictions on board size or layer count. It is this book's reference because the results can be passed on without a licensing hurdle — decisive for open-hardware publication (8.5).

The workflow in six steps:

1. **Draw the schematic** — place symbols, wire them, enter component values.
2. **Annotation and ERC** — number the parts, run the electrical rules check (open inputs, shorts).
3. **Assign footprints** — give every symbol its physical package (the step where beginners make the most mistakes).
4. **Layout** — place parts, route traces, pour the ground plane.
5. **DRC** — design rule check against the manufacturing specification.
6. **Export manufacturing data** — Gerber, drill file, placement data, BOM.

8.2.2 ▶️ E — Layout rules for analog circuits

These rules separate a working module from a humming one:

1. **A continuous ground plane** on one layer. It is the shortest return path for all currents and shields at the same time.
2. **Decoupling capacitors** (100 nF) directly at the supply pin, trace as short as possible (2.4.2).
3. **Separate analog and digital areas** spatially, join the ground planes at exactly one point (1.5.2).
4. **Keep sensitive nodes short:** OTA inputs, integrator summing node, S&H hold node. These nets are high-impedance and pick up everything.
5. **Route no signal trace under the timing capacitor** or parallel to clock lines.
6. **Star-shaped supply routing** instead of a chain (1.5.2).
7. **Mechanically decouple panel components** — forces on jacks and pots must not act on solder joints (5.3.4).
8. **Provide test points.** A few solder pads at critical nodes (rails, VCO output, envelope) save much time in fault-finding (5.4.2).

8.2.3 ▶️ E — Manufacturing: parameters you must know

Parameter	Common specification	Note
Layer count	2 (standard), 4 (with much digital)	4 layers allow a dedicated ground layer
Material thickness	1.6 mm	standard; 1.2 mm possible for panels
Copper weight	35 µm (1 oz)	sufficient for synth currents
Minimum trace/clearance	0.15–0.2 mm	staying conservative avoids scrap
Drill sizes	≥ 0.3 mm	smaller costs a surcharge
Soldermask/silkscreen	freely selectable	use it for labeling (5.3.2)

Service providers: JLCPCB, PCBWay, Aisler, Eurocircuits [to be verified: current prices, lead times, shipping to AT]. For one-offs the Asian vendors are considerably cheaper, the European ones faster and duty-free.

▶️ **B — The practical advice:** your first own board should be small and uncritical (a multiple, an attenuator). The learning value lies in **running through the chain**, not in the complexity of the circuit.

8.3 Firmware toolchains

8.3.1 ▶️ B — The options by platform

Platform	Simplest route	Advanced
AVR/Arduino	Arduino IDE	avr-gcc, PlatformIO
RP2040	Arduino core or MicroPython	Pico SDK (C/C++), PIO assembler
Teensy	Arduino + Teensyduino, Audio Library	C++ directly
Daisy	DaisyDuino (Arduino)	libDaisy + DaisySP (C++)
STM32	STM32CubeIDE	CMSIS, HAL, bare metal

▶️ **B — PlatformIO** (a VS Code extension) is the pragmatic middle path: one environment for many platforms, with library management and version control, without jumping into vendor IDEs.

8.3.2 ▶️ E — What is different in synth firmware

- **Real-time requirement.** Audio callbacks must not block: no dynamic memory allocation, no `printf`, no waiting functions in the audio path.
- **Determinism before throughput.** An occasionally missed buffer produces an audible click — worse than consistently slightly less compute power.
- **Store calibration data** (scaling, CV input offset) in non-volatile memory instead of hard-coding it.
- **Plan the bootloader/update path** from the start; a module that must be disassembled to be flashed will not be updated.

8.4 Design methodology

8.4.1 ▶️ E — The order that finds errors early

1. **Write down the requirement.** What should the module do, which inputs/outputs, what level range, how many HP, what power budget (T5)?
2. **Block diagram** before the schematic — clarify signal flow and interfaces.
3. **Simulate the critical block** (8.1) — usually the filter, exp converter or output stage.
4. **Breadboard prototype** of the critical part only (2.6.3) — with the caveat that precision analog performs worse there.
5. **Complete the schematic**, ERC clean.
6. **Layout**, DRC clean, check the manufacturing data (Gerber viewer!).
7. **Populate the first article and test stage by stage** (5.2.4, 5.4).

8. **Document**, and only then build a series.

8.4.2 ▶️ E — Test protocol

A brief, repeatable protocol per module saves time on every further unit:

- **Visual inspection** (placement, polarity, solder joints).
- **Short-circuit check** of the rails **before** powering up.
- **Measure current draw** and compare with the calculation (T5) — a marked deviation indicates a fault.
- **Functional tests** per block with defined input signals and expected output values.
- **Calibration** in a fixed order (5.4.1).
- **Record the results** (serial number, trimmer positions, anomalies).

8.5 Publishing open hardware

8.5.1 ▶️ B — What belongs to it

A project only becomes buildable when these components exist:

Component	Purpose
Source files (KiCad project)	modifiability — the core of "open"
Manufacturing data (Gerber, drill file)	direct orderability
BOM with order numbers	procurement without guesswork
Build instructions	order of assembly, pitfalls
Calibration instructions	without them no analog VCO works
Panel files (SVG/DXF)	fabricating the front panel (5.3)
Firmware + source code	for digital modules
Licence statement	legal certainty for builders

The most common omission in published DIY projects is a missing **calibration procedure** — the circuit is documented, but without the calibration steps the build stays out of tune.

8.5.2 ▶️ E — Licences for hardware

Software licences fit hardware only in part, because circuit boards do not enjoy copyright in the sense that source code does. Established options:

Licence	Character	Note
CERN-OHL-S	strongly reciprocal (copyleft)	modifications must stay open
CERN-OHL-W	weakly reciprocal	permits proprietary combination
CERN-OHL-P	permissive	no obligation to give back
CC BY-SA	widespread, but fuzzy for	well suited to documentation

Licence	Character	Note
	hardware	
TAPR OHL	older	has become rarer

In practice: a CC licence for the **documentation**, a CERN-OHL variant for the **hardware source files**, a software licence (GPL/MIT/Apache) for the **firmware**. This split is customary in the scene and legally cleaner than a single blanket licence.

8.5.3 ▶️ B — Where to publish

- **A repository** (Git) for source files and firmware — with tags for revisions.
- **A project page** with images, a demo and instructions.
- **Archiving with a DOI** for durable citability of documentation and dataset.
- **Community platforms** of the scene for visibility and feedback [to be verified: currently relevant platforms].

▶️ **E — Test the reproducibility:** the test of a publication is not whether it *looks* complete, but whether a third person can build a working module from it alone. Anyone with the opportunity should have exactly that attempted once before calling the project finished.

8.6 Cross-references

- **Circuits to simulate:** Part 3 (basic circuits), Part 4 (modules).
- **Mechanics and panels:** Part 5.3. **Format requirements:** Part 6.1.
- **Firmware target platforms:** Part 7.2. **Power budget:** tool T5.
- **Fault-finding on the first article:** Part 5.4.2.
- **The open-hardware landscape as a model:** Part 6.4.
- **[to be verified]** before publication: current manufacturing prices and lead times, KiCad version status, QSPICE status, relevant community platforms. Web audit per the textbook-relationship rule.

Part 9 — Practical Compendium

> A reference part. Not a reading chapter but a reference: canonical basic circuits, fault-finding trees, a glossary and a curated project register. All references lead back into the explanatory chapters.

9.1 Circuit cookbook

The recurring basic circuits as a compact reference. Each is derived in the chapter named; here only the purpose, the core formula and the pitfall.

9.1.1 Op-amp basic circuits (Part 3.1)

Circuit	Core formula	Pitfall
Impedance converter	V = 1	for buffered multiples, EG output
Non-inverting	V = 1 + Rf/R1	V always ≥ 1
Inverting	V = −Rf/R1	virtual ground at the − input
Summer	Uout = −Rf·Σ(Ui/Ri)	DC-couple the CV mixer!
Integrator	dUout/dt = −Uin/(RC)	10 M resistor against drift
Comparator + hysteresis	UHyst = Uout·R1/(R1+R2)	without hysteresis, chatter

9.1.2 The exponential converter (Part 3.3, 4.1.2)

Purpose: linear CV → exponential frequency (1V/oct). **Core:** IC = IS·e^(UBE/UT); input divider to ~17.9 mV/oct; matched pair; tempco +3300 ppm/K thermally coupled. **Pitfall:** without tempco and thermal coupling the tracking drifts; keep the summing node low-impedance.

9.1.3 VCO core (Part 4.1)

Purpose: voltage-controlled frequency. **Core:** f = IC/(C·ΔUthreshold); integrator charges, comparator resets; sawtooth primary, the rest derived. **Pitfall:** reset speed limits the top frequency; hi-freq trim.

9.1.4 VCF (Part 4.2)

Purpose: voltage-controlled timbre. **Core:** fc = 1/(2πRC) per stage; resonance through feedback; self-oscillation at high resonance. **Pitfall:** OTA input overdriven → distortion; cutoff tracking needs an exp converter.

9.1.5 VCA (Part 4.3)

Purpose: voltage-controlled loudness. **Core:** Iout = gm·Uin; gm ∝ IABC; linear (modulation) vs. exponential (loudness). **Pitfall:** control feedthrough → click; input divider against distortion; trim the offset.

9.1.6 EG (Part 4.4)

Purpose: contour over time. **Core:** U(t) = UZ(1−e^(−t/τ)), τ = RC; switch-over at ~95 %. **Pitfall:** buffer with low bias current; film capacitor; sustain is a level, not a time.

9.1.7 Utilities (Part 4.7)

Circuit	Core	Chapter
Attenuverter	op-amp, pot between inv./non-inv.	4.7.2b
Slew limiter	RC + buffer, separate rise/fall	4.7.2e
Sample & hold	CD4066 + hold capacitor + FET buffer	4.7.2f / 3.4.2

Circuit	Core	Chapter
Ring modulator	AD633 (four-quadrant) or diode ring	4.7.2h
Noise source	Zener/transistor + high gain	4.6.2

9.2 Fault catalogue and troubleshooting trees

9.2.1 Basic principle

Bisect the signal path (5.4.2). Power first, then signal tracing from the middle, then visual inspection, then components individually.

9.2.2 Fault tree "no sound"

```
No sound
├─ Rails present? (DMM at IC pins)
│   ├─ no → reverse polarity? fuse? PSU? short?
│   └─ yes ↓
├─ VCO oscillating? (oscilloscope at VCO output)
│   ├─ no → timing C? reset switch? supply at the VCO IC?
│   └─ yes ↓
├─ Signal passes the VCF? (compare in/out)
│   ├─ no → cutoff fully closed? OTA supply? wiring?
│   └─ yes ↓
├─ VCA opens? (check control voltage at the VCA)
│   ├─ no → is the EG delivering CV? gate arriving? offset?
│   └─ yes ↓
└─ Output stage? (level, coupling C, jack)
```

9.2.3 Symptom–cause table

Symptom	Most likely causes (in order)
No sound	power → VCO stalled → VCA closed → wiring
Detuned / poor tracking	tempco missing → pair not coupled → scale trim → passive CV splitting (1.3.2)
Runs away when warm	tempco/thermal coupling → wait for warm-up (4.1.4)
Click on notes	control feedthrough → attack too steep → DC offset (4.3.5)
Hum (50/60 Hz)	ground loop → decoupling → PSU proximity → shielding (1.5)
Chirping/digital noise	digital/analog ground not separated → decoupling (7.5.2)
Noise	gain structure → high-impedance nodes → OTA divider (1.5.3)
Long EG times unreachable	buffer bias current → electrolytic instead of

Symptom	Most likely causes (in order)
	film → leakage (4.4.5)
S&H drifts	buffer bias → hold capacitor → switch residual current (3.4.2)
VCA does not close	offset trim → CV never reaches 0 V (4.3.7)
Filter oscillates uncontrollably	resonance feedback → phase (4.2.7)

9.2.4 Cause frequency (the realistic expectation)

In order of likelihood: **soldering fault → wrong component value fitted → part reversed/misoriented → wiring error → circuit error → defective component.** The defective component is the *rarest* cause — looking there first wastes time.

9.3 Glossary (short form, bilingual)

DE	EN	Short definition
Steuerspannung (CV)	control voltage	a voltage that controls a parameter (1.4)
1 Volt pro Oktave	1 volt per octave	standard: +1 V → double the frequency (1.4.2)
Gate	gate	a state signal “key pressed” (4.4.1)
Trigger	trigger	a short pulse at the attack (4.4.1)
Hüllkurve	envelope	the contour over time of a control voltage (4.4)
Transkonduktanz	transconductance	current per voltage, gm (2.3.4)
Selbstoszillation	self-oscillation	filter oscillates at high resonance (4.2.6)
Tempco	tempco	a temperature-compensating resistor (3.3)
Matched Pair	matched pair	matched transistors (2.2.2)
Slew	slew	rate limiting / portamento (4.7.2e)
Aliasing	aliasing	fold-back across Nyquist (7.3.3)
Nyquist-Frequenz	Nyquist frequency	half the sample rate (7.3.2)
Attenuverter	attenuverter	attenuator with inversion (4.7.2b)
Wavefolder	wavefolder	creates harmonics by folding

DE	EN	Short definition
		(5.1.2)
Low-Pass Gate	low-pass gate	combines VCA + low-pass (4.3.6)
HP	HP	width unit, 5.08 mm (6.1.1)
Rail	rail	supply rail, e.g. +12 V (6.1.2)

(Full glossary in the appendix.)

9.4 Project register

Curated entry points into the open-source DIY landscape (details and assessment in Part 6.4).

For the first build: - MFOS “Noise Toaster” / teaching projects — documented, beginner-suitable. - Lunetta circuits (CD40106) — an audible result with minimal means (2.3.2).

For individual modules: - YuSynth — proven VCO/VCF/VCA/EG recreations. - Music Thing Modular — utilities, Turing Machine. - Befaco — open kits.

For hybrid/digital modules: - Mutable Instruments (code open) — as a study object for hybrid architecture. - The Daisy/Teensy ecosystem — for your own digital modules (7.2).

To try without hardware: - VCV Rack — a software modular system (7.6).

> **[to be verified]** before publication: all project names, links, availabilities and activity status against current primary sources (source-seriousness rule: no social-media sources, only robust project pages/repositories).

9.5 Cross-references

- **Derivation of all circuits:** Parts 3 and 4.
- **Systematic fault-finding:** Part 5.4.2. **Instrumentation:** Part 2.5.
- **Formats and landscape:** Part 6. **Your own development:** Part 8.
- **Interactive calculators:** tools T1–T7.
- **Appendices:** A formula collection, B chip profiles, C Eurorack specification, D tool/software register.

Appendices

A reference part. Formulas, chip profiles, format data and a tool register for quick lookup. All values are guide and orientation figures; safety- or function-critical numbers are to be checked against the relevant datasheet before use.

Appendix A — Formula collection

A.1 Basic quantities (Part 1)

Quantity	Formula	Note
Frequency/period	$f = 1/T$	Hz ↔ s
dB (voltage)	$a = 20 \cdot \log_{10}(U_2/U_1)$	field quantity
dB (power)	$a = 10 \cdot \log_{10}(P_2/P_1)$	
Voltage divider	$U_L = U_0 \cdot R_L/(R_i+R_L)$	impedance matching
Thermal voltage	$U_T = kT/q \approx 25.85$ mV @ 300 K	core of the exp converter

A.2 Op-amp basic circuits (Part 3)

Circuit	Formula
Non-inverting	$V = 1 + R_f/R_1$
Inverting	$V = -R_f/R_1$
Summer	$U_{out} = -R_f \cdot \Sigma(U_i/R_i)$
Integrator	$U_{out}(t) = -(1/R\,C)\int U_{in}\,dt$
Hysteresis (Schmitt)	$U_{Hyst} = U_{out,pp} \cdot R_1/(R_1+R_2)$

A.3 Oscillator and 1V/octave (Parts 4.1, 3.3)

Quantity	Formula
1V/oct law	$f = f_0 \cdot 2^{(U_{CV}/1V)}$
Shockley	$I_C = I_S \cdot e^{(U_{BE}/U_T)}$
mV per octave	$U_T \cdot \ln 2 \approx 17.9$ mV
VCO frequency	$f = I_C/(C \cdot \Delta U_{threshold})$
555 astable	$f = 1.44/((R_1+2R_2) \cdot C)$
Schmitt osc. (40106)	$f \approx 1/(2.2 \cdot R\,C)$

A.4 Filter (Part 4.2)

Quantity	Formula
Corner frequency (1 pole)	$f_c = 1/(2\pi R\,C)$
Transfer (1-pole LP)	$H(f) = 1/(1 + j\,f/f_c)$
Q/damping	$Q = 1/(2\zeta)$
Resonance boost	$\approx 20 \cdot \log_{10}(Q)$ dB ($Q > 0.707$)
Slope	n poles → n·6 dB/octave

A.5 Envelope and RC (Part 4.4)

Quantity	Formula
Time constant	$\tau = R \cdot C$

Quantity	Formula
Charging	$U(t) = U_Z(1-e^{(-t/\tau)})$
Discharging	$U(t) = U_0 e^{(-t/\tau)}$
1τ / 3τ / 5τ	63.2 % / 95.0 % / 99.3 %

A.6 OTA, VCA, S&H (Parts 2.3.4, 3.4, 3.5)

Quantity	Formula
Transconductance	$g_m \approx I_{ABC}/(2 U_T)$
OTA output current	$I_{out} = g_m \cdot U_{in}$
S&H droop	$dU/dt = I_{leak}/C$
LED series resistor	$R = (U_V - U_{LED})/I_{LED}$

A.7 Digital (Part 7)

Quantity	Formula
Nyquist	$f_s > 2 \cdot f_{max}$
Aliasing	$f_{alias} =$
DAC resolution	step = range/2^bit
Cents per step	(step[V]/1V)·1200
BBD delay	$t_d = N/(2 f_{clk})$
Buffer latency	t = buffer size/f_s
Biquad	$y[n]=b_0x[n] +b_1x[n-1]+b_2x[n-2]-a_1y[n-1]-a_2y[n-2]$

A.8 Eurorack power (Part 6.1)

Quantity	Formula
Rail sum	$I_{total,rail} = \Sigma I_{i,rail}$ (rails separate)
Headroom	$I_{usable} = I_{PSU} \cdot (1 - reserve\%)$
HP width	width[mm] = HP·5.08

Appendix B — Chip profiles

[to be verified] before publication: current availability, reissue designations and sources of every chip against datasheet and distributor.

B.1 Timer / logic

Chip	Function	Core value	Note
NE555 / TLC555	timer astable/monostable	$f=1.44/((R_1+2R_2)C)$	the CMOS variant (TLC/7555) is quieter

Chip	Function	Core value	Note
CD40106	6× Schmitt inverter	hysteresis internal	one osc. per inverter, a DIY favorite
CD4066	4× analog switch	R_ON ~80–300 Ω	reset/routing/S&H
CD4046	PLL	R/C VCO internal	frequency multiplication, sync
CD4040/4024	binary divider	÷2^n	octave rows, top octave
CD4013	D flip-flop		EG state logic
CD4015/4006	shift register		LFSR noise

B.2 Amplifiers / OTA

Chip	Function	Core value	Note
TL072 / TL074	dual/quad op-amp, JFET	slew 13 V/µs	DIY standard, good for CV
LM13700	dual OTA + buffers	g_m=I_ABC/(2U_T)	heart of VCA/VCF; input divider mandatory
CA3080	single OTA		predecessor; reissue AS3280/V3280
THAT2180 / V2164	Blackmer/current VCA	dB-linear	studio/poly, very clean
AD633	four-quadrant multiplier		ring modulator

B.3 Dedicated synth ICs (original → reissue)

Original	Function	Reissue	Note
CEM3340	VCO	AS3340 / V3340	saw/tri/pulse, sync, internal tempco
CEM3320	VCF	AS3320 / V3320	4-pole, voltage-controllable
CEM3360 / SSM2164	dual VCA	AS3360 / V3360	
CEM3310 / SSM2056	EG	AS3310 / V3310	voltage-controllable times
SSM2044	VCF 4-pole LP	V2044	

B.4 BBD / special

Chip	Function	Note
MN3005/3007/3207	bucket brigade (BBD)	analog delay/chorus; reissue V series
MN3101	BBD clock	

Chip	Function	Note
NE570/571	compander	against BBD noise
THAT300/320	transistor array	matched pair for the exp converter

B.5 Standard semiconductors

Part	Use
1N4148	small-signal, logic, clipping
1N5817/5819	Schottky, reverse-polarity protection
BC547/BC557	NPN/PNP universal
J201 / 2N5457	JFET, controllable resistor
7812/7912, LM1117	voltage regulators

Appendix C — Eurorack specification in brief

[to be verified] against the Doepfer A-100 primary source.

C.1 Mechanics

Quantity	Value
Height (panel)	128.5 mm (3U)
Width	HP × 5.08 mm; case row usually 84 or 104 HP
Fixing	M3, slotted holes
Depth	not standardized — check before buying

C.2 Power supply (16-pin bus)

Rail	Purpose
+12 V	analog positive rail
−12 V	analog negative rail (the ribbon cable's red stripe!)
GND	ground (several pins)
+5 V	digital rail — **not always present**
CV/gate	optional bus (rarely used)

C.3 Signal levels (convention, not normed)

Signal	Range
Audio	±5 V (10 Vpp)
CV unipolar	0…+8 V (up to +10 V)

Signal	Range
CV bipolar	−5…+5 V
Pitch	1 V/octave
Gate/trigger	0 V / +5 V (threshold ~1–2.5 V)
Output R_i	~1 kΩ
Input R_in	~100 kΩ

Appendix D — Tool and software register

[to be verified] current versions, licences, availability.

D.1 Simulation & EDA

Tool	Purpose	Licence
Falstad Circuit Simulator	learning, intuition	free, browser
LTspice	SPICE, accurate	free (proprietary)
ngspice	SPICE, open source	OSS
KiCad	schematic+layout+manufacturing	OSS
QSPICE	SPICE, new	free [t.b.v.]

D.2 Firmware & DSP

Tool	Platform
Arduino IDE / PlatformIO	AVR, RP2040, Teensy, Daisy, STM32
Pico SDK	RP2040 (C/C++, PIO)
Teensy Audio Library	Teensy
libDaisy + DaisySP	Daisy
STM32CubeIDE	STM32

D.3 Instrumentation (order of acquisition)

1. Digital multimeter
2. Lab supply with current limiting
3. Oscilloscope (≥ 2 channels, 20–50 MHz)
4. Tuner / frequency counter
5. Function generator, capacitance meter (nice to have)

D.4 Software modular system

Tool	Purpose
VCV Rack	virtual Eurorack, learning & design

Tool	Purpose
	(7.6)

D.5 Manufacturing (service providers)

[to be verified] prices, lead times, shipping to AT.

Provider	Type
JLCPCB, PCBWay	PCB (cheap, Asia)
Aisler, Eurocircuits	PCB (EU, fast)
Thonk, Befaco, Modular Addict	kits/components
Reichelt, Mouser, Digikey, TME	components in general

Cross-references

- Derivation of all formulas: Parts 1, 3, 4, 7. Chip context: Part 2.3.
- Format details: Part 6.1. Tool usage: Part 8.
- Interactive calculators for the formulas: tools T2 (filter), T3 (VCO), T4 (EG), T5 (power).