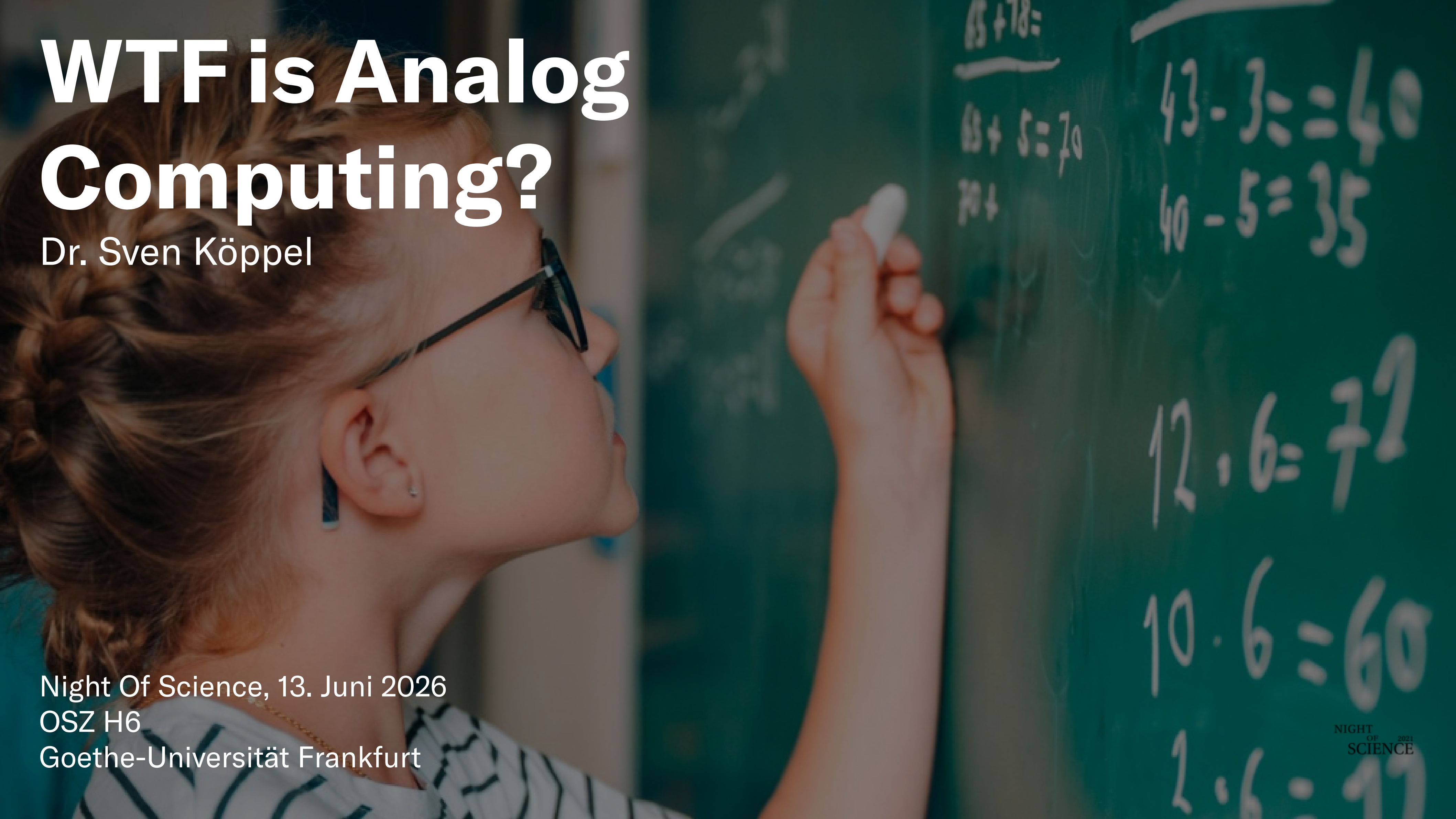


WTF is Analog Computing?

Dr. Sven Köppel

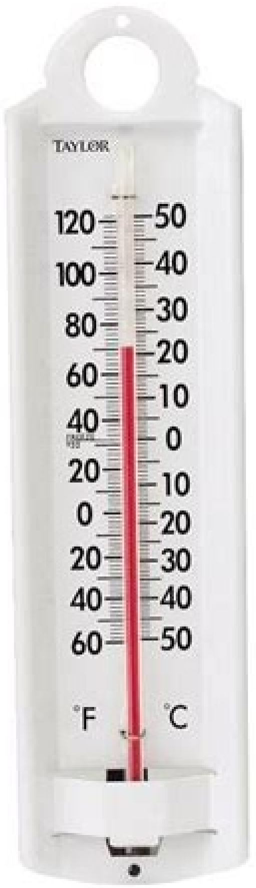
Night Of Science, 13. Juni 2026
OSZ H6
Goethe-Universität Frankfurt

NIGHT OF SCIENCE 2021

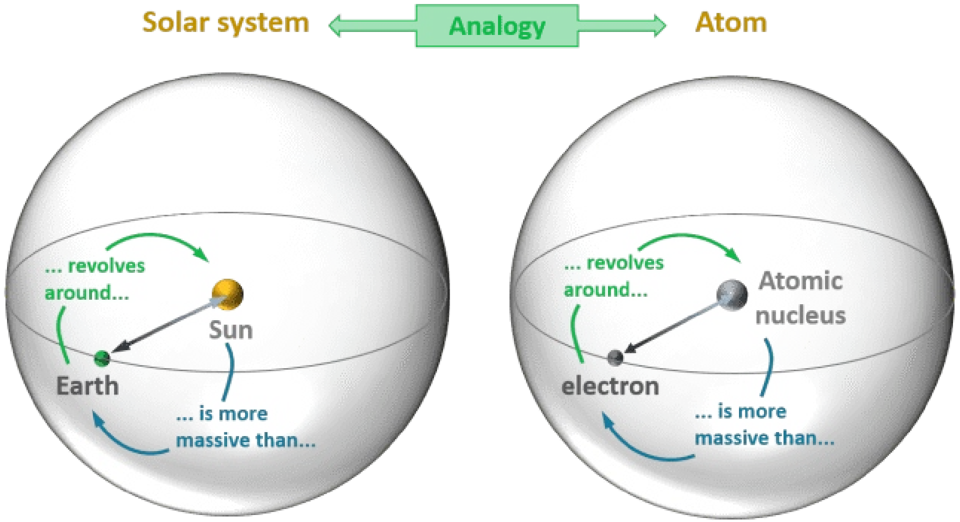
Die Analoge Welt

JPL
computers
1936

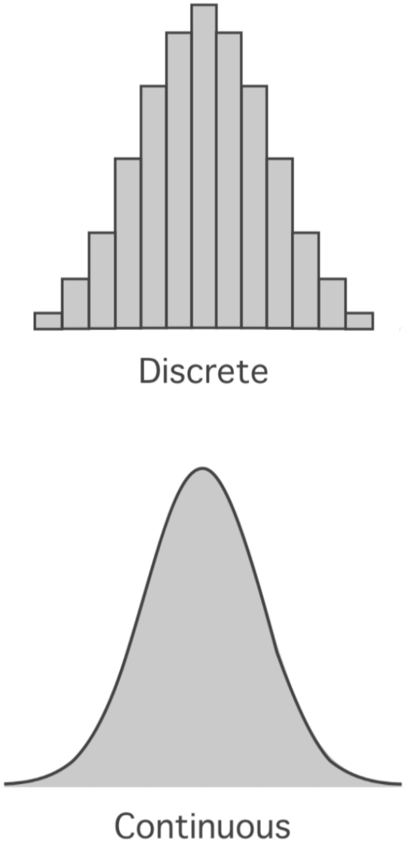
1) Analogie



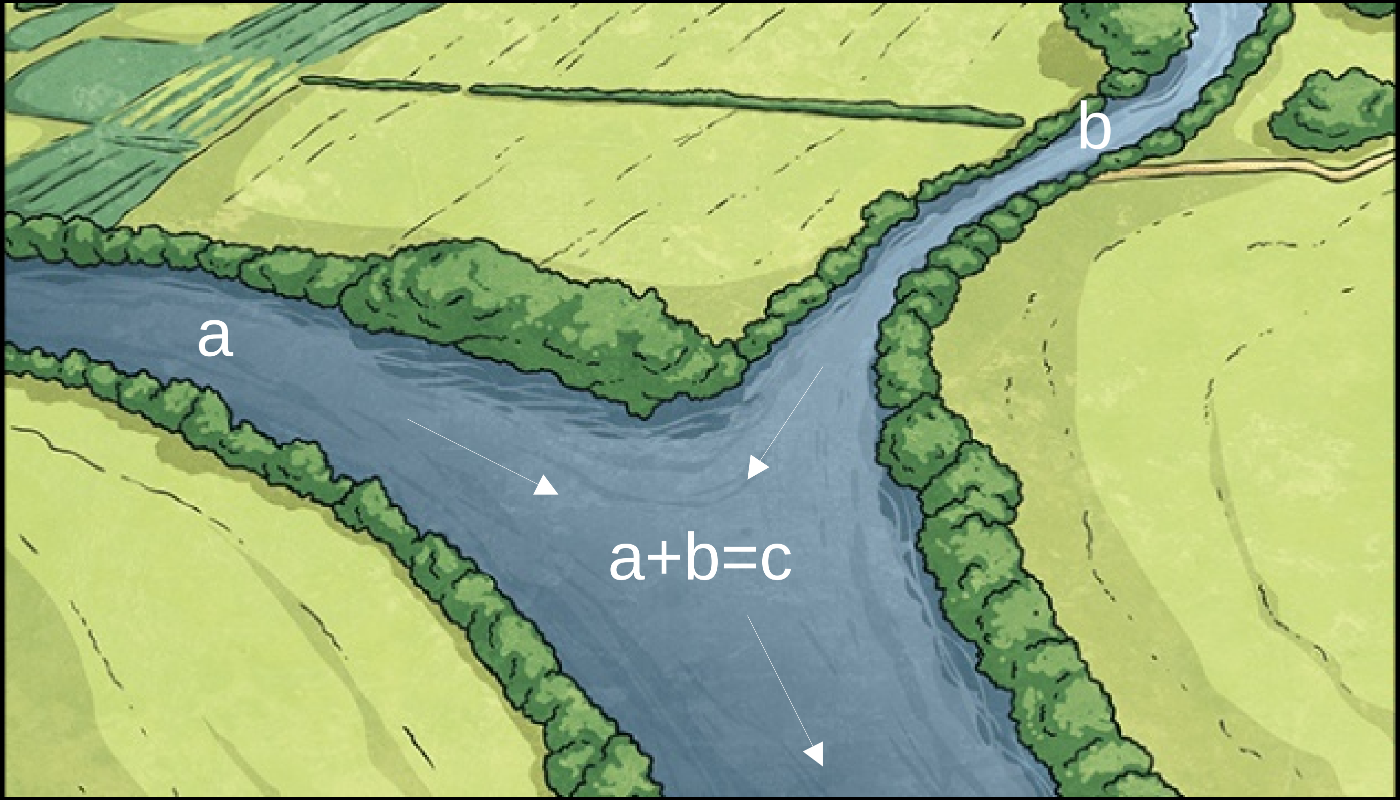
2) Modellbildung und Abbildung



3) Kontinuierlich



Mit Analogien rechnen



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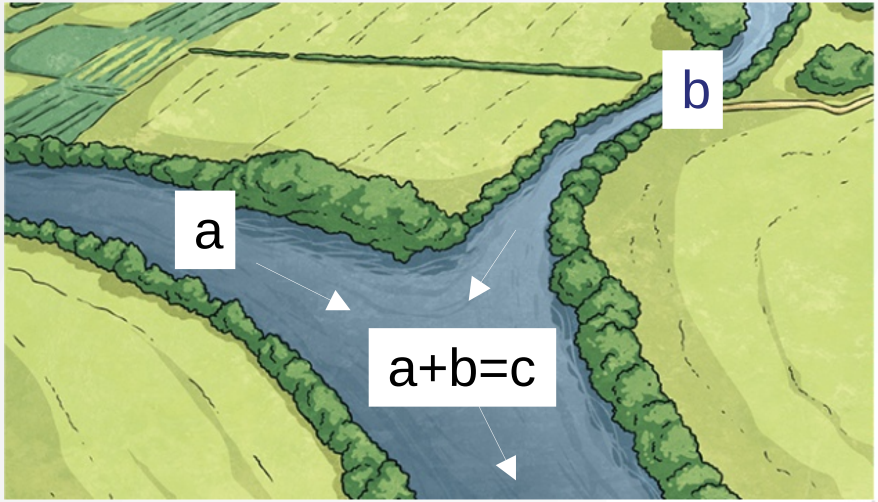
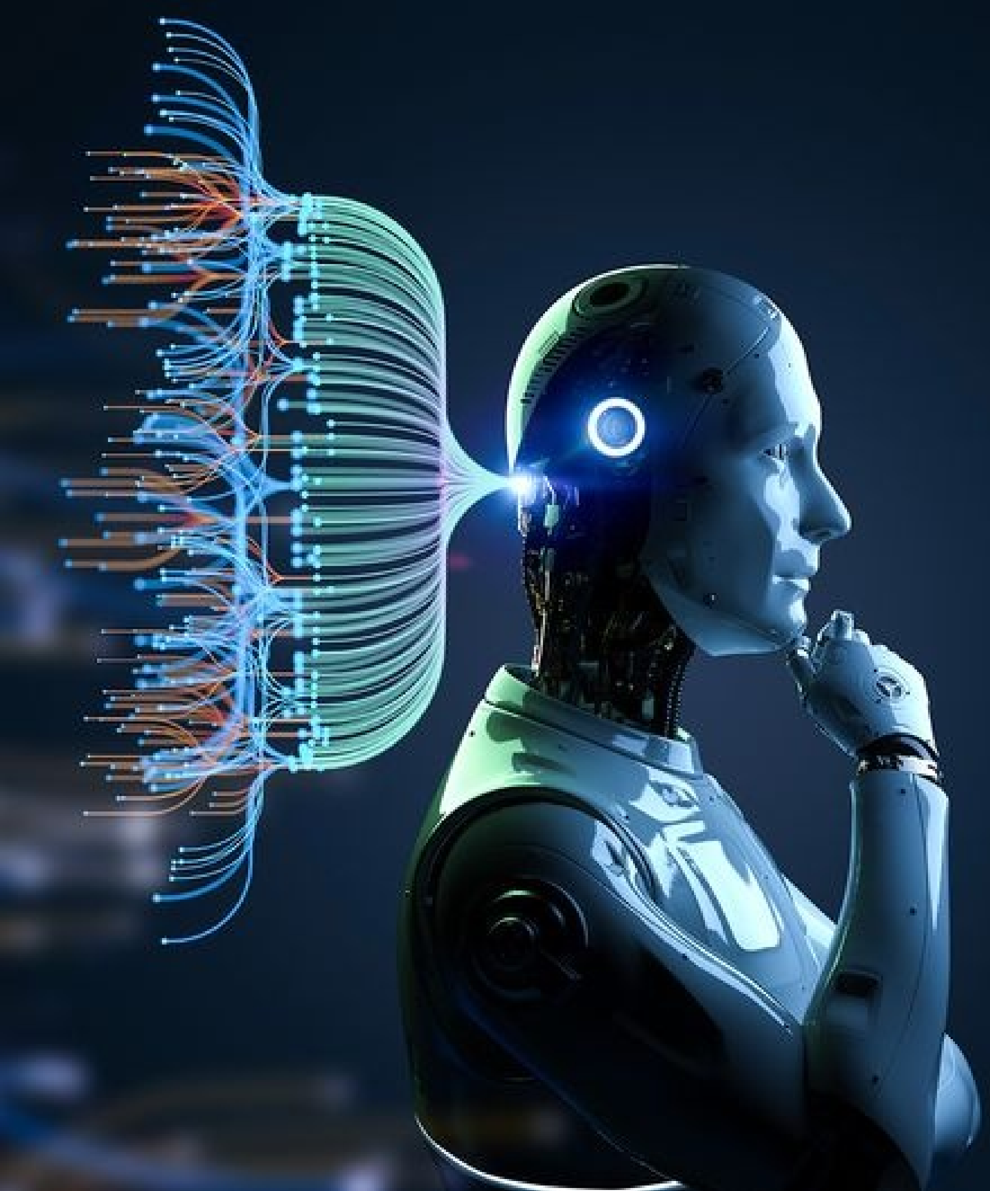
Digital vs Analog

Digital Arithmetics

4	7	3	·	1	7
		4	7	3	0
	+	$_1$3	3	1	1
		8	0	4	1

Analog processes in nature





NVIDIA


Klimawandel
durch KI

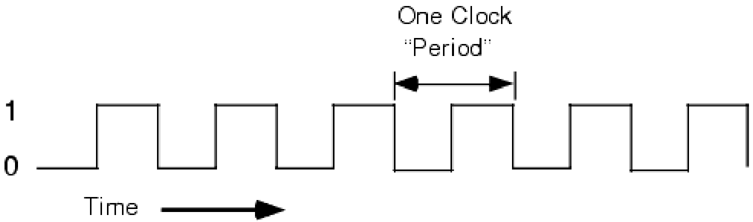
Warum werden Computer heiss?

Landauer-Prinzip! [R. Landauer 1961]

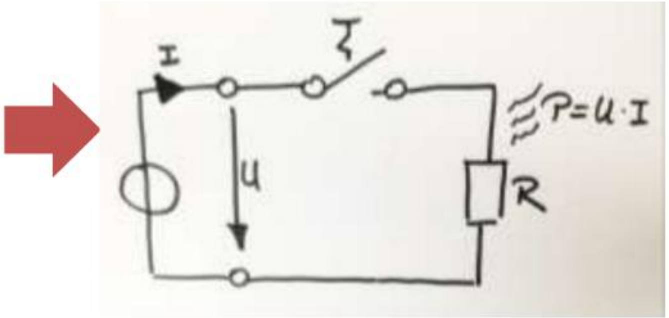
$$E_{\text{Gesamt}} = E_{\text{Signalverarbeitung}} + E_{\text{Wärme}}$$

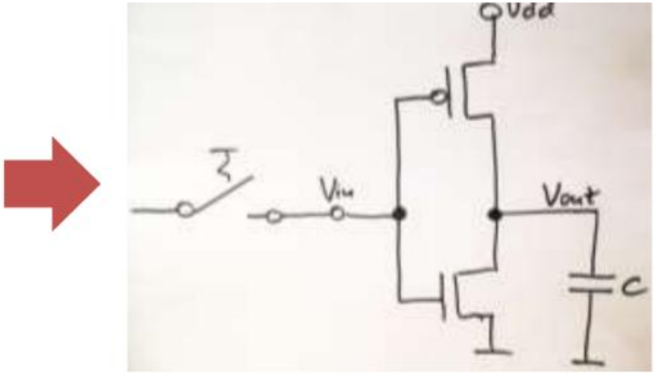
Landauer-Limit (bei Raumtemperatur):

$$W \sim 3 \times 10^{-21} \text{Joule/bit}$$



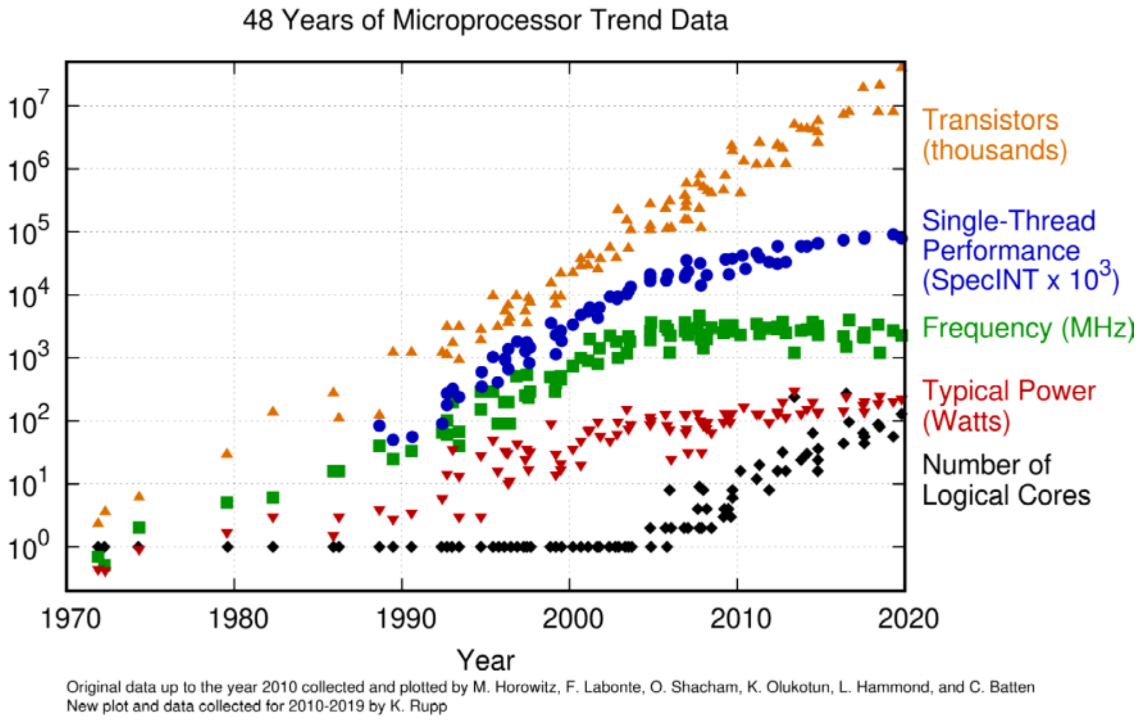
https://www.lecker.de/wie-macht-man-das-perfekte-spiegelei-71193.html



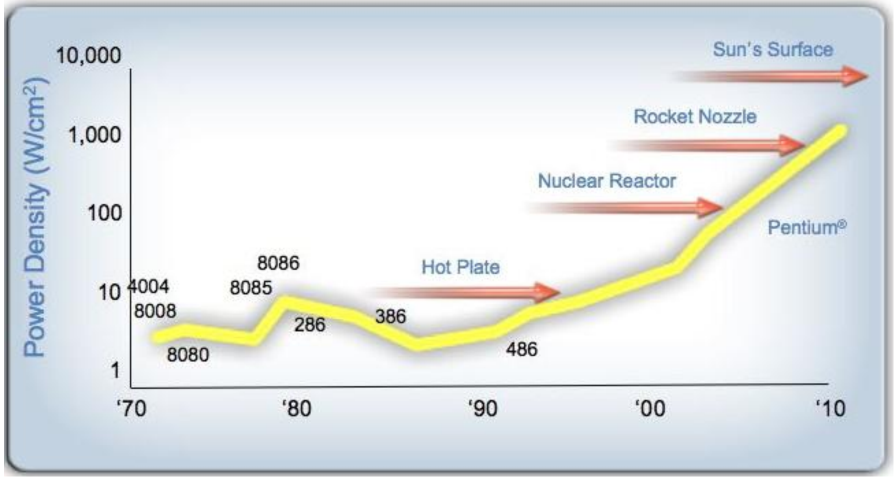


Wärmeentwicklung: Fortschritte und Trends

„Moore's Law“: Fortschritte nur noch bei Parallelisierung, nicht mehr Takt.

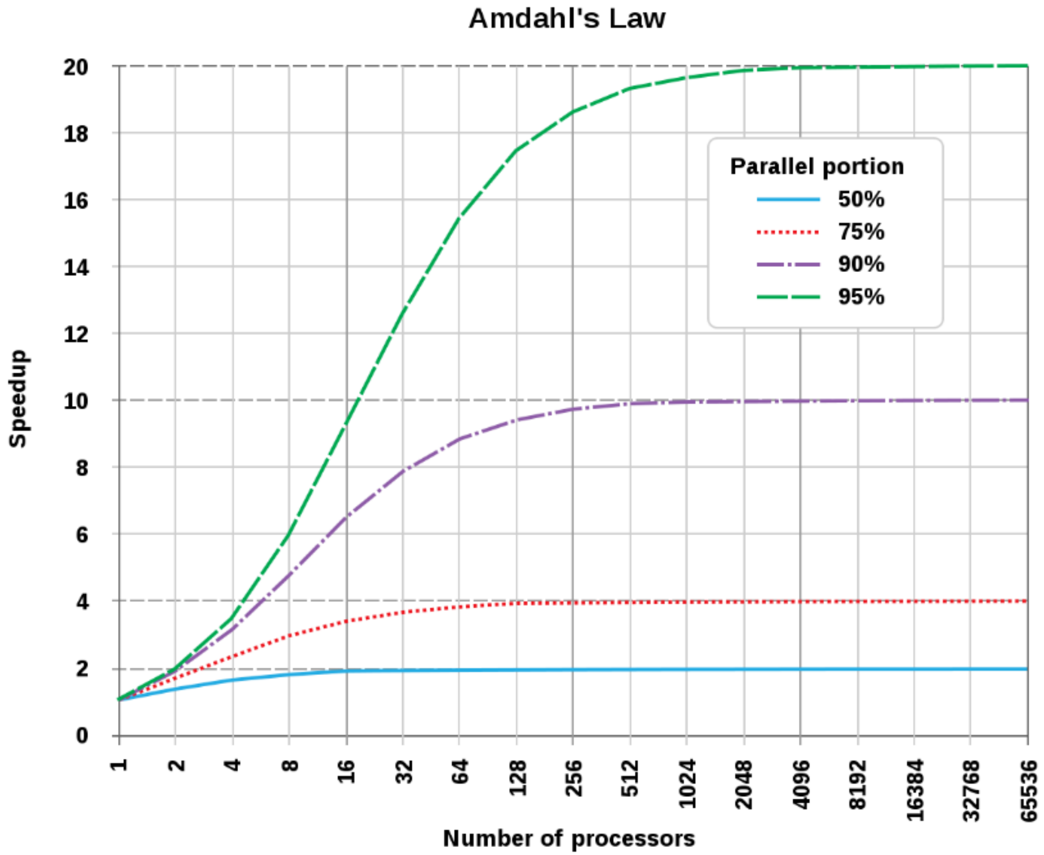


„Energy barrier“



Bildquellen: wccftech.com

Grenzen der Parallelisierbarkeit: Amdahl’s Gesetz



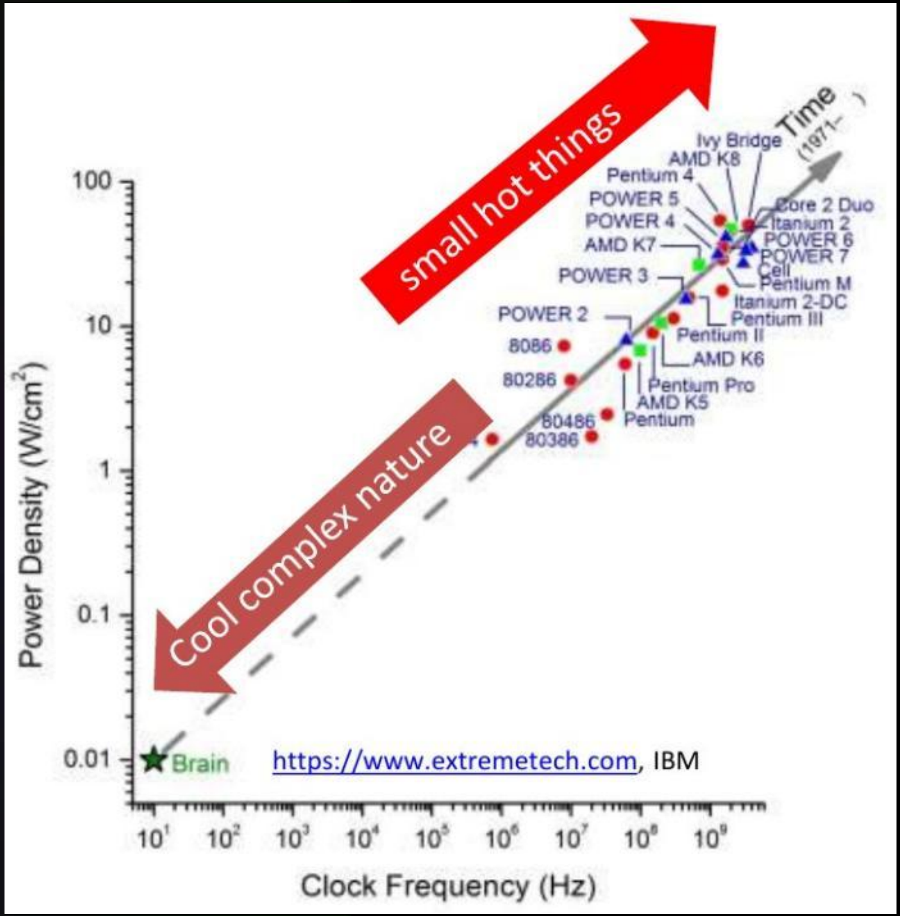
Manycore-Architekturen und High Performance Cluster lassen Fortschritt zu.

Doch der energetische Preis dafür ist sehr hoch!

Bei 95% Parallel portion:

3000 x Computer (Leistung) aber nur 20 x Speedup

Eine Lösung: Adopt natural computing like in the brain



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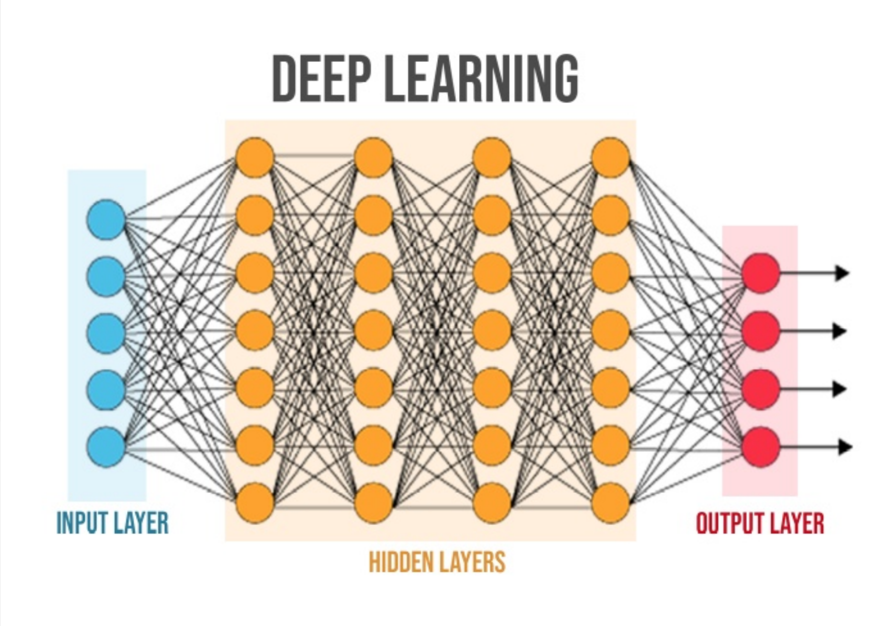
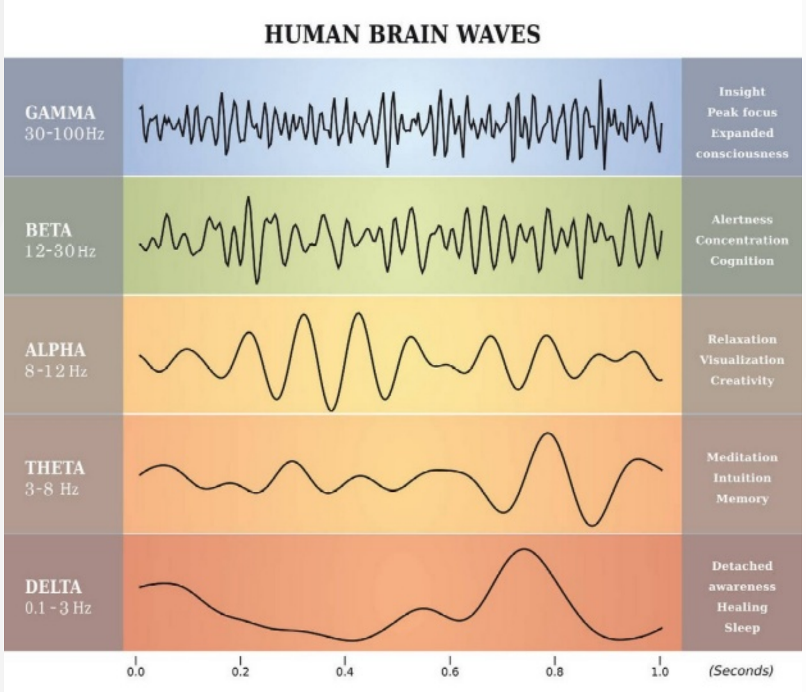
Compute as the Human Brain

Digital Arithmetics



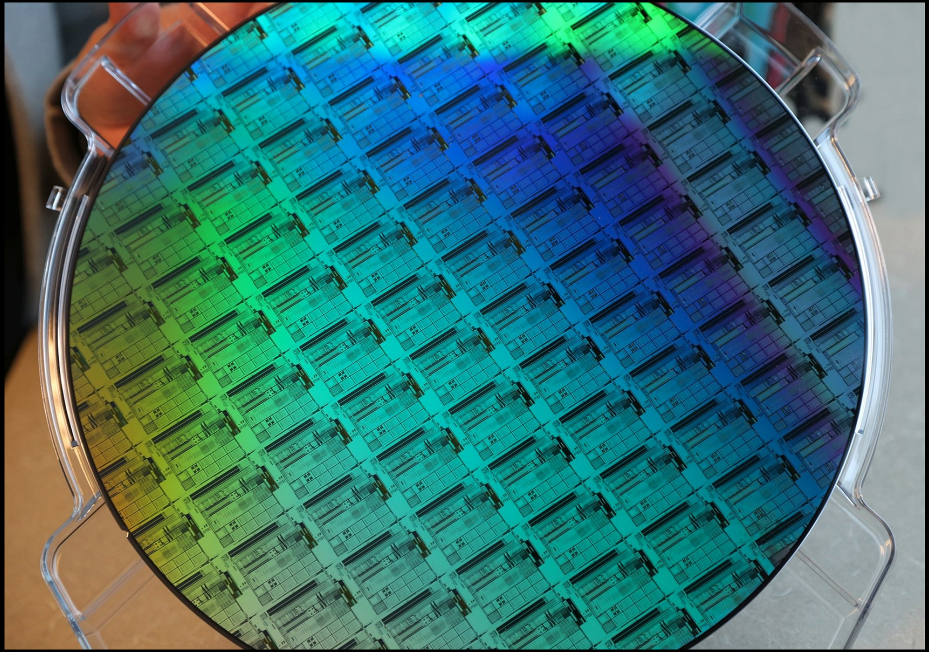
Symbolic computing & sparse linear algebra

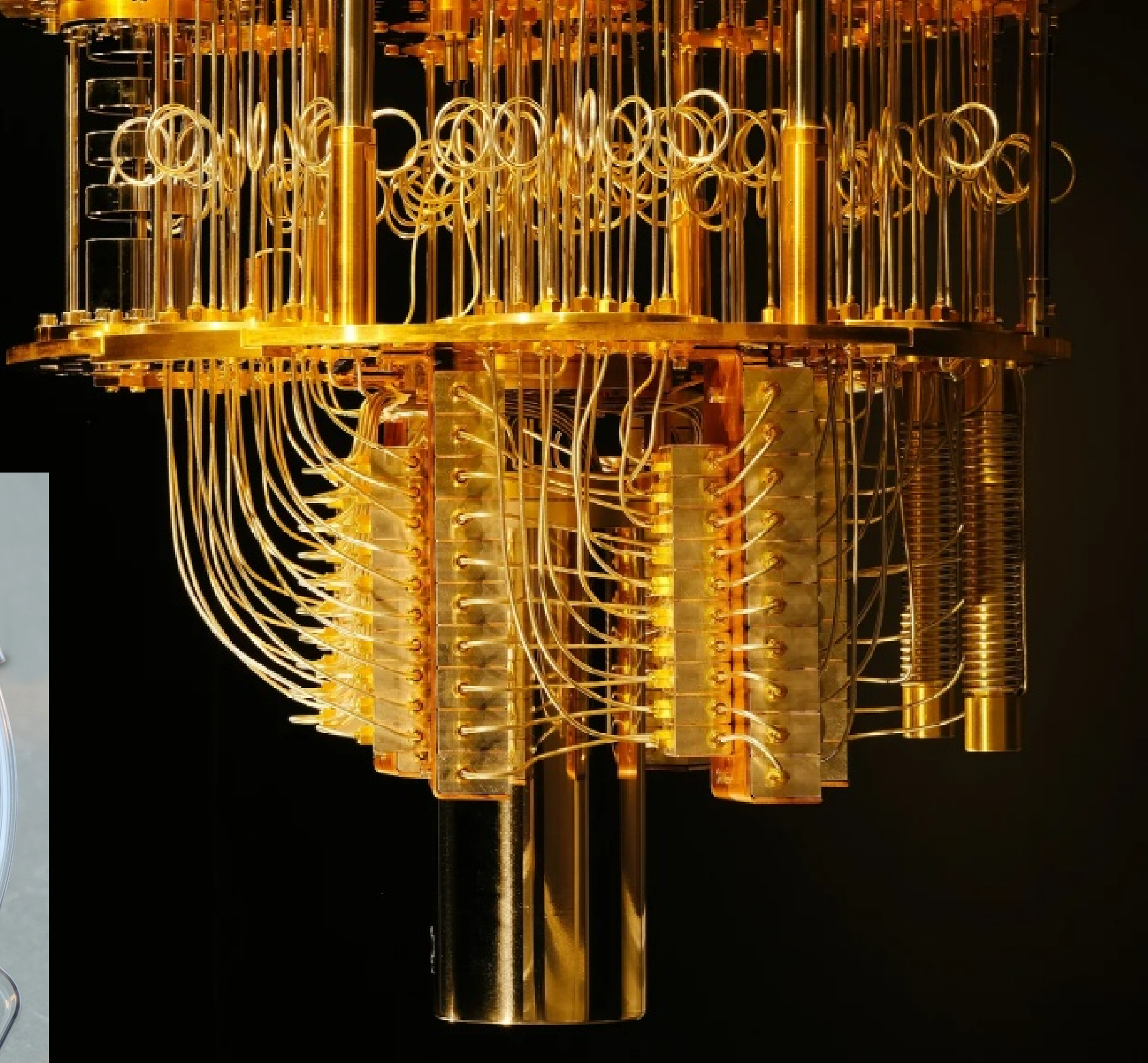
Analog processes in nature



Wave-based computing & dense interconnects

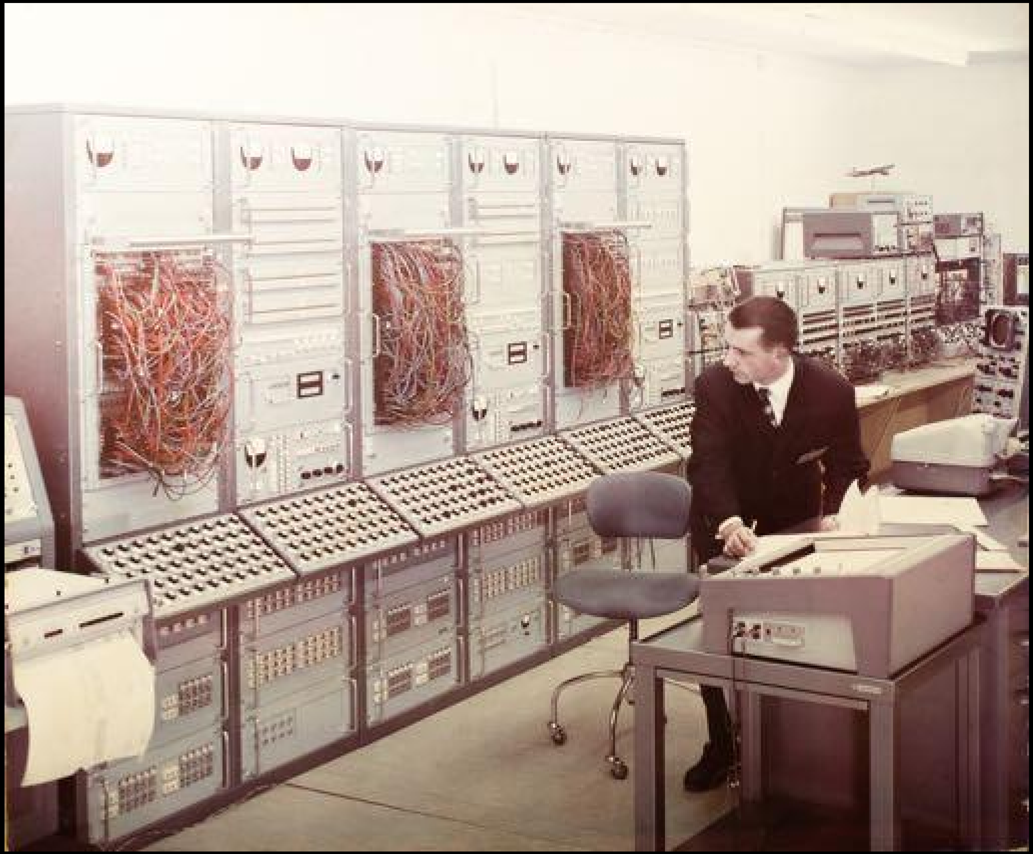
Quantum Computing,
Photonics, Memristors,
Beyond CMOS, etc.

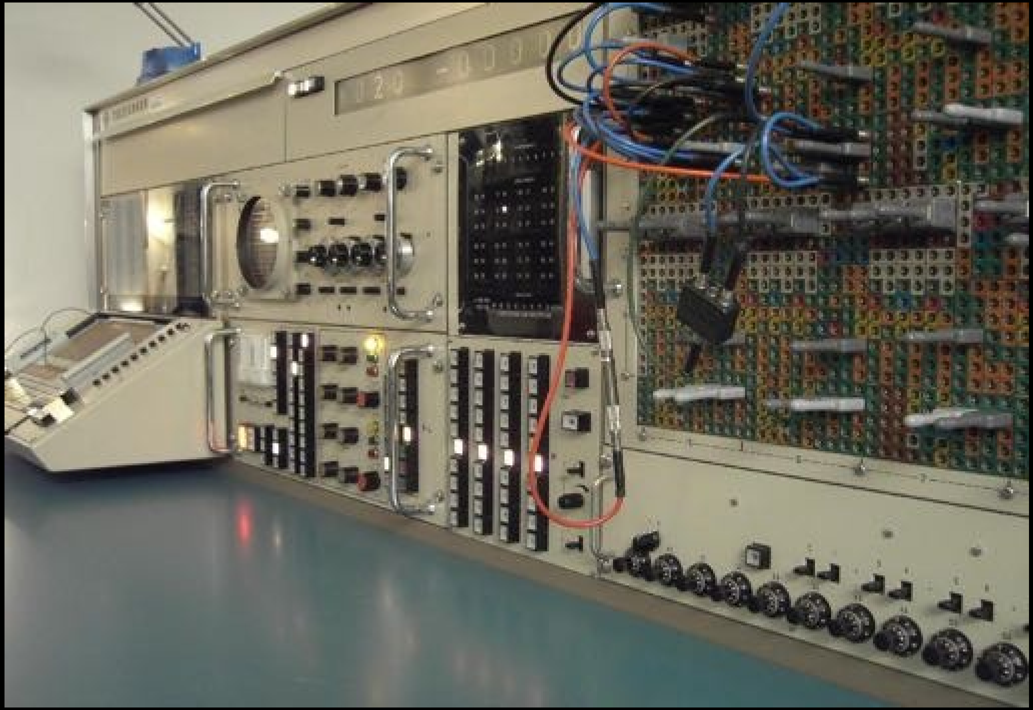




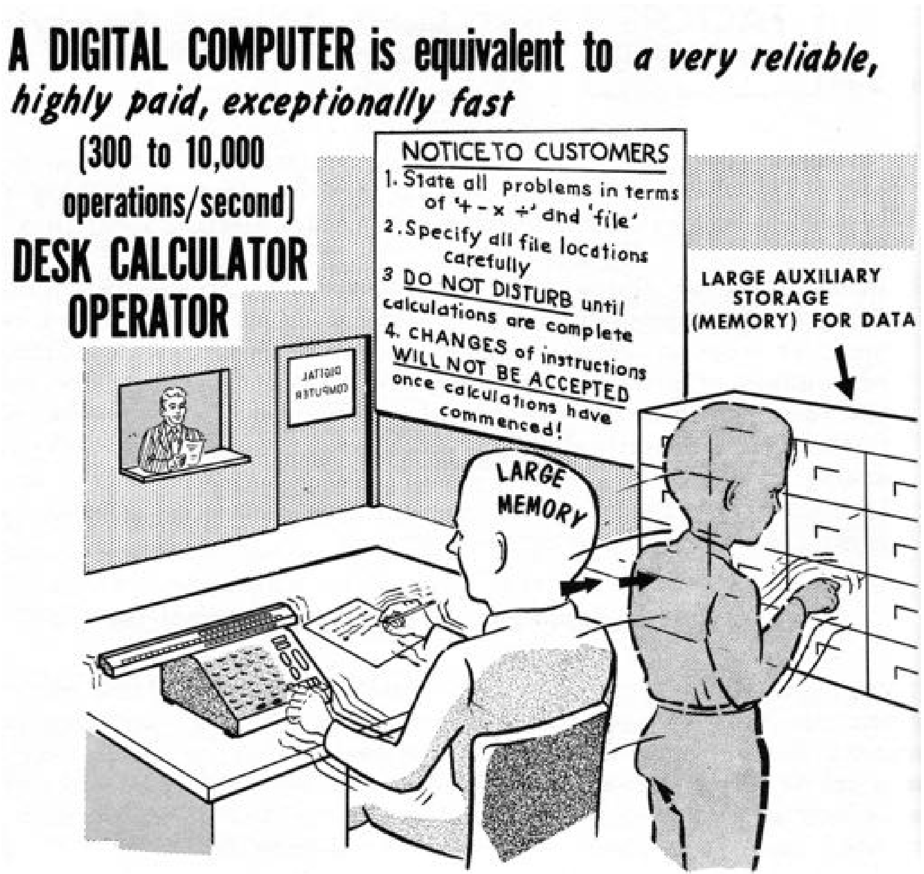
Geht das nicht einfacher?

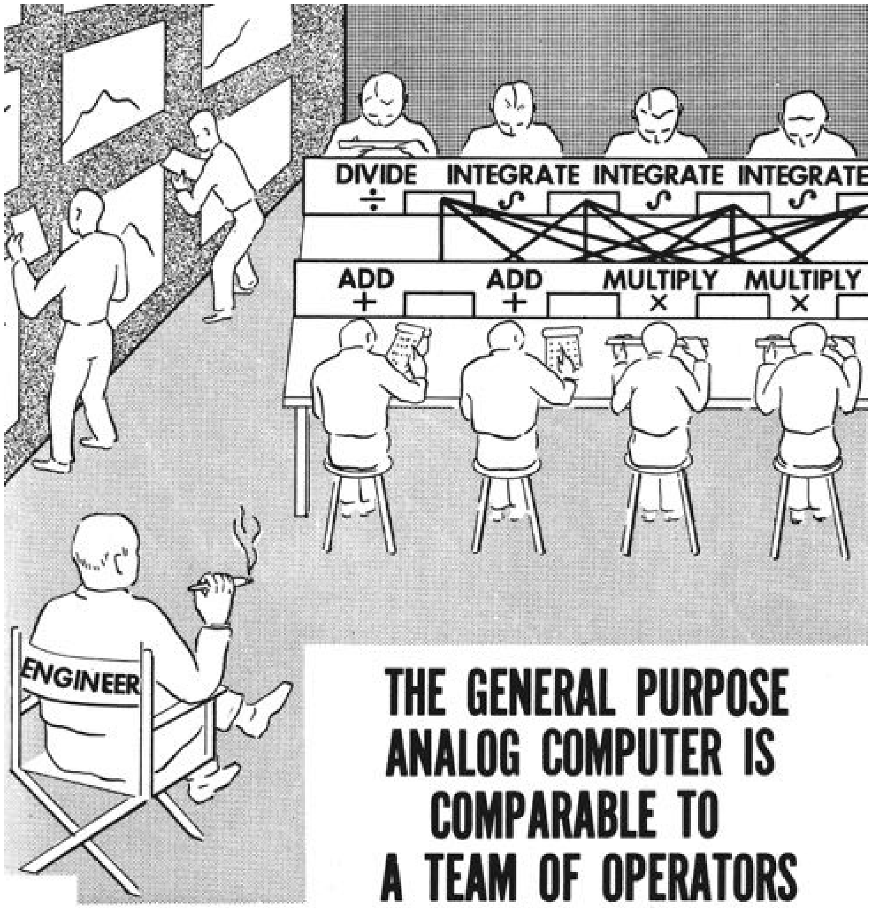
Historische Analogrechner



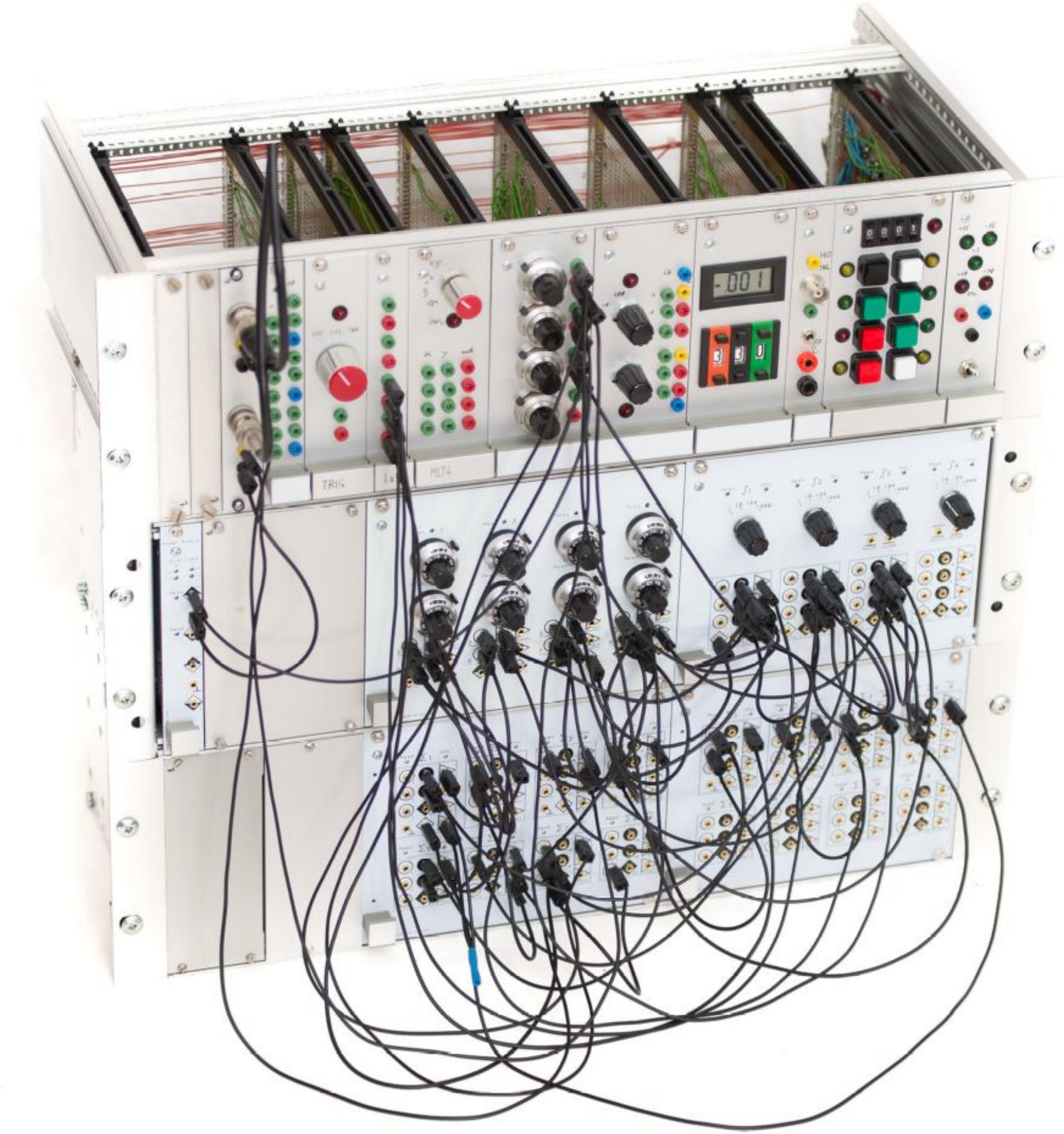


Telefunken-Analogrechner aus den 1960ern → www.analogcomputermuseum.org





Bildquellen: T. Truitt, Basics of Analog Computers, 1960; via Bernd Ulmann



Die Rückkehr des Analogrechners

- Namensgebend ist die Analogiebildung mit elektrischen Schaltkreisen.
- Intrinsisch parallele Datenfluss-verarbeitung statt sequentieller Algorithmen.
- Extrem energieeffizient: Jedes Elektron zählt.
- Kontinuierliche Werte und kontinuierliche Zeit: Kein Takt.

anabrid

Wir gründeten die Anabrid GmbH:

Wiederentdeckung des Analogienrechnens

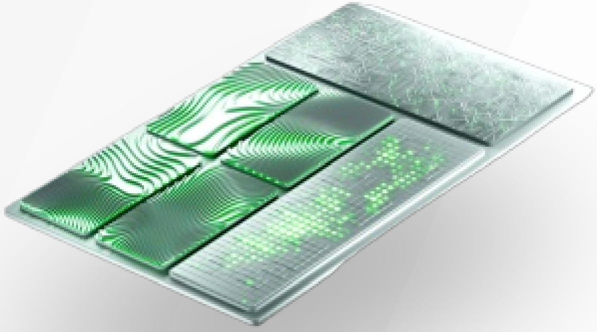
The Analog Thing
»Hacker's toolkit«

SPRIN-D

REDAC Analog Supercomputer

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center

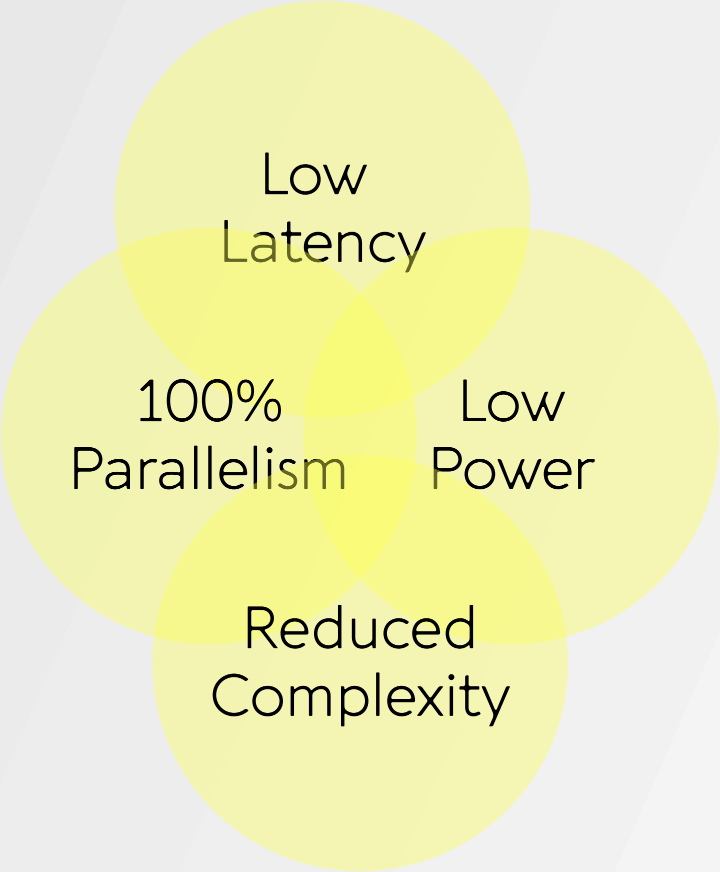
QCi DLR Quantencomputing Initiative

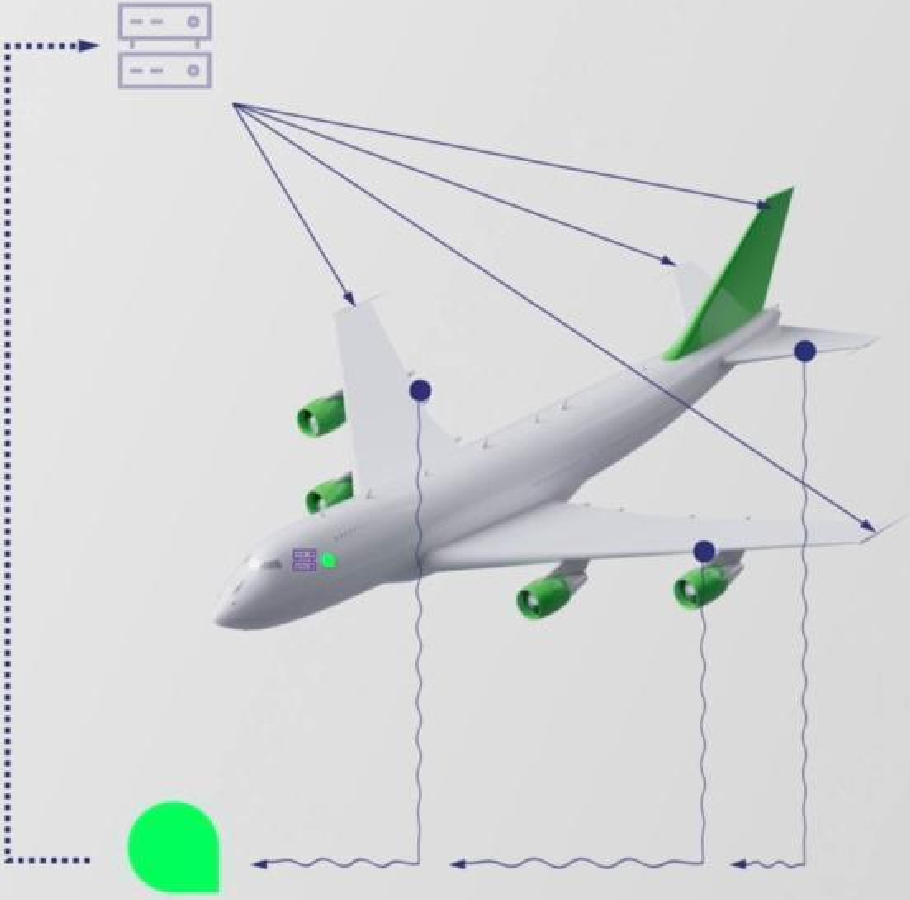


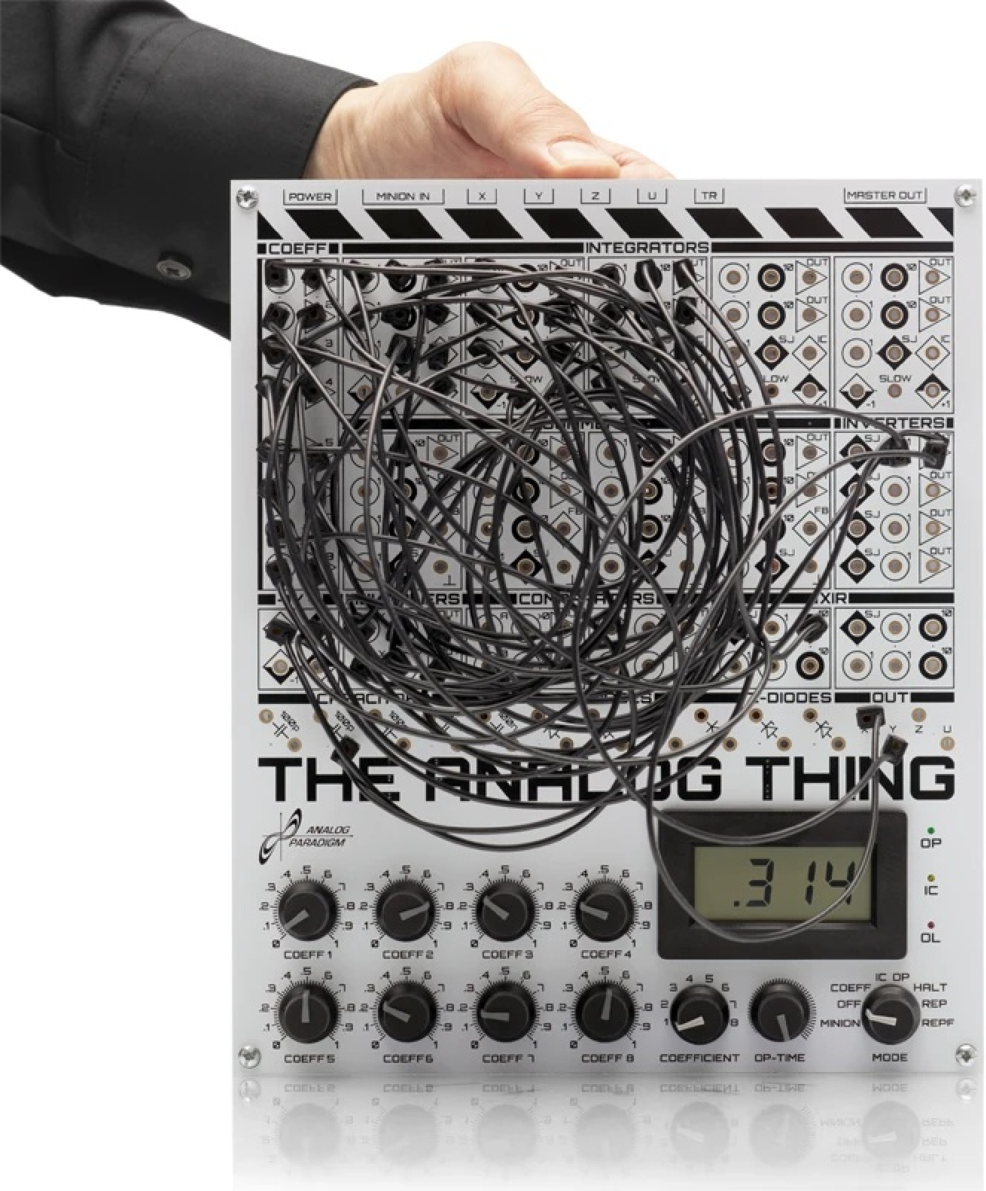
G-PAC: 65nm CMOS

Talking to industry

Reasons why to go analog

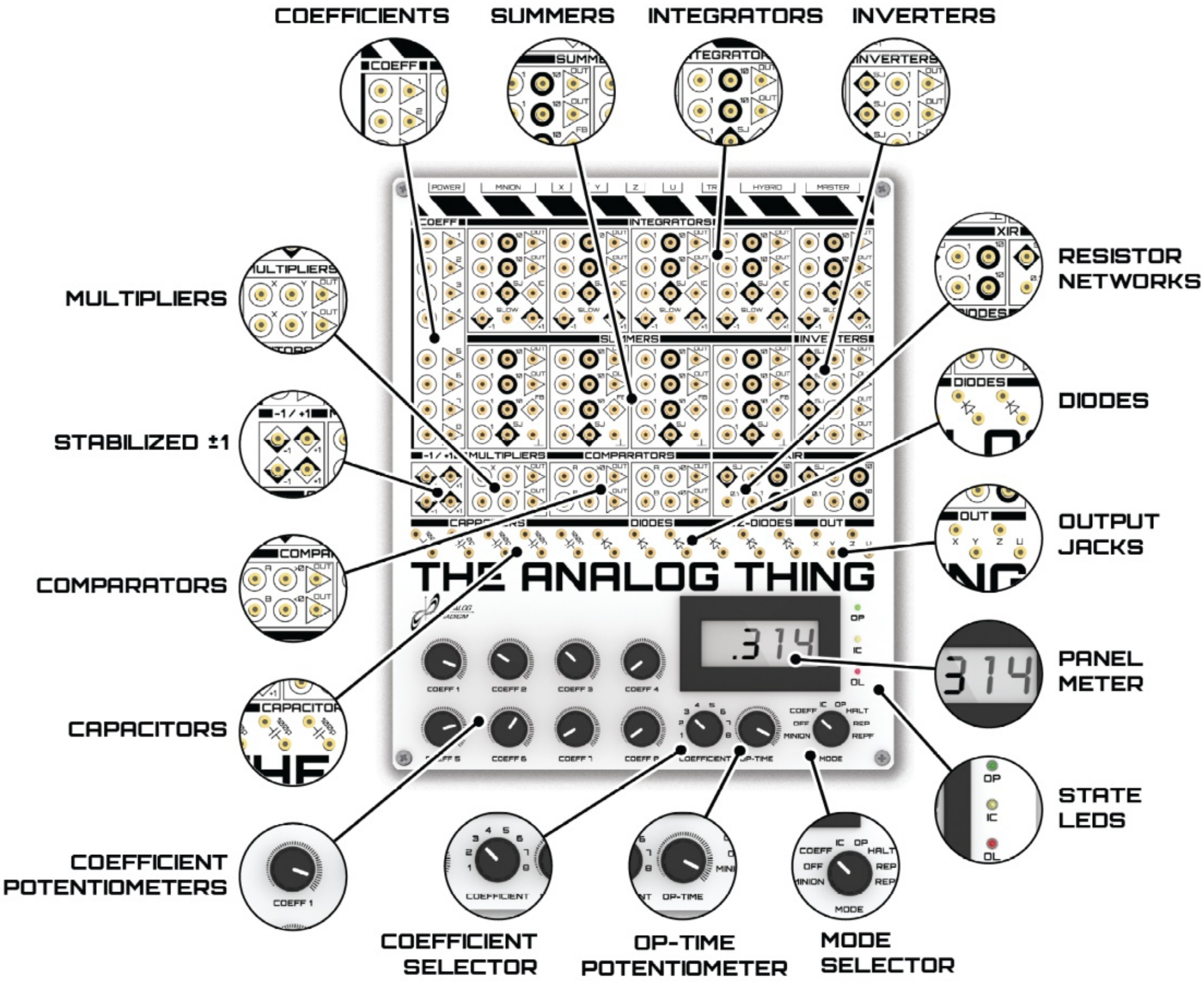






The Analog Thing

- Erschwinglicher Rechner für Ausbildung und Lehre.
- Open Source-Hardware soll zum Basteln einladen.
- Einfache Schnittstellen an Arduino, Raspberry Pi, etc.
- Start ohne Laborequipment möglich (dank Soundkarte)


COEFFICIENTS
SUMMERS
INTEGRATORS
INVERTERS
MULTIPLIERS
RESISTOR NETWORKS
STABILIZED ±1
DIODES
COMPARATORS
OUTPUT JACKS
THE ANALOG THING
PANEL METER
CAPACITORS
STATE LEDS
COEFFICIENT POTENTIOMETERS
COEFFICIENT SELECTOR
OP-TIME POTENTIOMETER
MODE SELECTOR

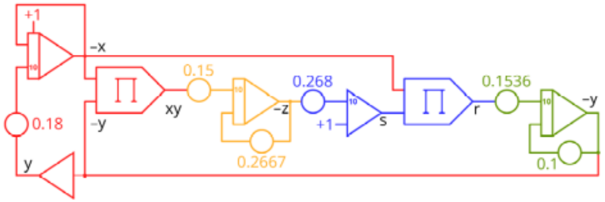
$$-x = -\int 1.8y - x \, dt + C$$

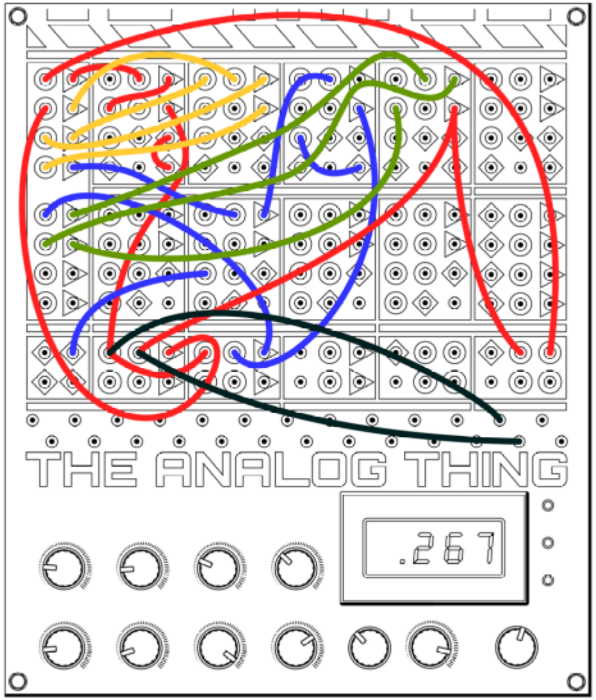
$$-z = -\int 1.5xy - 0.2667z \, dt$$

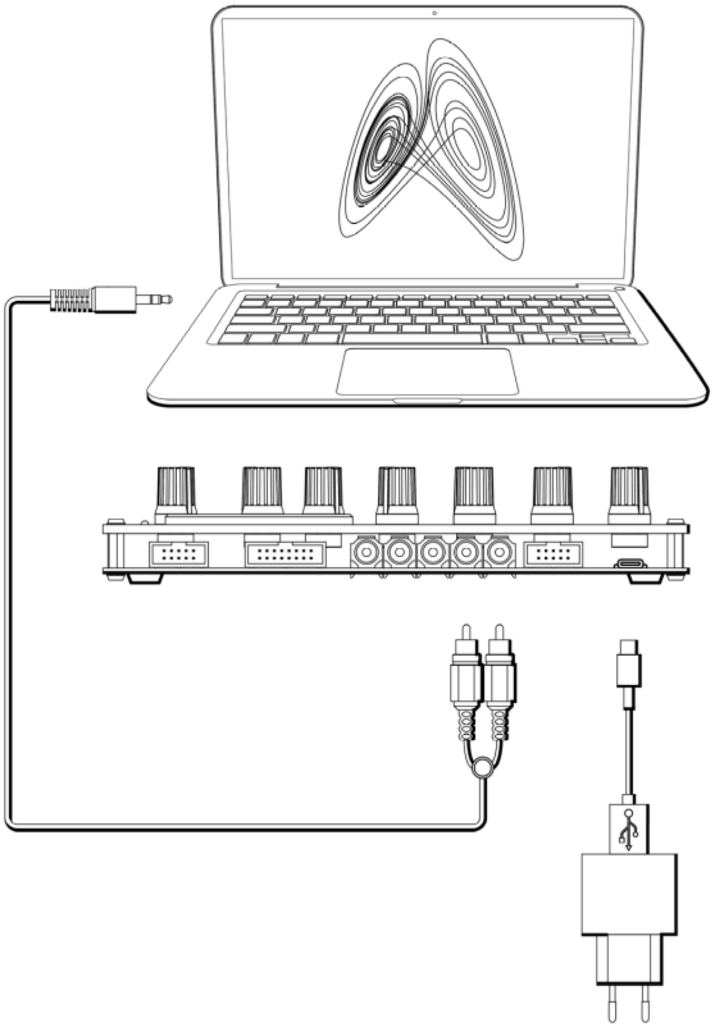
$$s = -(1 - 2.68z)$$

$$r = -xs$$

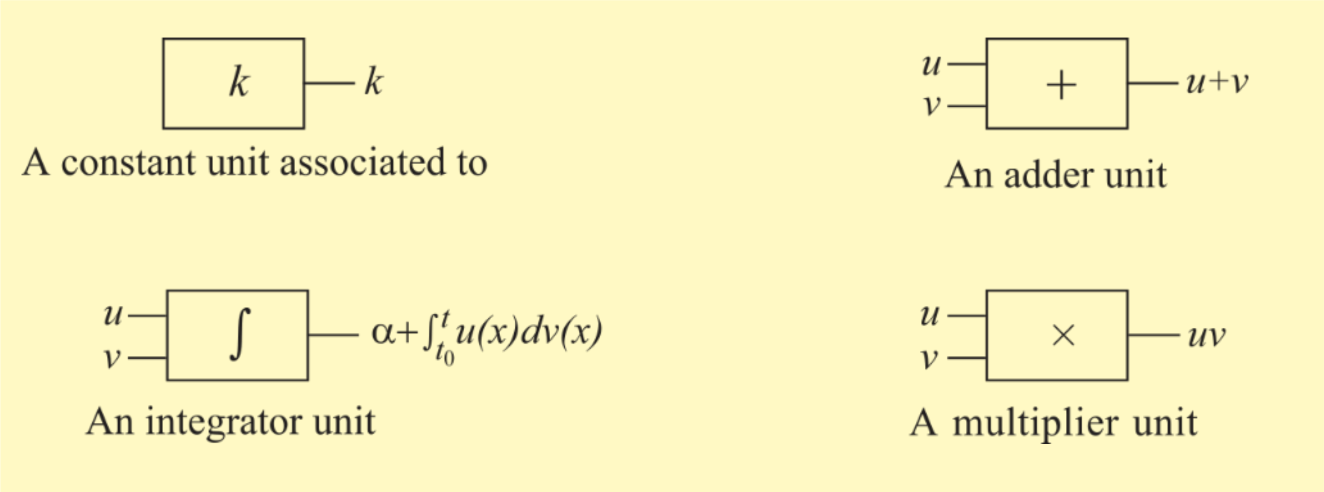
$$-y = -\int 1.536r - 0.1y \, dt$$







Bausteine des Analogrechners! The General Purpose Analog Computer



Claude Shannon [1941] hat für Analogrechner gemacht, was Turing für Digitalrechner gemacht hat.

- Kein Algorithmus, kein Speicher
- Alle Rechenelemente rechnen ständig und gleichzeitig

Bildquellen: Daniel Graca http://www.dp-pmi.org/uploads/3/8/1/3/3813936/shannon_2016.pdf

Computational Physics: Das „Hello World“ aus der Analysis

1 Will folgende Differentialgleichung (z.B. Bewegungsgleichung) lösen:

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = f(t, y(t))$$

2 Umschreibung in Integralgleichung:

$$y(t) = \int_0^t f(t, y(t))\mathrm{d}t$$

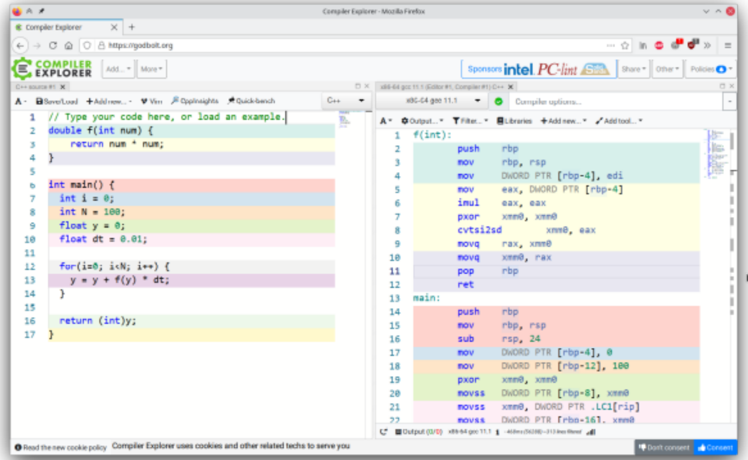
3 Diskretisierung

$$y_i \approx \sum_{i=0}^{N} f(t, y(t))\Delta t$$

4 Programmierung

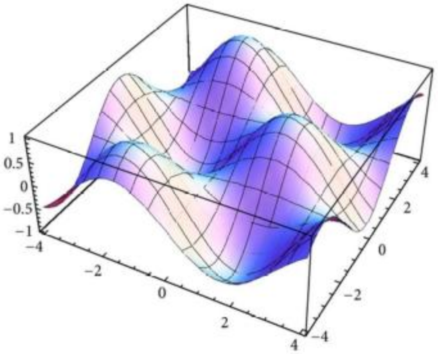
```
void main() {
  int i = 0;
  float y = 0;
  float dt = 0.01;

  for(i=0; i<N; i++) {
    y = y + f(y) * dt;
  }


  printf(„final y = %f“,y);
}
```

5 Kompilieren und laufen lassen



goldbolt.org

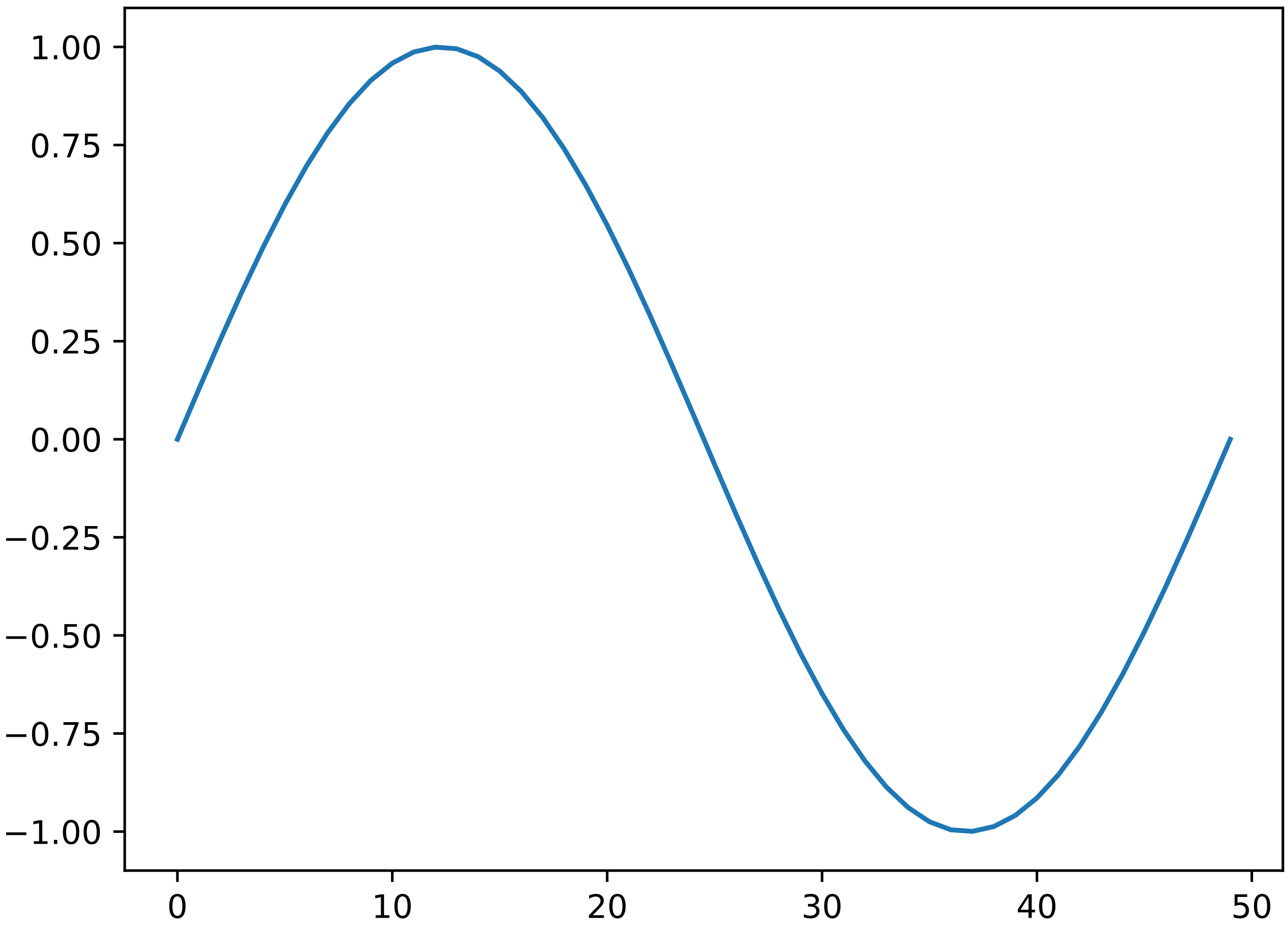
6 Auswerten

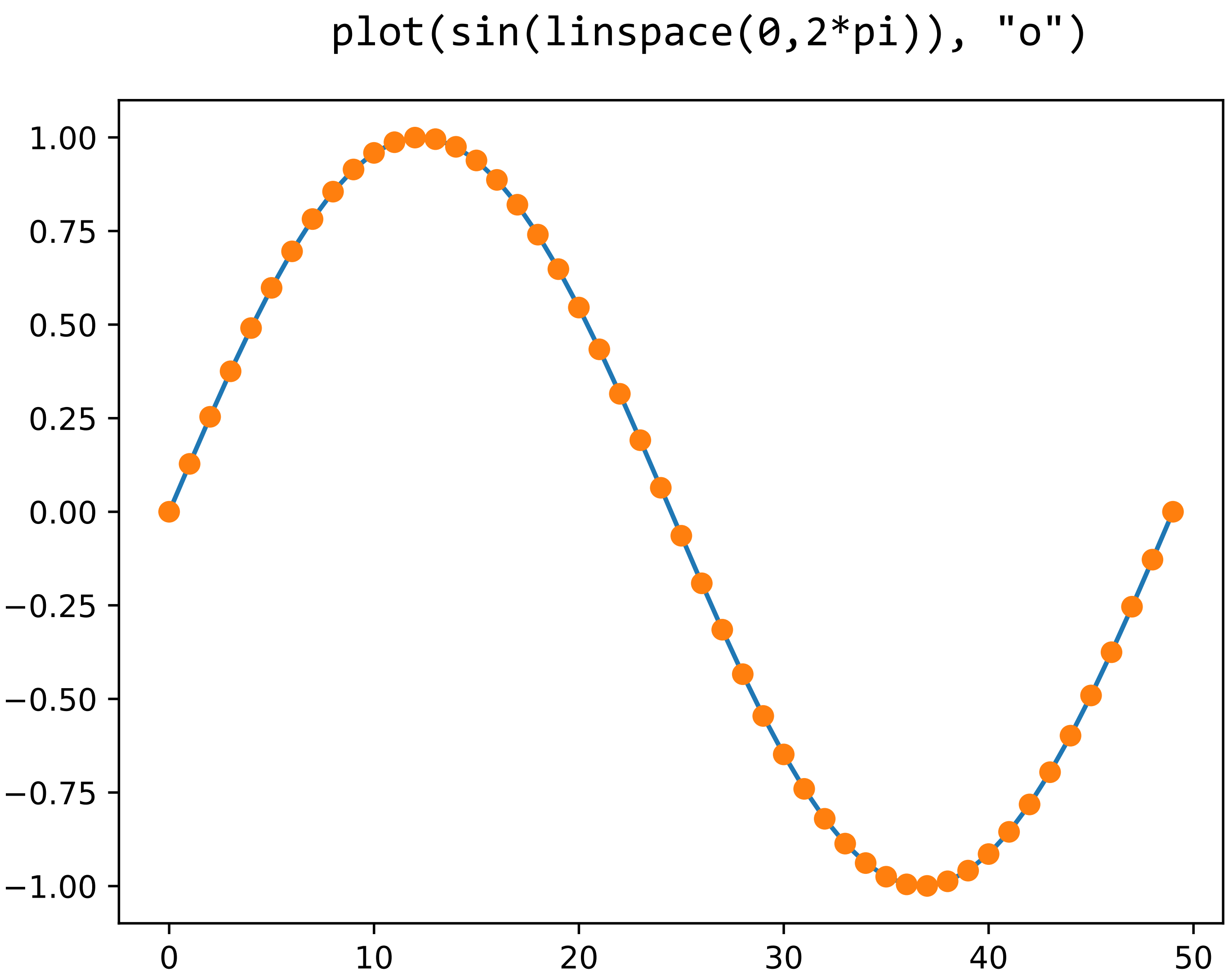


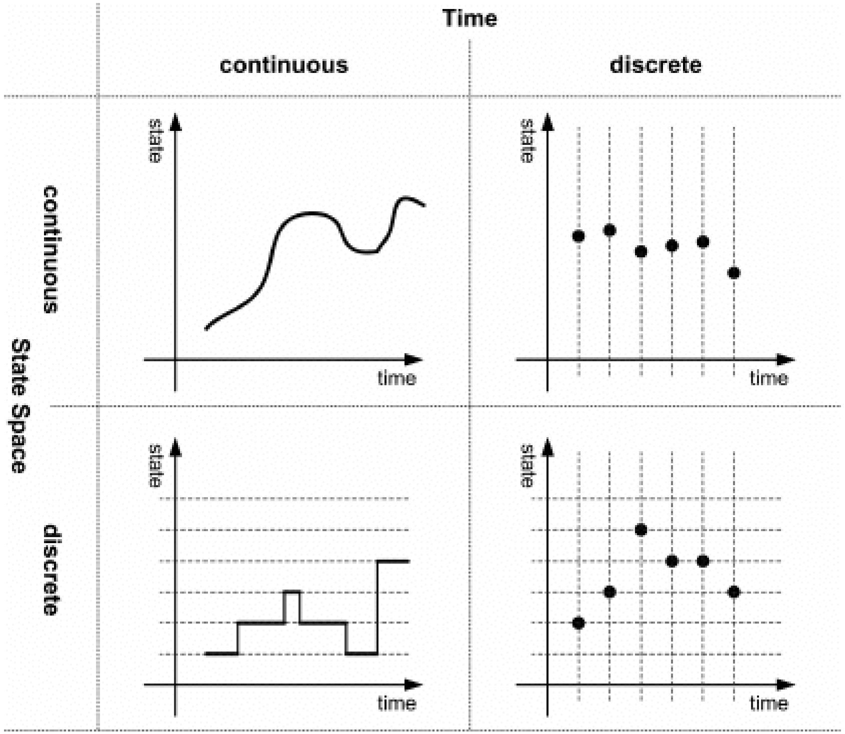
Mathematica

7 Whaaaa!

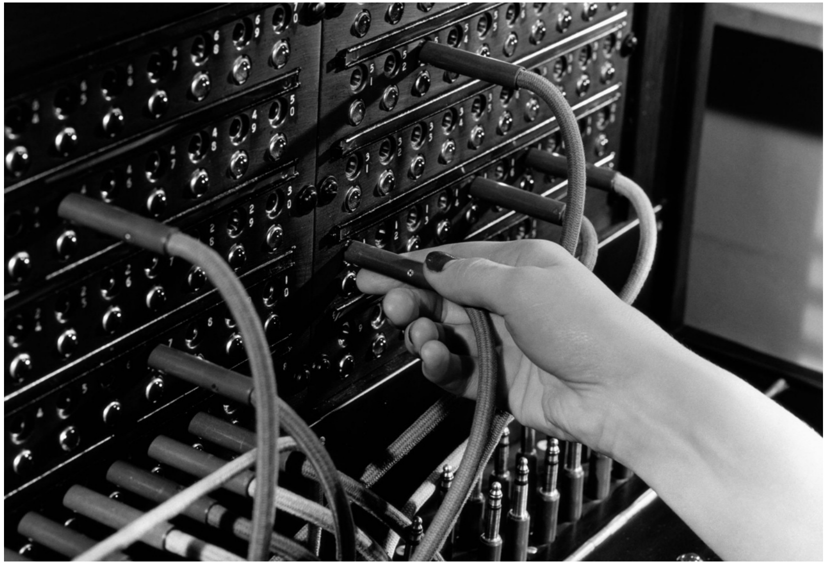
plot(sin(linspace(0,2*pi)))

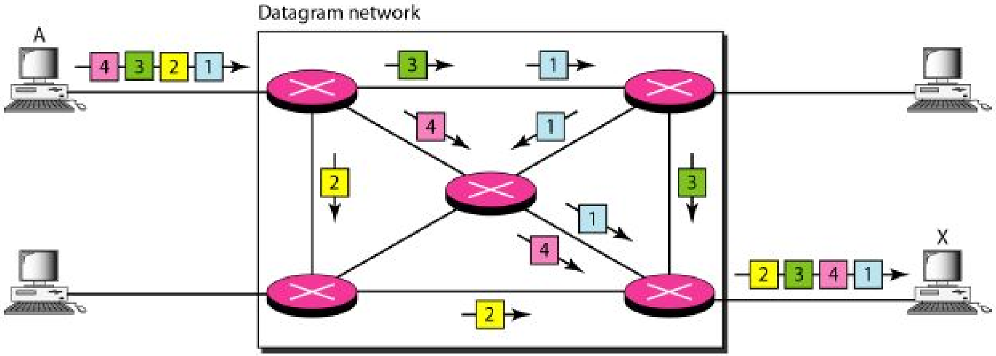



plot(sin(linspace(0,2*pi)), "o")
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
10
20
30
40
50



[10.14279/tuj.eceasst.27.385]





Analog rechnen: „Hello World“ aus der Elektrotechnik / Informatik

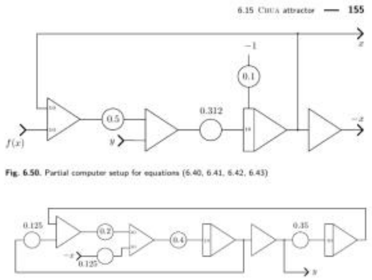
1 Will folgende Differentialgleichung (z.B. Bewegungsgleichung) lösen:

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = f(t, y(t))$$

2 Umschreibung in Integralgleichung:

$$y(t) = \int_0^t f(t, y(t))\mathrm{d}t$$

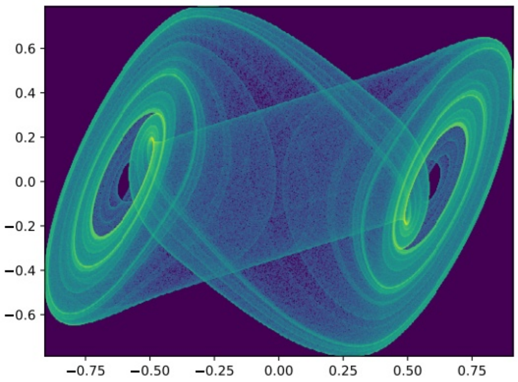
3 Auf elektrische Ersatzschaltung abbilden



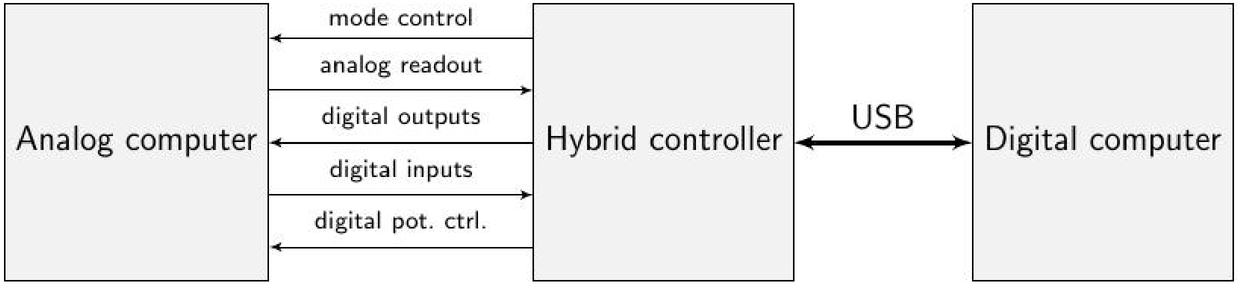
4 Programmierung

```
# Chua attractor, chapter 6.15 from Bernds book
# Below is the scaled version (equations)

x0 = const(0.1)
x1 = mult(-10, neg(sum(x, fx)))
x2 = neg(sum(y, mult(0.5, x1)))
x  = neg(sum(mult(3.12, neg(int(x2, dt, 0))), x0))

y1 = neg(sum(z, neg(mult(0.125, y))))
y2 = neg(sum(mult(1.25, x), mult(2, y1)))
y  = mult(4, neg(int(y2, dt, 0)))

z  = int(mult(3.5, y), dt, 0)

f1 = abs(sum(mult(0.7143,x),  0.2857))
f2 = abs(sum(mult(0.7143,x), -0.2857))
f3 = neg(sum(f1, neg(f2)))
fx = sum(mult(0.714, x), mult(0.3003, f3))

dt = const(0.001)
```

5 Auswerten



Automatisierung: Digital + Analog = Hybrid



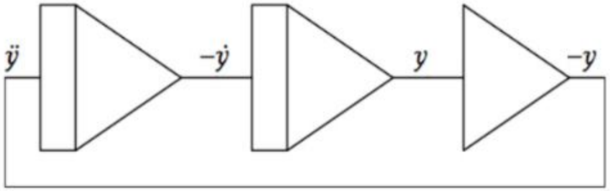
Analogrechnen: Ein Beispielprogramm

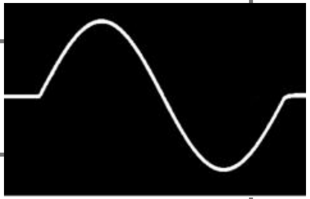
Harmonischer Oszillator:

$$\ddot{y} + \omega^2 y = 0$$

Umschreiben zu:

$$\ddot{y} = -y \qquad (\text{mit } \omega = 1)$$





Mit Anfangswerten und Allgemein:

$$y_0 = a\sin(\phi)$$
$$\dot{y}_0 = a\omega\cos(\phi)$$

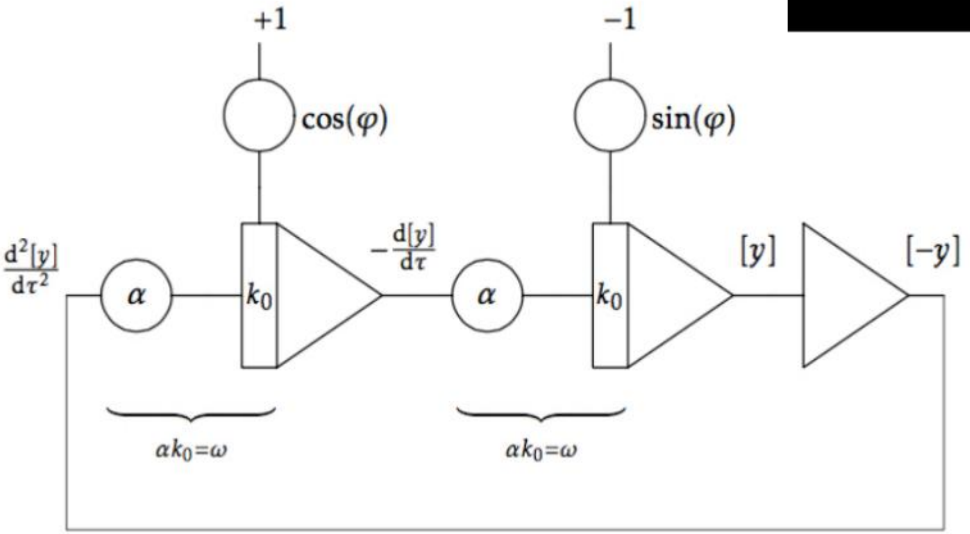
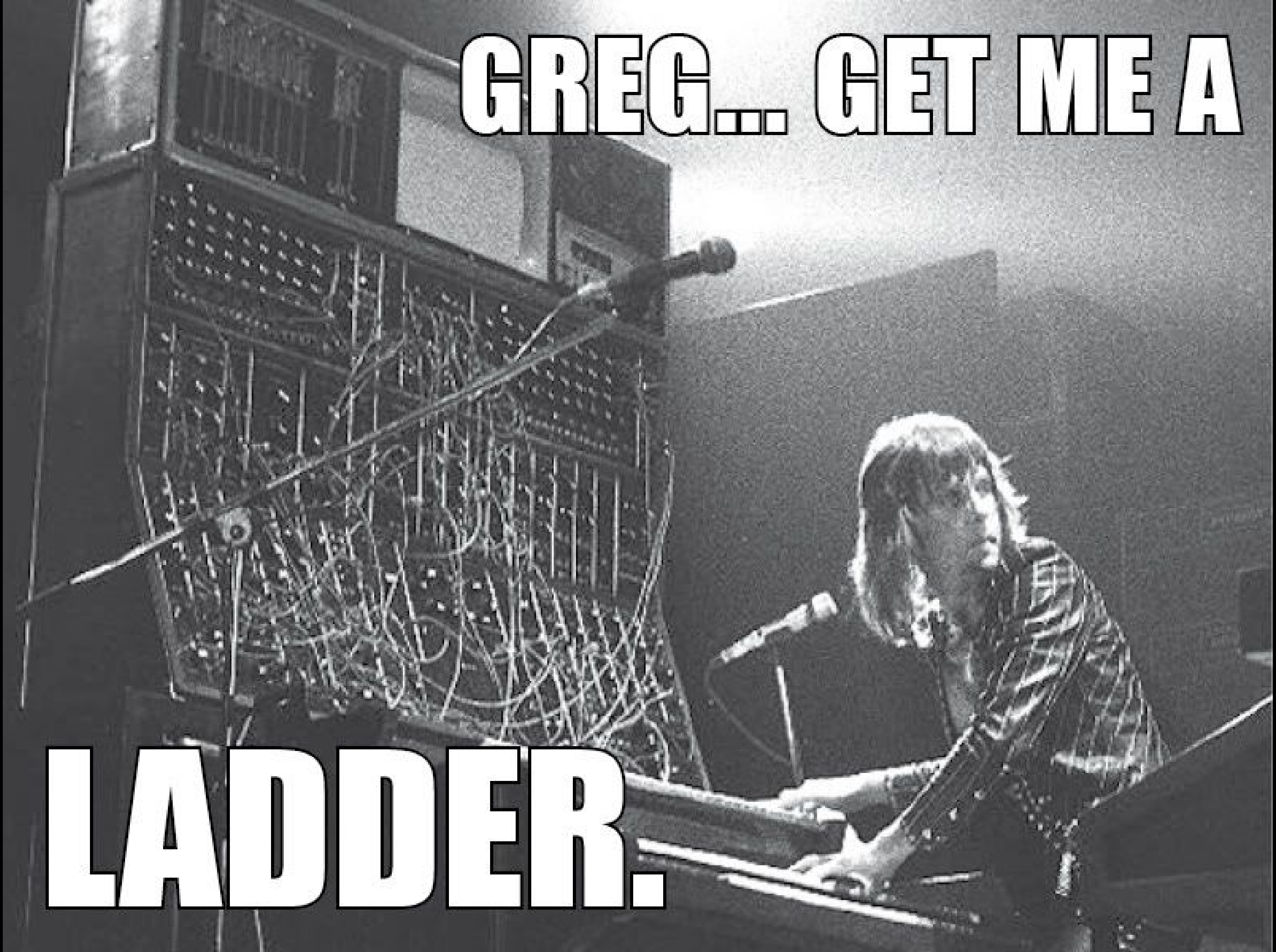


Bild- und Slidequelle: Bernd Ulmann


GREG... GET ME A
LADDER.

WTF is Analog Computing?

Dr. Sven Köppel
koeppel@anabrid.com

Vielen Dank für eure Aufmerksamkeit!

Kommt vorbei und probiert THATs aus
Oder schaut auf the-analog-thing.org
Oder auch: Youtube „Analog Computing“