Analog computers

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- Mechanical analog calculators & computers
- Electronic analog computers
- Demonstrations
- The future. Literature and links

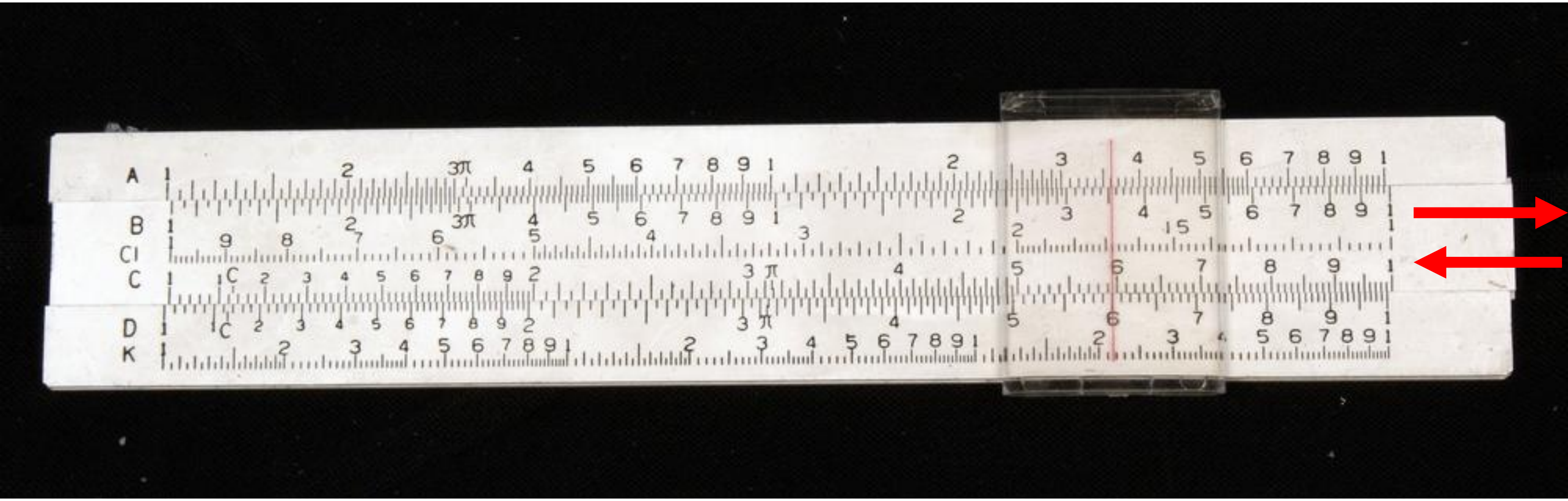
Definition

- An analog computer works in a continuous manner (a digital computer functions in discrete steps).
- An analog computer uses a model which behaves in a similar way (= in an "analog" way) to the problem to be solved.

The oldest analog computers were purely mechanical systems, later systems were electronic devices.

Mechanical analog computer

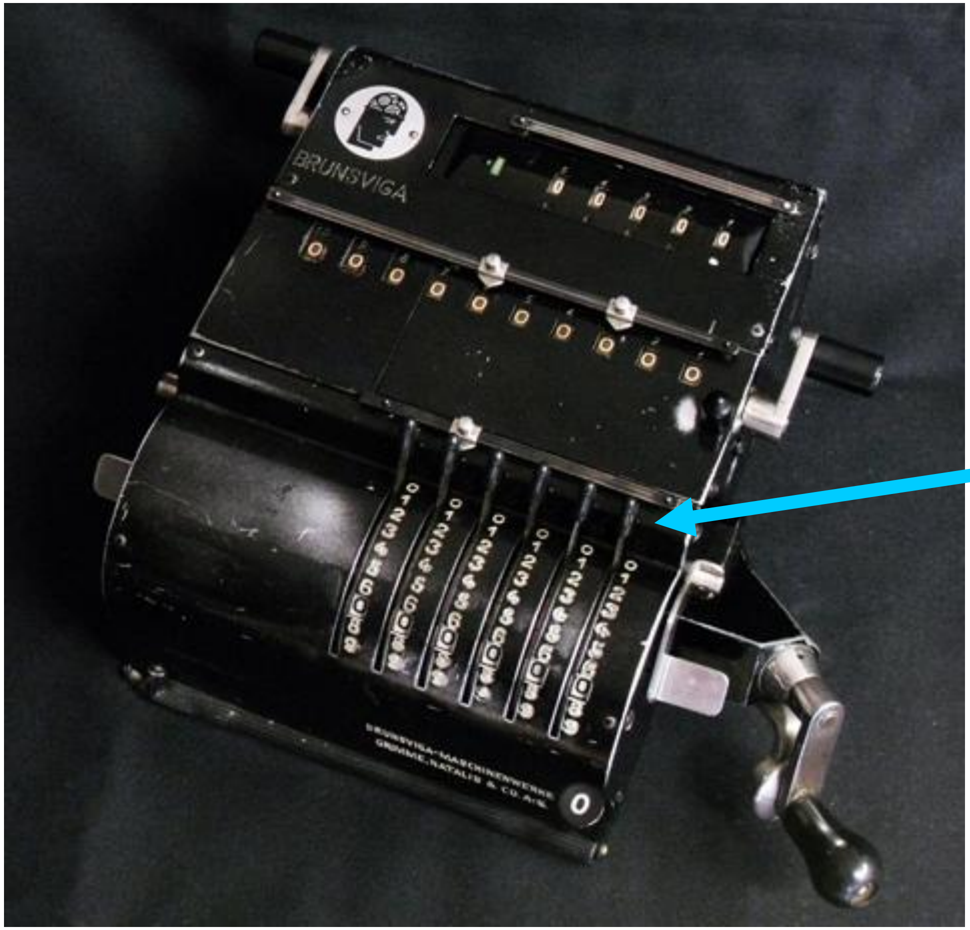
Example: Sliderule



Central ruler moves continuously.

Mechanical digital computer

Example: Brunsviga calculator (mod. 10, 1925)



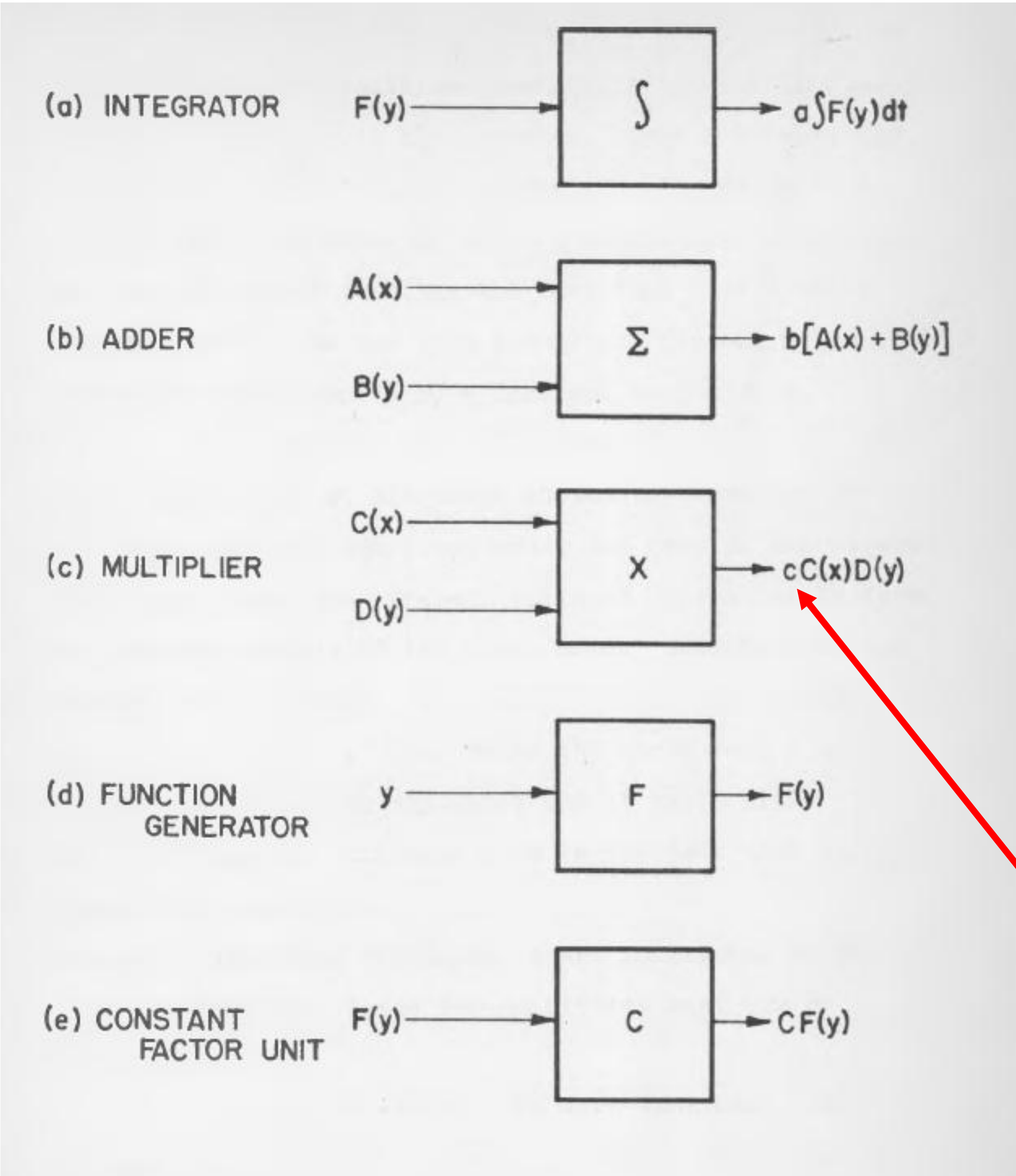
Slider can take only fixed positions 0…9

Mechanical analog computer

Antikythera, 78 BC (astrolabe)
Oldest analog computer known:
at least 30 gears!
(found in 1900 by sponge divers)

Several rebuilds since 1978
(Antikythera Mechanism Research project)

Mechanical analog computer



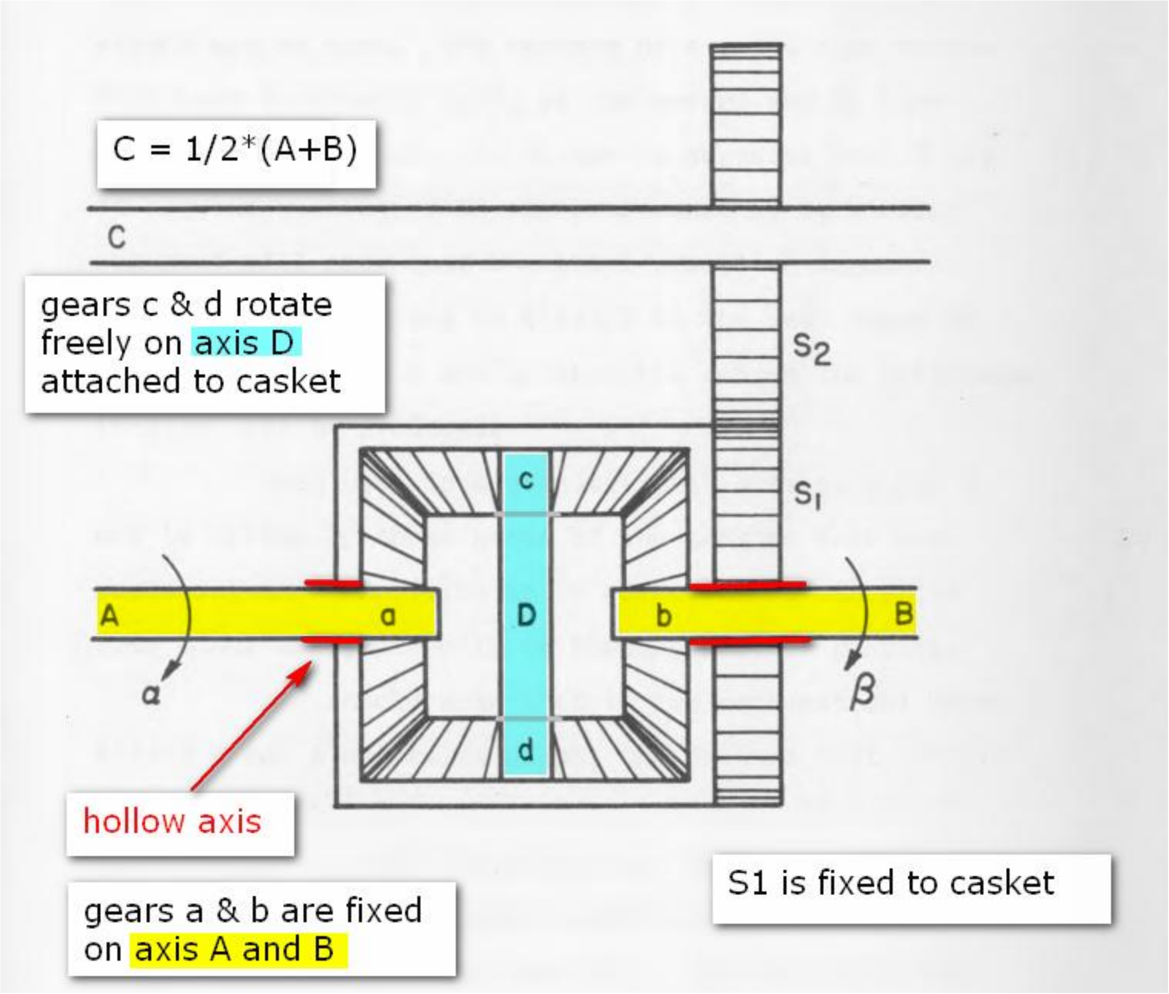
Only 5 functions are needed to solve (nearly) any problem described by ordinary differential equations

F.J. Miller:
Theory of Mathematical Machines, 1947

Output is proportional to the mathematical operator !

Mechanical analog computer

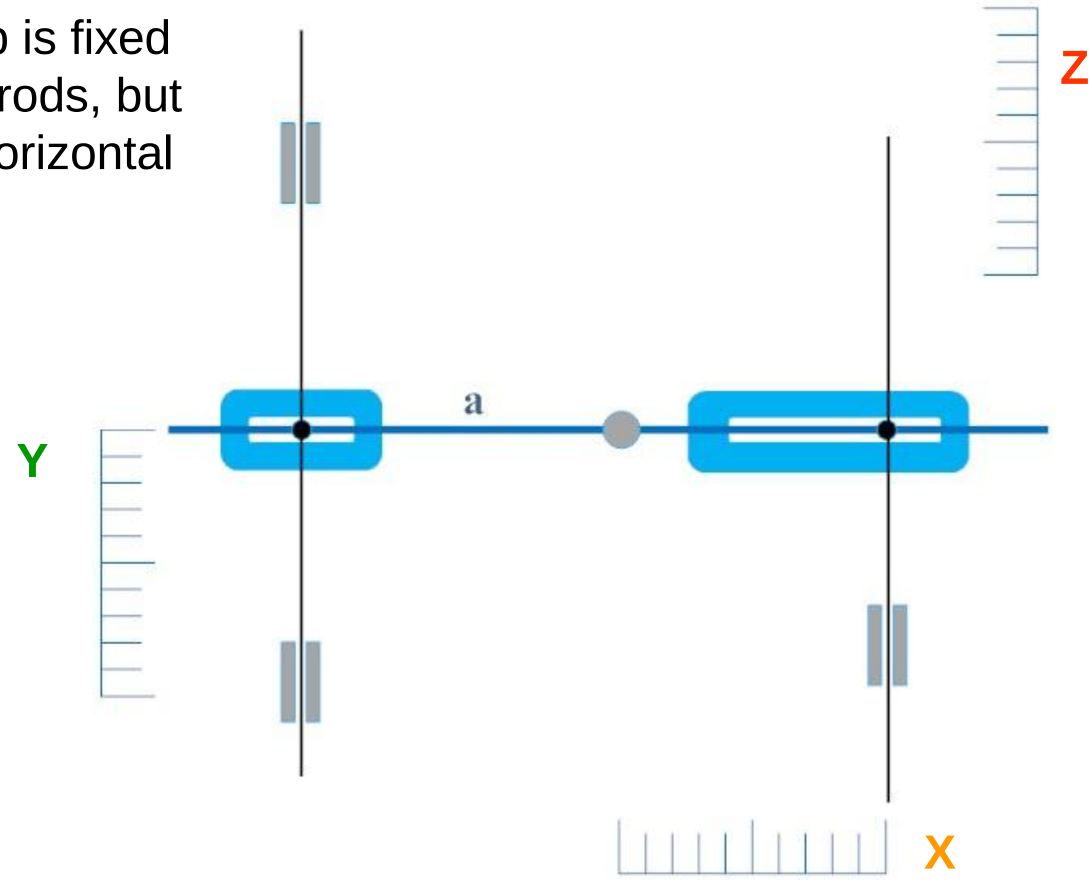
Example: Adder [Thesis J.E. Kasper, 1955]



Mechanical analog computer

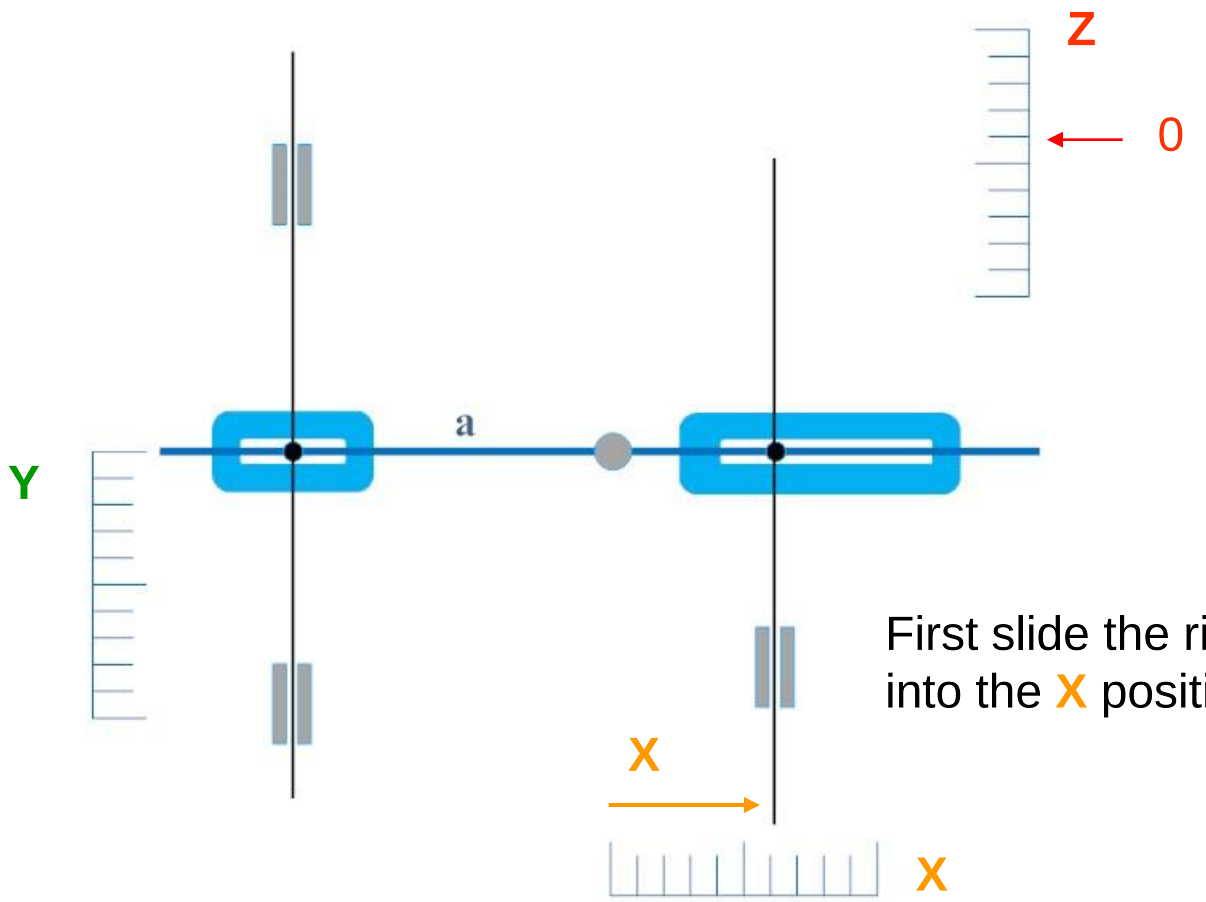
Example: Multiplicator [Mathematische Instrumente, Meyer zur Capellen, 1941]

The black knob is fixed on the vertical rods, but slides on the horizontal level.



Mechanical analog computer

Example: Multiplicator [Mathematische Instrumente, Meyer zur Capellen, 1941]

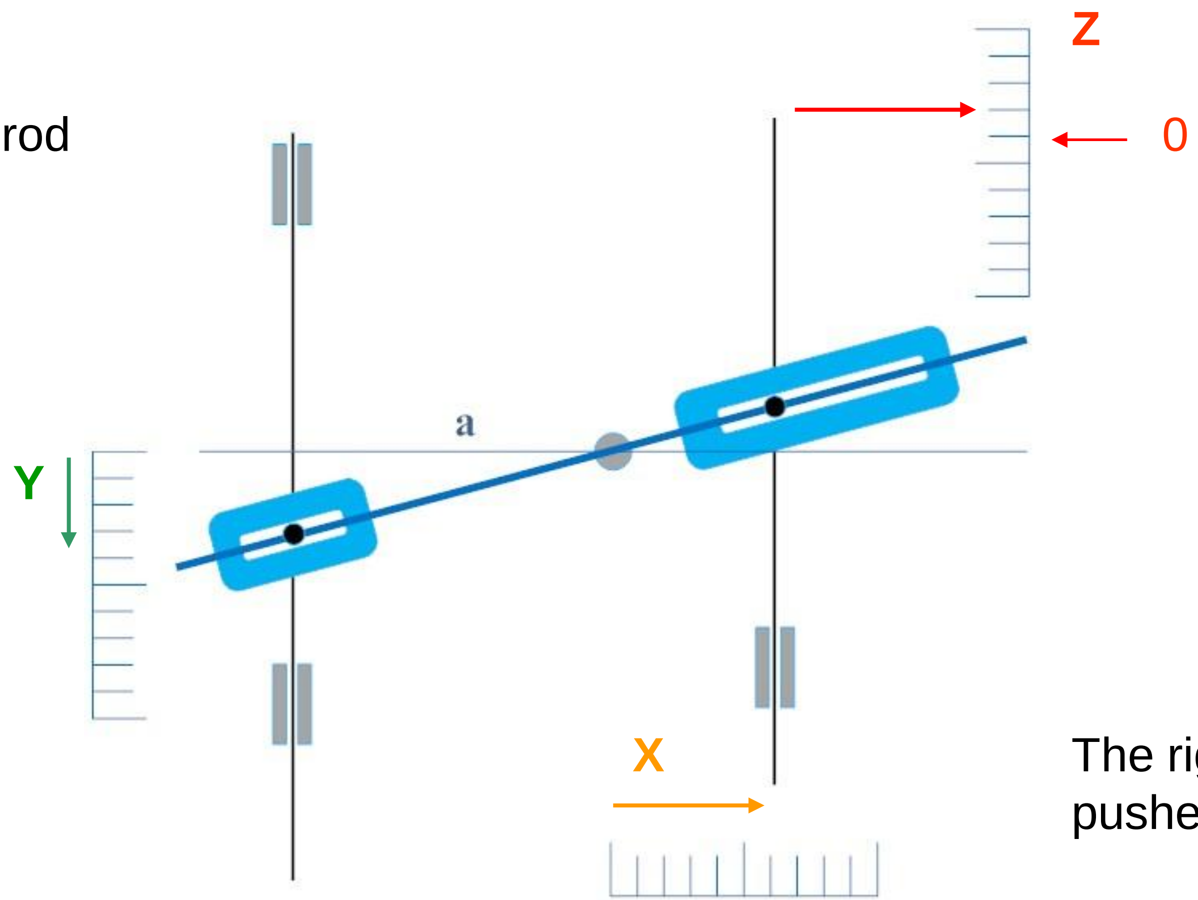


First slide the right rod into the X position.

Mechanical analog computer

Example: Multiplicator [Mathematische Instrumente, Meyer zur Capellen, 1941]

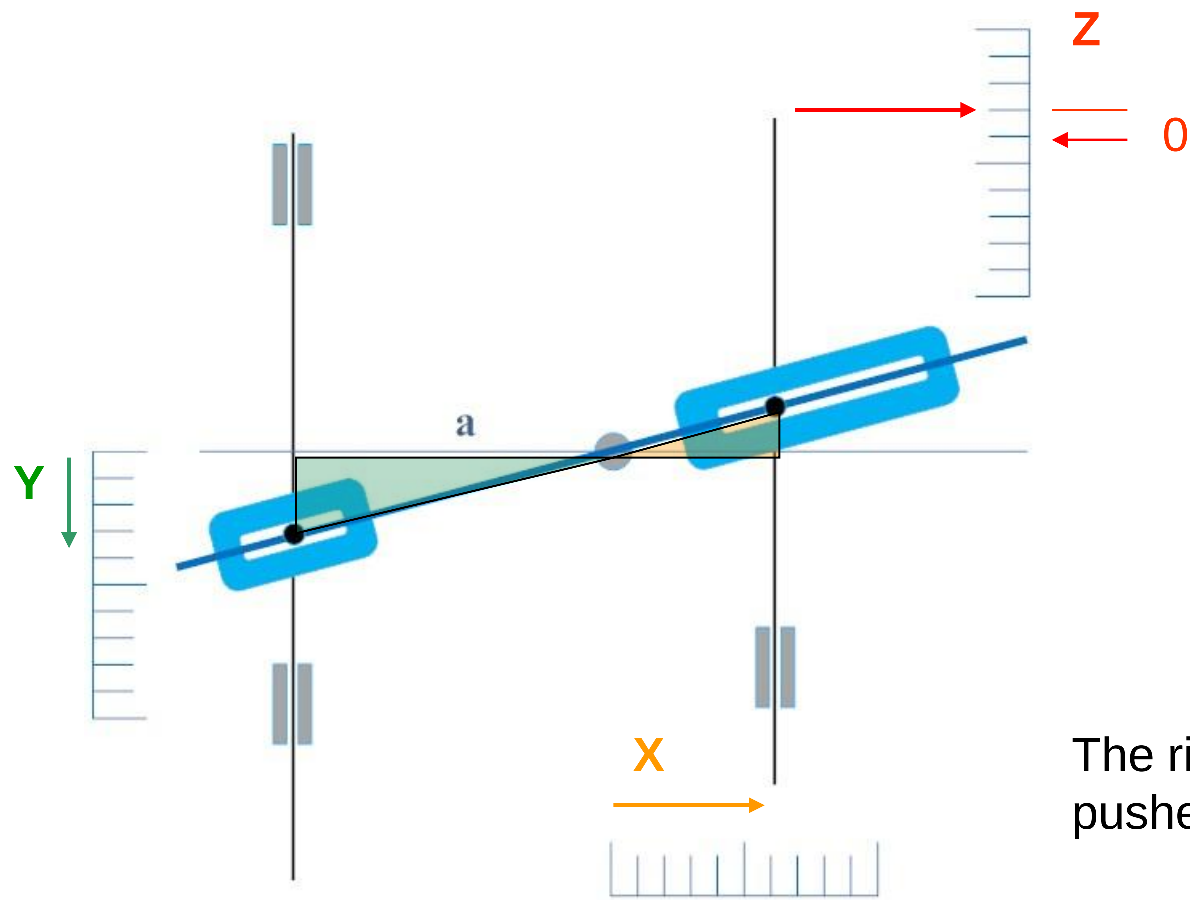
Now push the left rod down into the **Y** position



The right rod is pushed up by **Z**

Mechanical analog computer

Example: Multiplicator [Mathematische Instrumente, Meyer zur Capellen, 1941]



The right rod is pushed up by Z

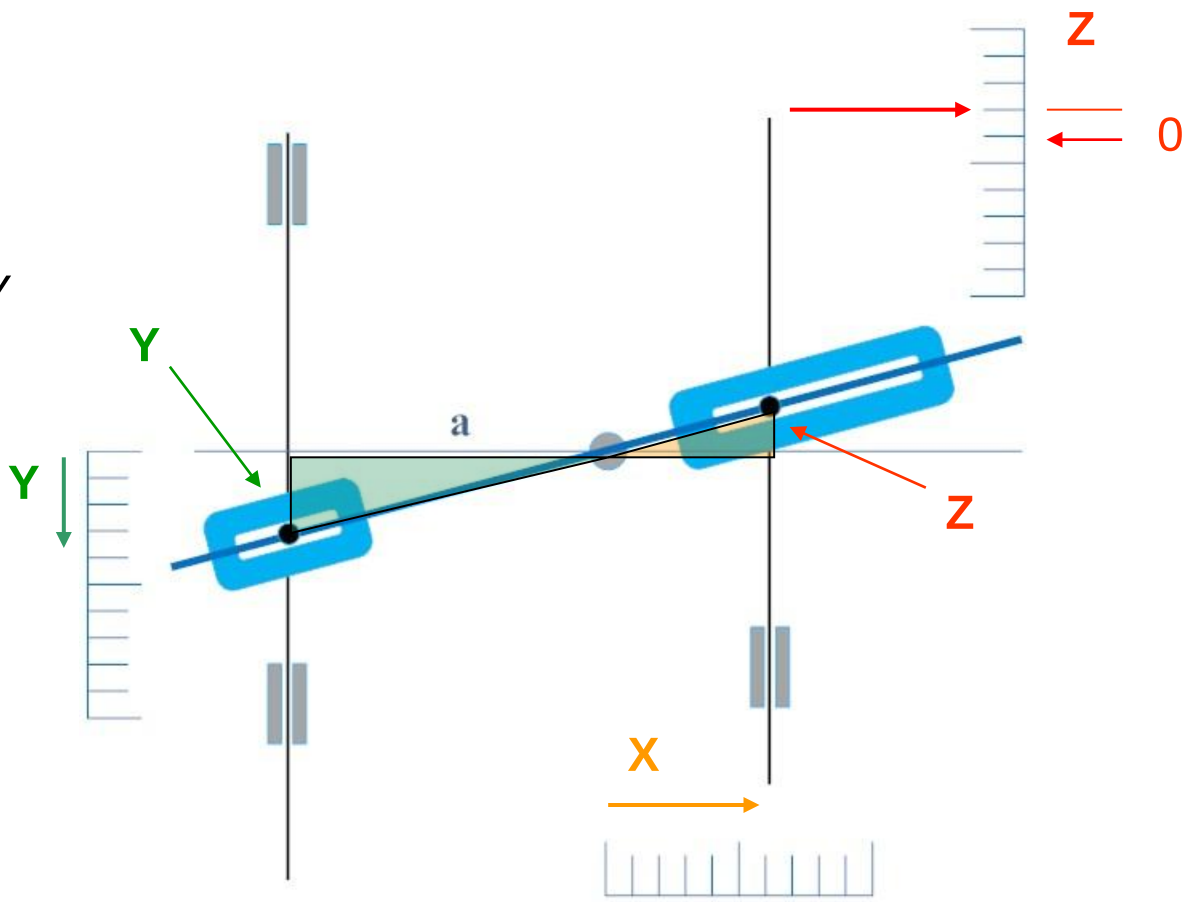
Mechanical analog computer

Example: Multiplicator [Mathematische Instrumente, Meyer zur Capellen, 1941]

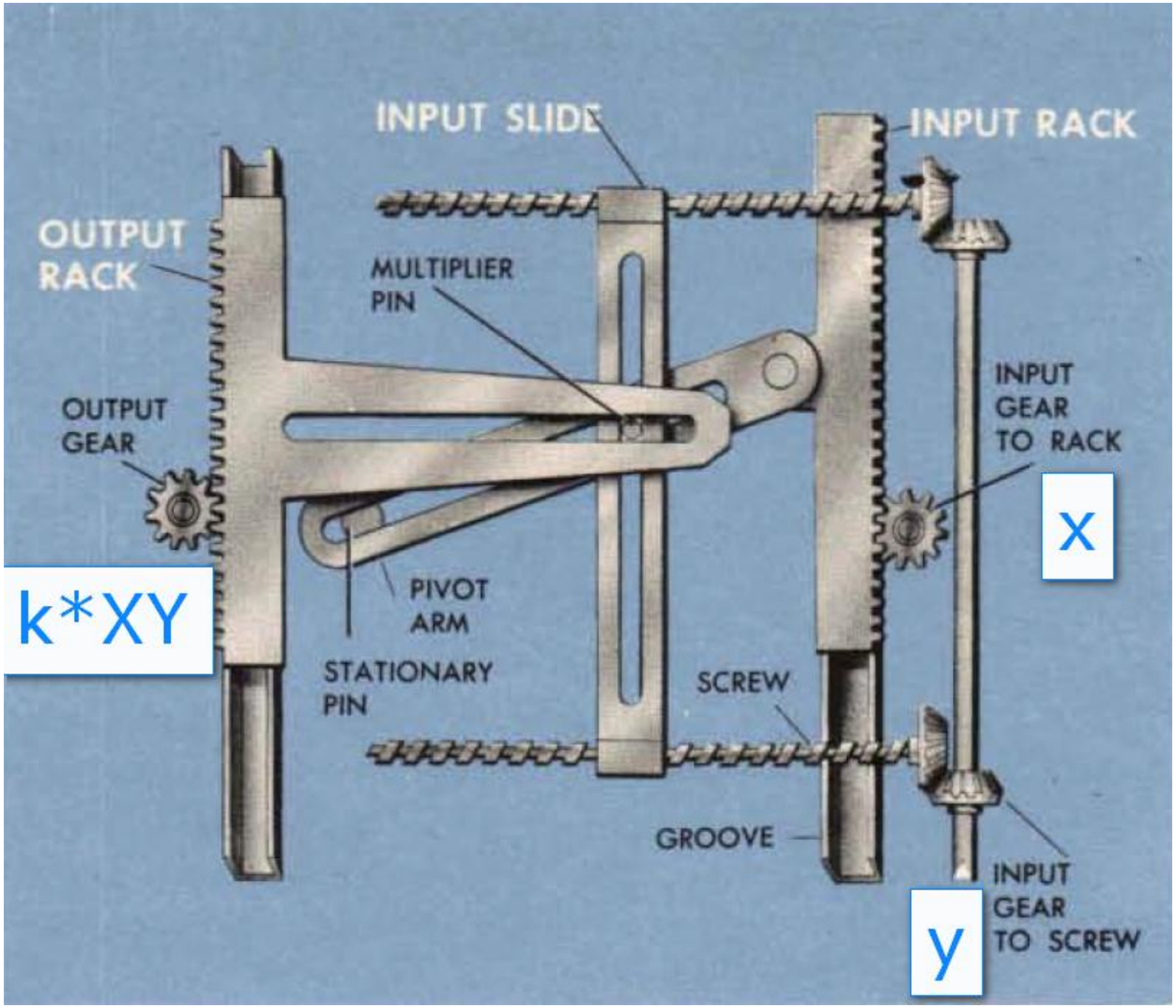
Z/X = Y/a

Z = 1/a*(X*Y)

Z = proport. to X*Y



Military screw multiplier



From ordnance pamphlet 1140
Gun and Fire control (US Navy)
http://archive.hnsa.org/

Logarithm calculator

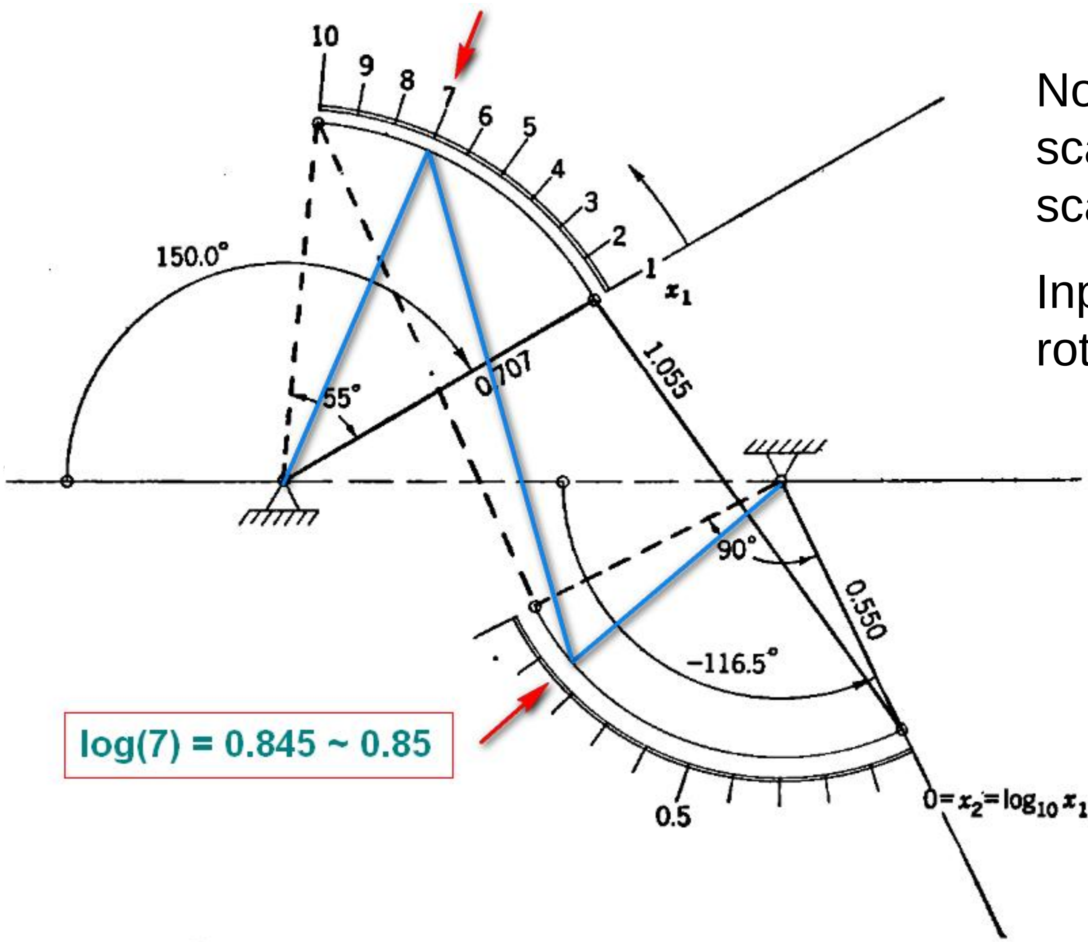


Fig. 5·28.—Approximate mechanization of $x_2 = \log_{10} x_1$.

Note the regular scaling of both scales!

Input and output are rotations.

Svoboda, 1946

Sinus generator

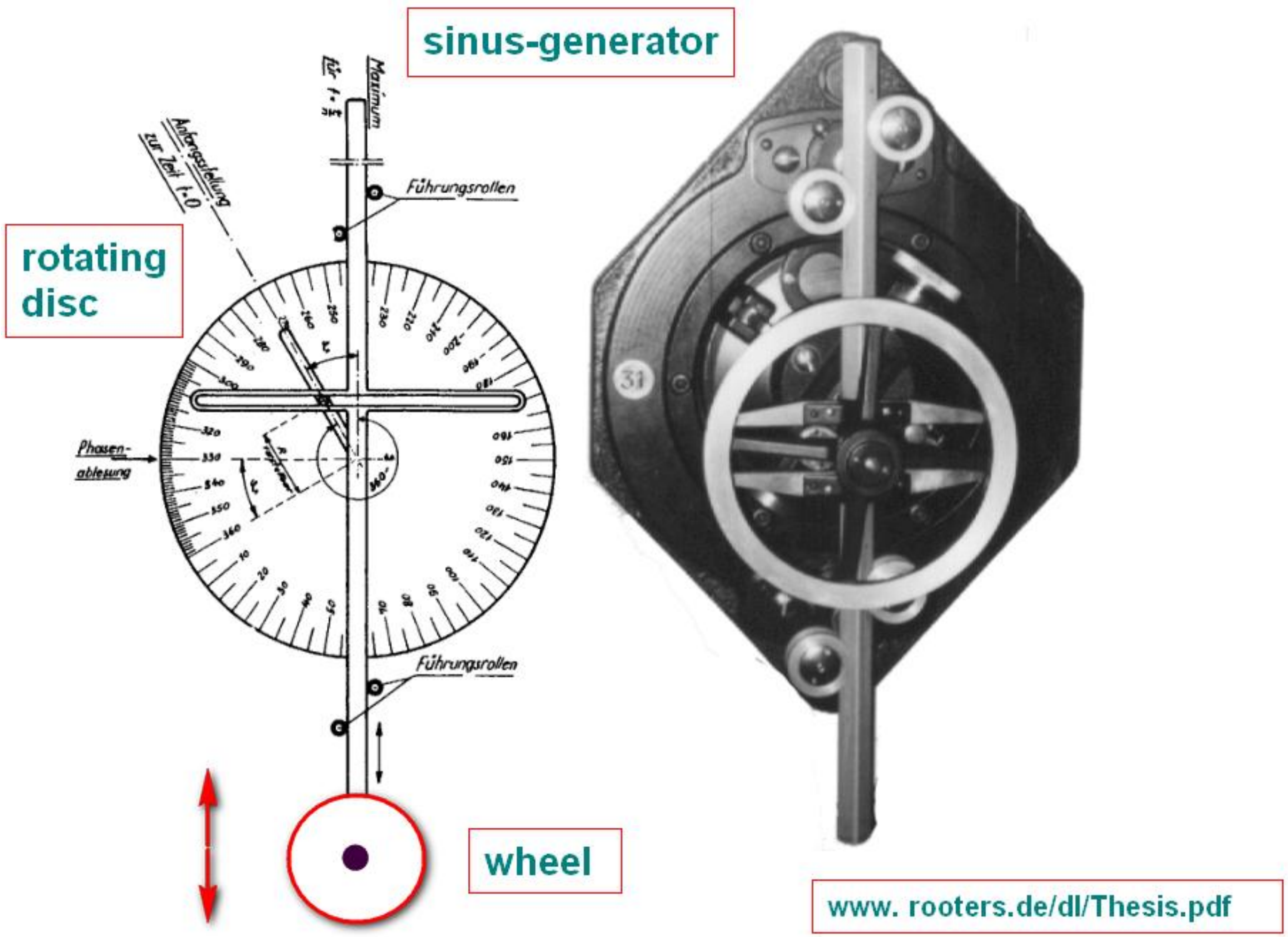


Abbildung 17: Generator zur Erzeugung harmonischer Schwingungen. Links Zeichnung (entnommen [Sag55] S. 33) und rechts Foto eines Generators der zweiten deutschen Gezeitenberechnungsmaschine

Tide calculator (1)

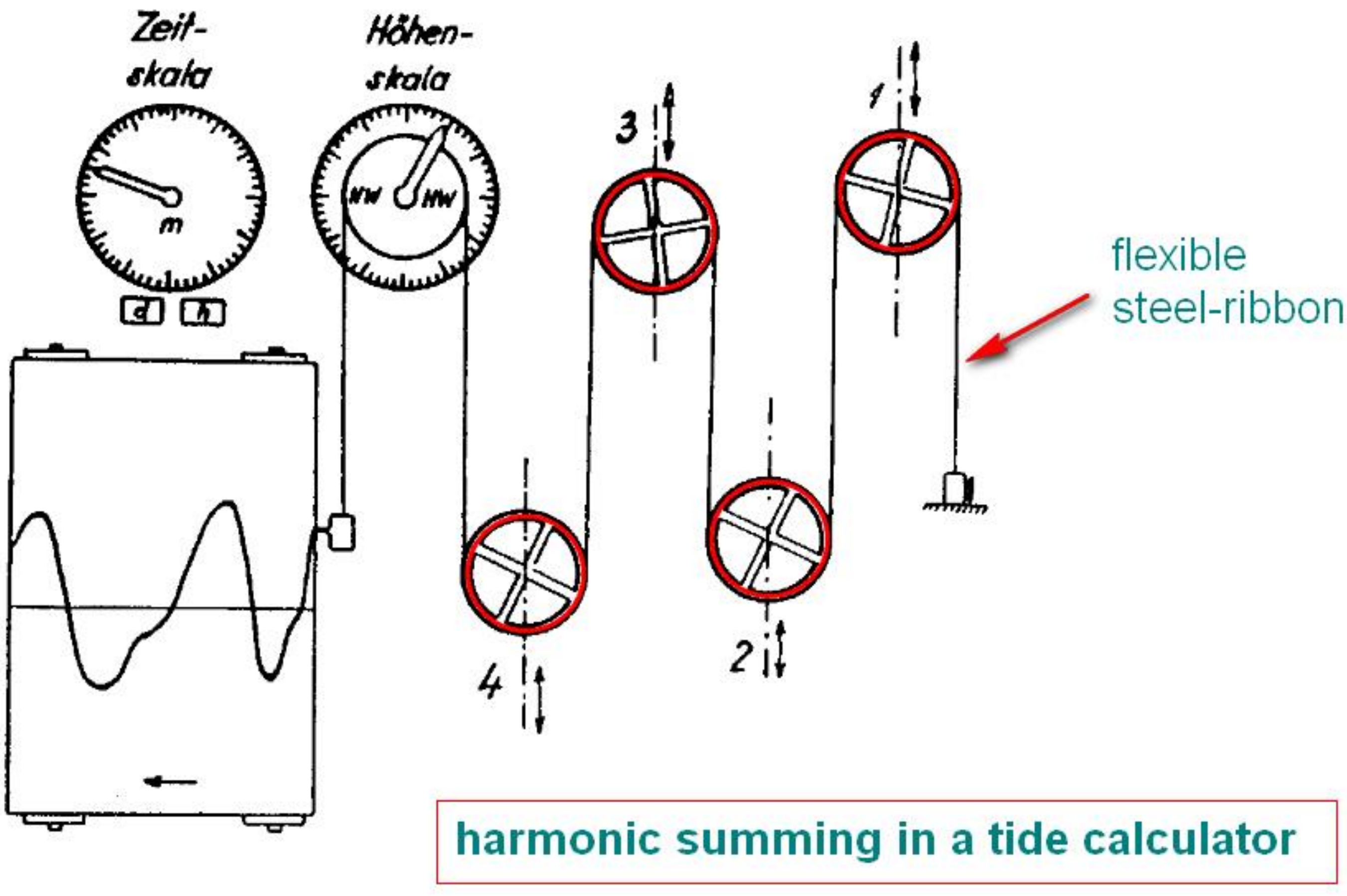
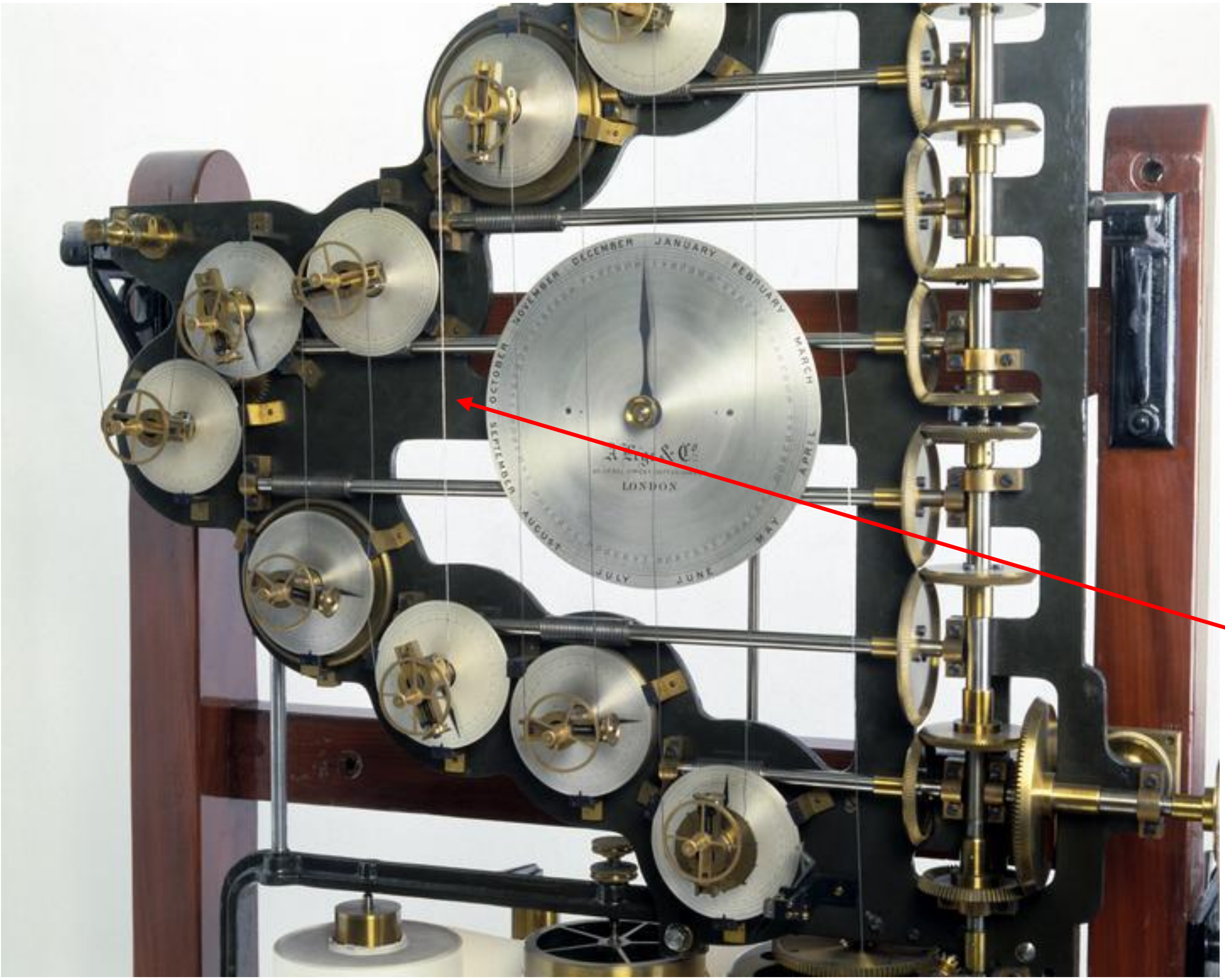


Abbildung 18: Mechanische Überlagerung harmonischer Schwingungen. (Entnommen [Sag55] S. 35)

Tide calculator (2)



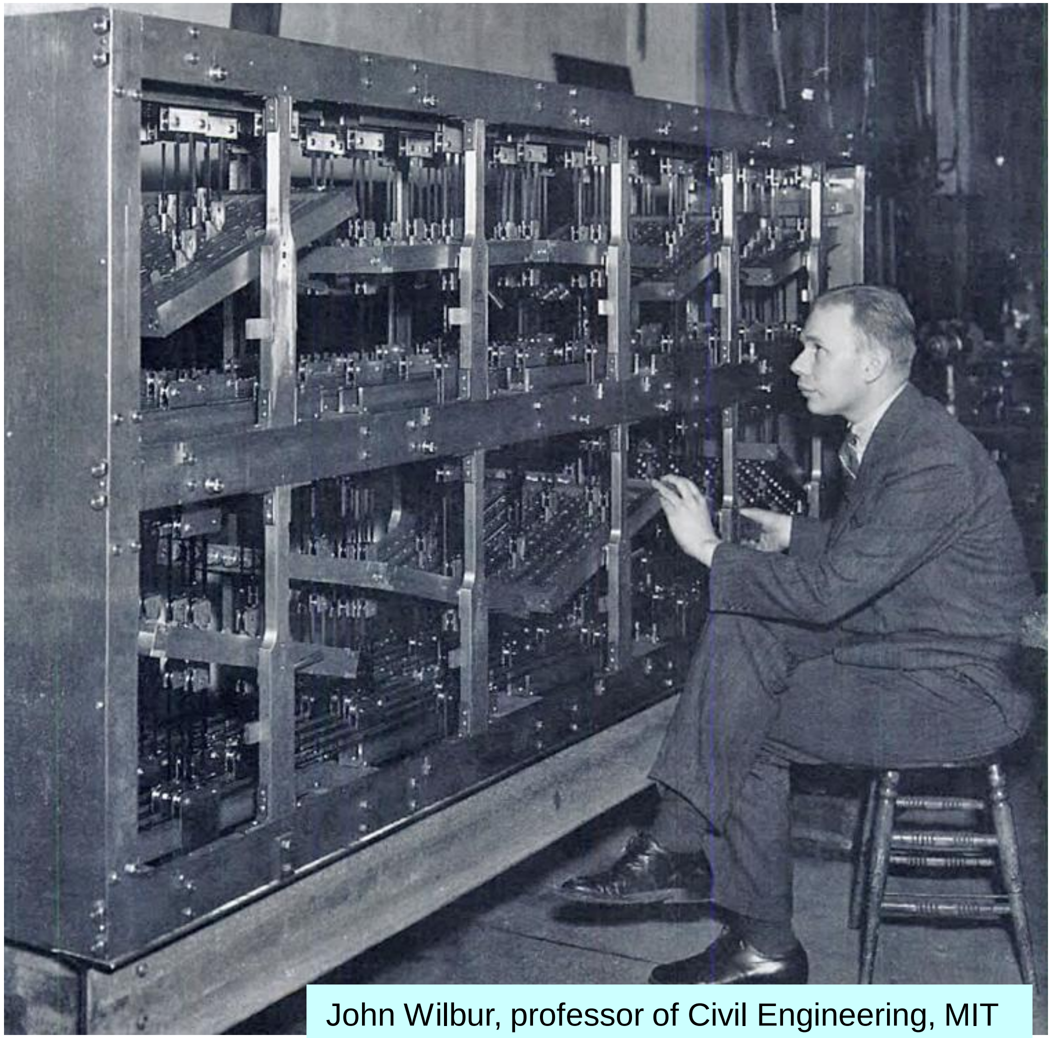
Kelvin tide predictor 1872: 10 harmonics

Steel wire

Lord Kelvin & Roberts: 1879, 20 harmonics

Equation solver (1)

The Wilbur machine (MIT, 1936) solves systems of linear equations (13000 parts, > 1000 pulleys)



John Wilbur, professor of Civil Engineering, MIT

Built to solve systems of 9 linear equations:

The sine of the angle of the slotted plate gives the solution of one variable.

(9 plates which 9 double-pulleys for every equation, 10th plate for the constants).

Only used once by Harvard economist W.W.Leontief to calculate an economic model which needed 450000 multiplications.

Equation solver (2)

One plate of the Wilbur machine:

Wilbur machine: time to solve a system ~1 to 3 hours. Without the machine Leontief's model would have needed 2 years at 120 multiplications/hour

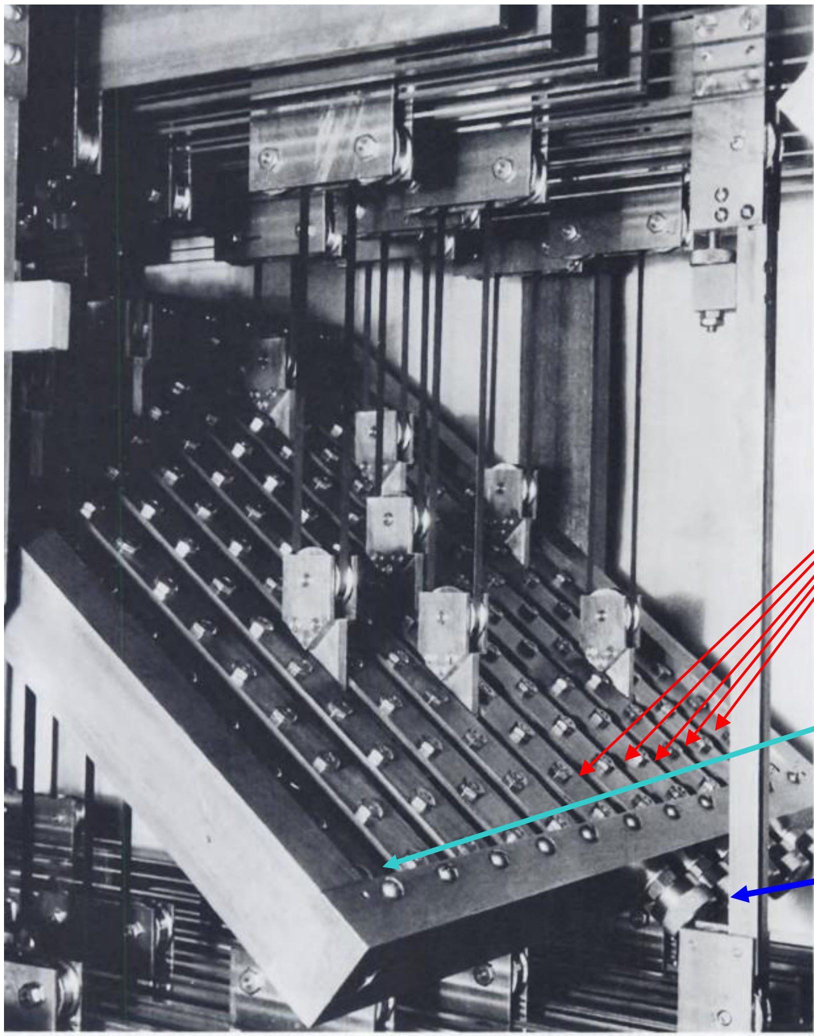


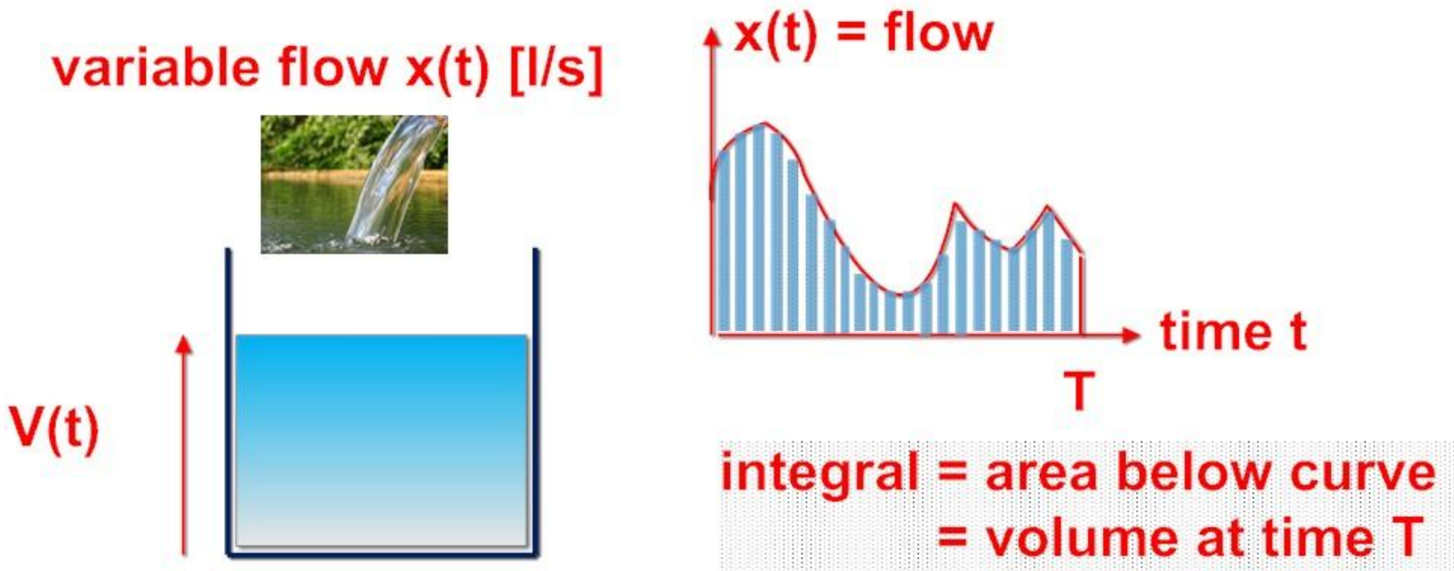
Figure 12. The detail shows one of the plates with some of its nearly 1000 pulleys leading the steel tape. Above and below some of them can be shifted horizontally. Notice the controlling knobs at the plate. (Photo MIT Museum)

9 slots: one for each variable

10^{th} slot to read sin(angle)

Micrometer screw to move the pulley (set the coefficient)

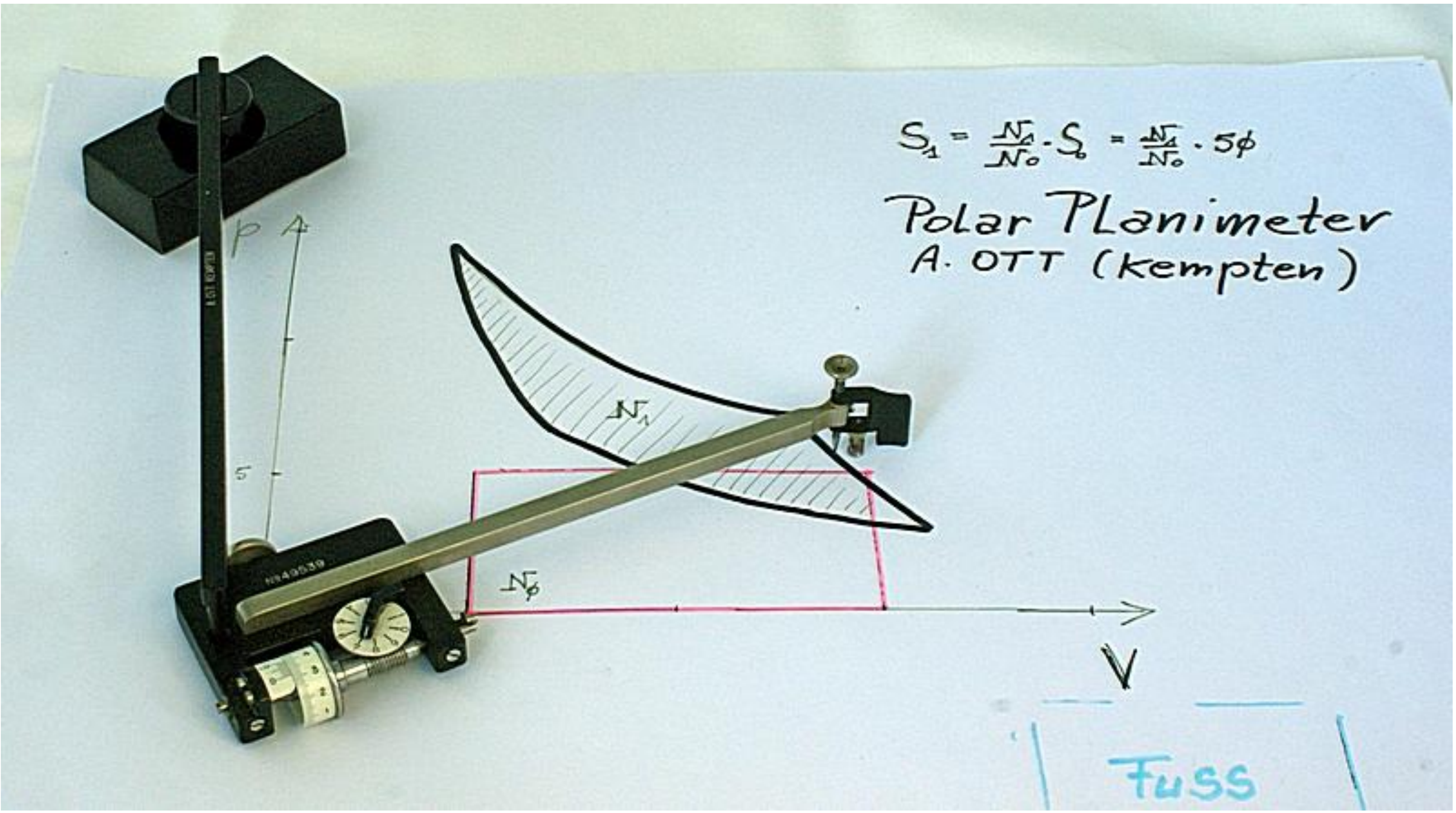
What is an integral?



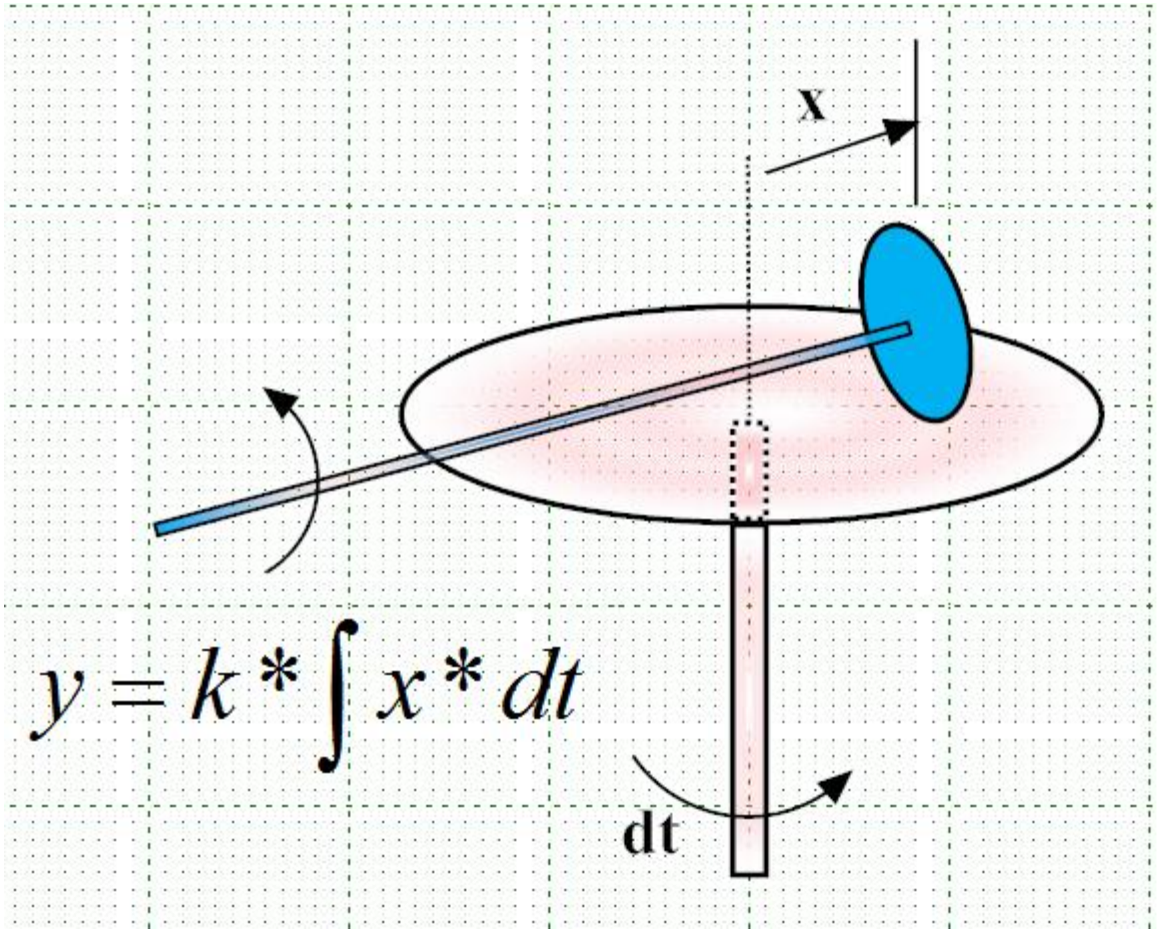
$$V = k * \int_{0}^{T} x(t) * dt$$

Integrators: planimeter

Made from approx. 1850 - 1970



Integrators: disc type

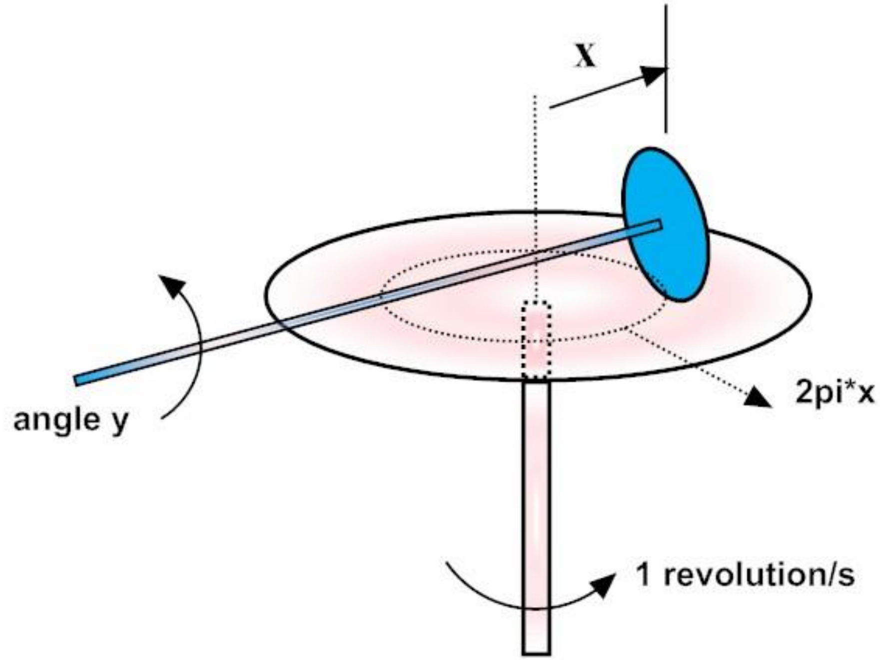


The Kelvin disc integrator

usually roughened glass disc

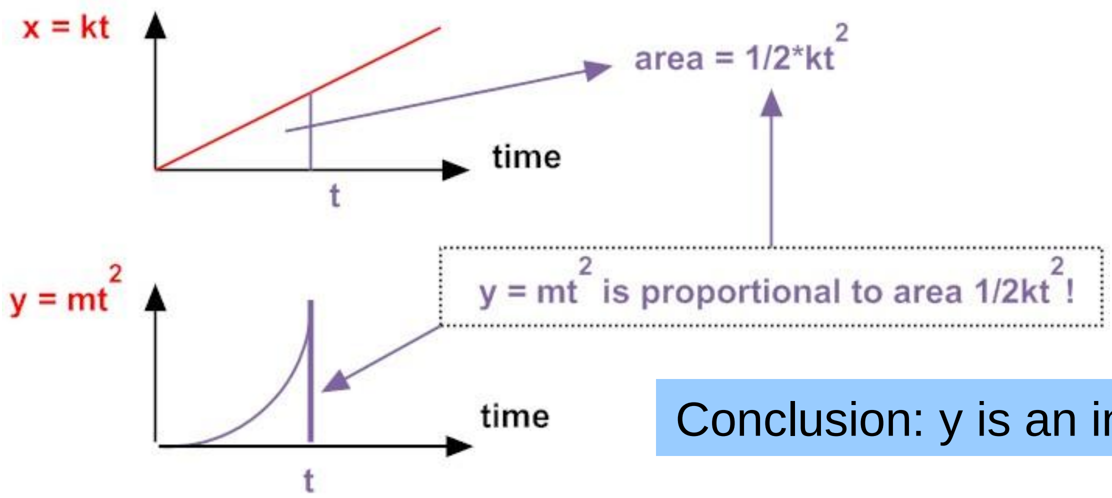
If x increases linearly in time, y increases proportional to the square of time.

“Proof”



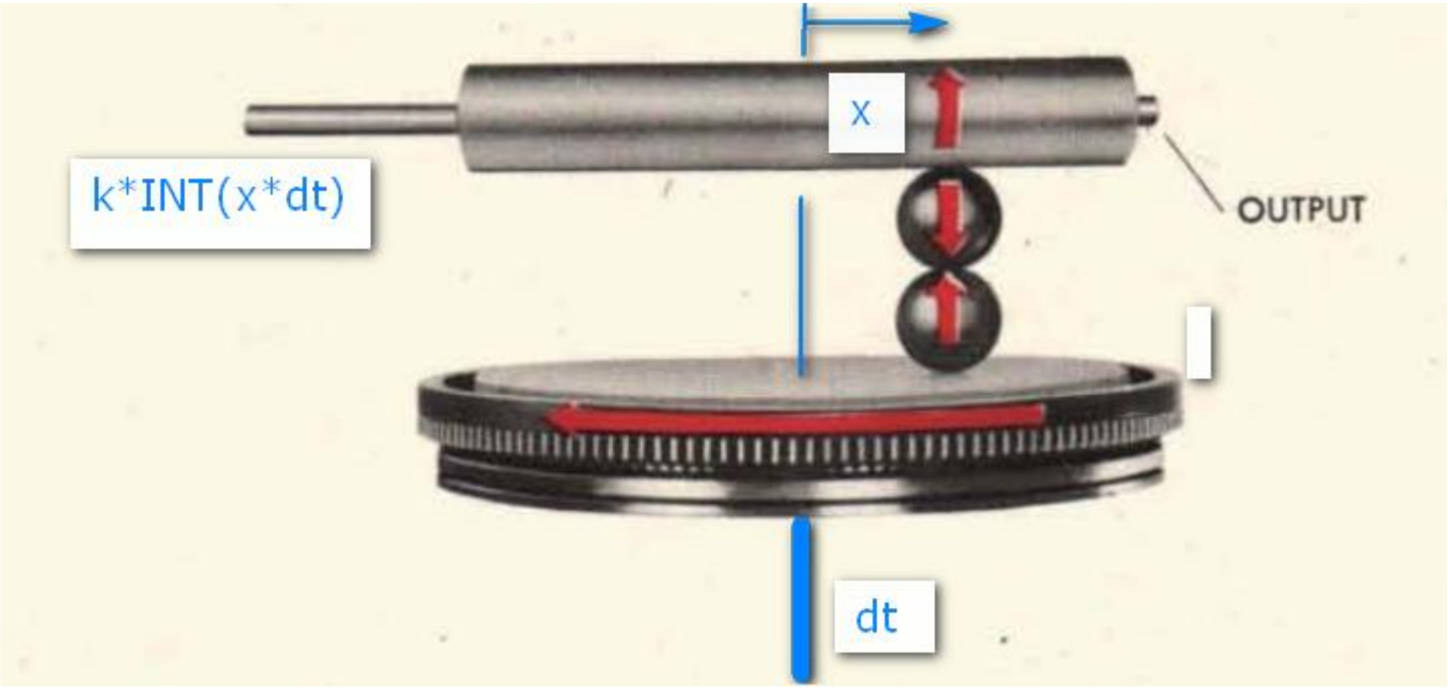
1. In 1 second angle y = (2pi*x/2pi*r)*2pi = (x/r)*2pi [r = radius of small disk]
2. In t seconds angle y = (x/r)*2pi*t
3. If x increases linearly with t: x = k*t and y =kt/r*2pi*t = 2pi*k/r*t^2 = m*t^2

so y = m* t^2



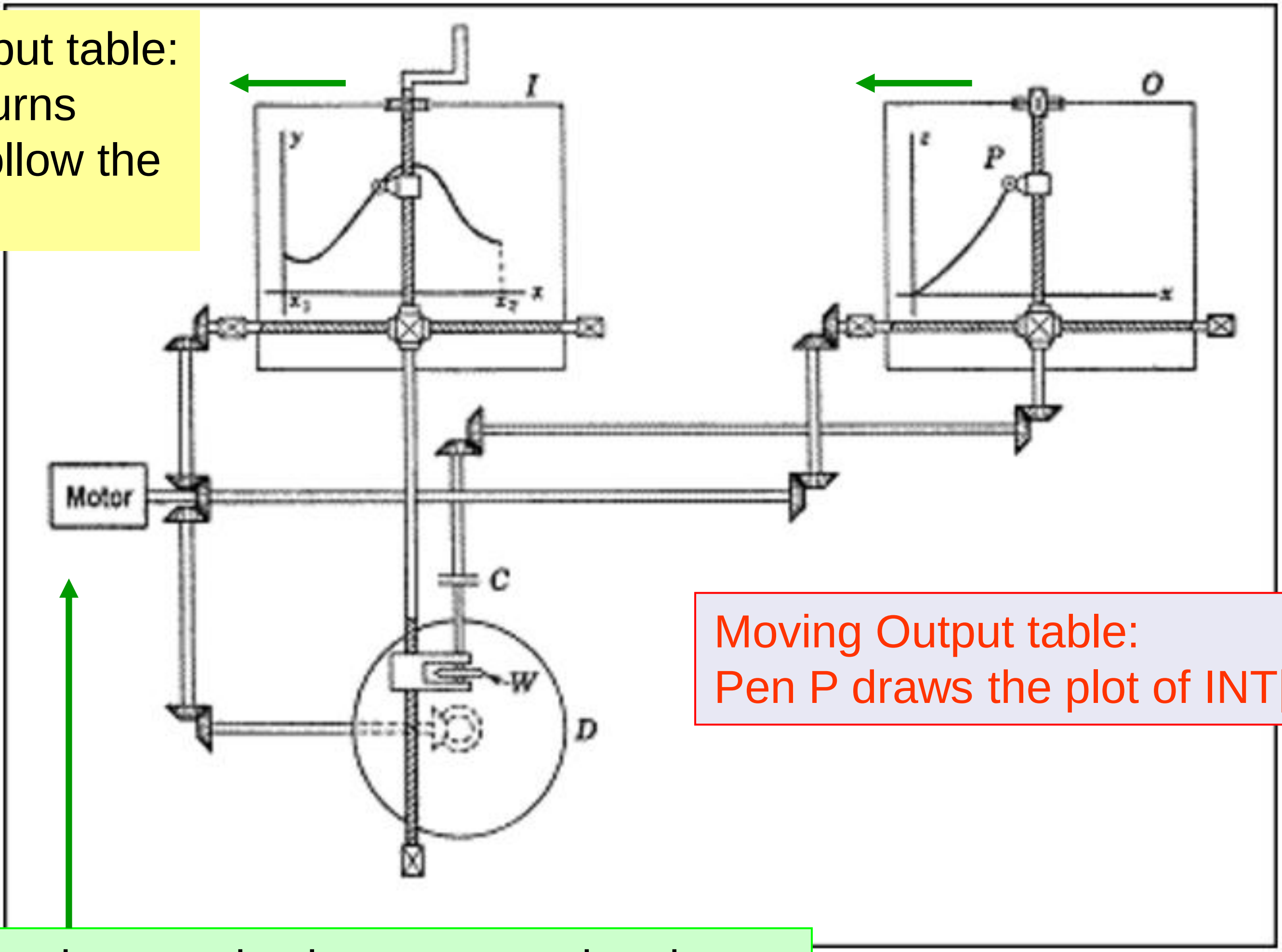
Conclusion: y is an integral

Integrator: roller type



Example of an integration

Moving Input table: operator turns crank to follow the curve f(t)

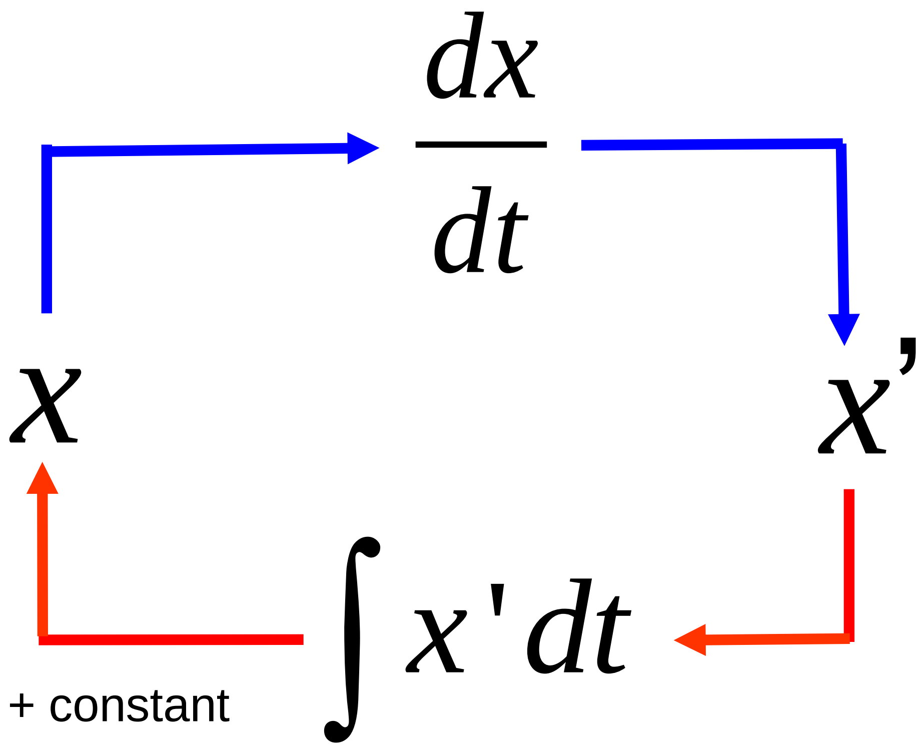


Moving Output table:
Pen P draws the plot of INT[f(t)]

Motor gives time t: spins integrator and makes progression on the horizontal axis of the tables

Integration and differentiation

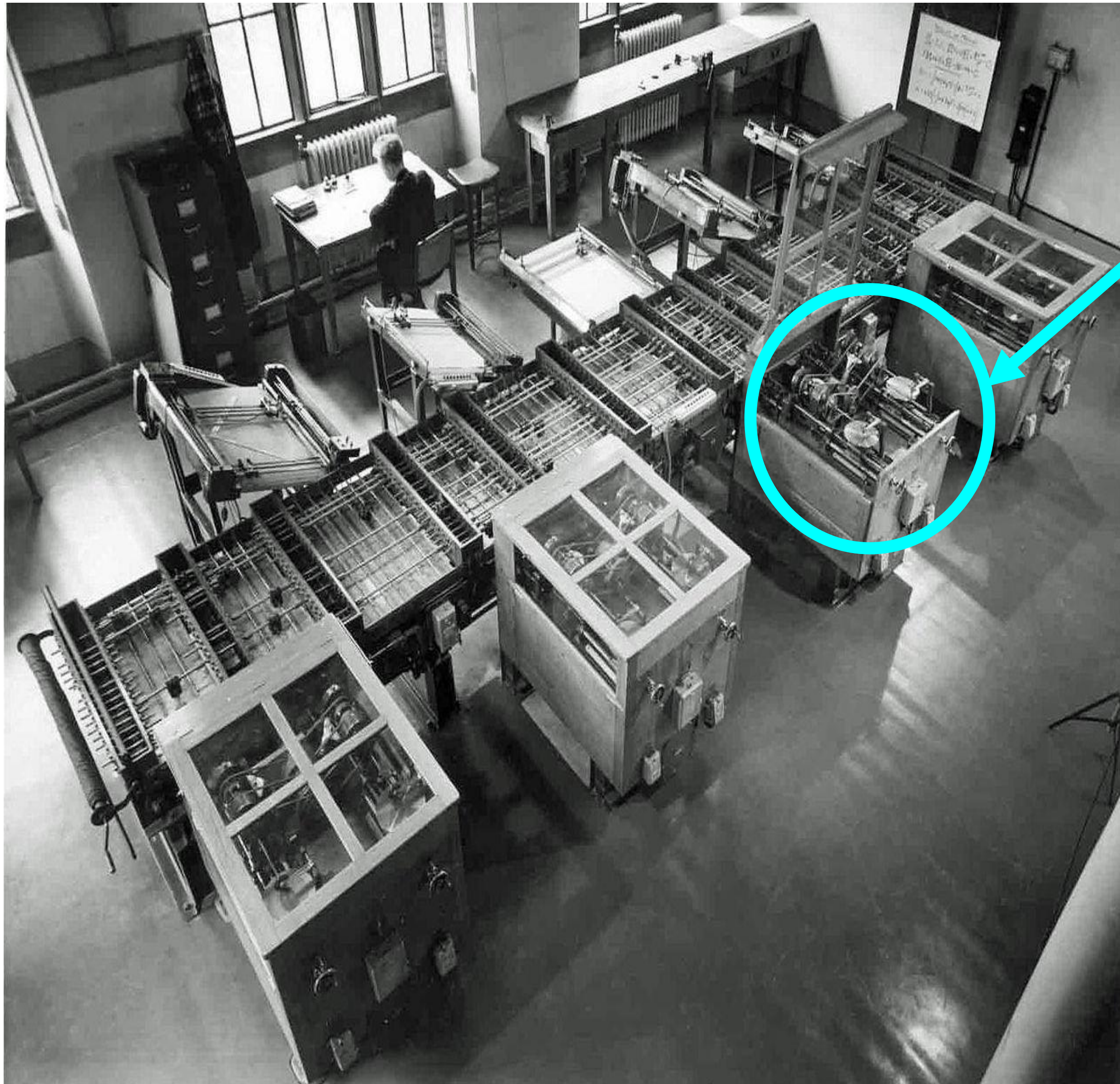
x(t) is a function of time



Differentiation (derivation) and integration are inverse operations.

Differential analysers use integrators to solve differential equations, i.e. equations containing derivatives.

Differential analyser (1)



Solving differential equations by integration:

1. Vannevar Bush, MIT, 1931
2. Rebuilt using Meccano elements by Douglas Hartree & Arthur Porter, Manchester Uni, 1934.

Differential analyser (2)

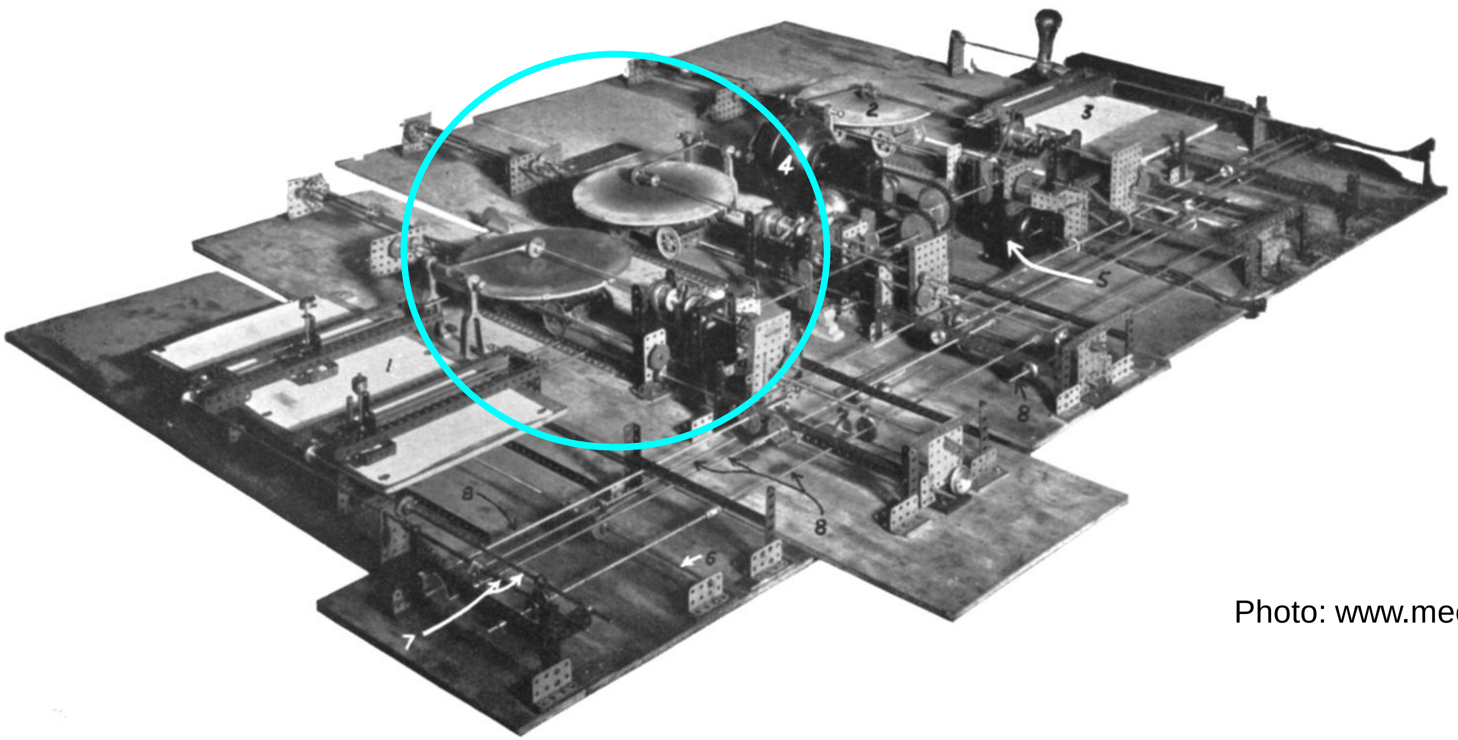


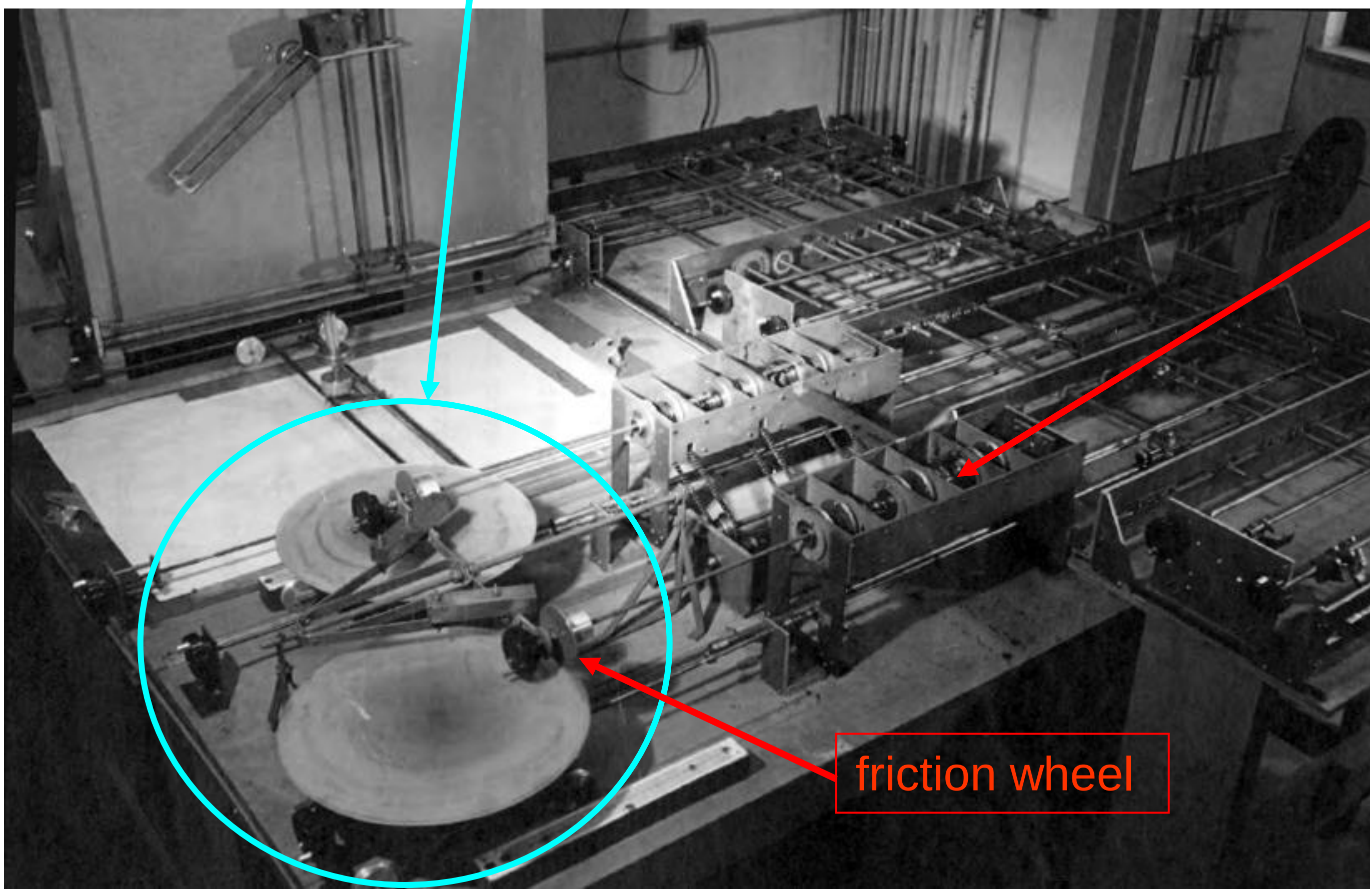
Photo: www.meccano.us

The 4th integrator module of the Hartree-Porter D-A.

The Meccano D-A was probably used by Dr. Barnes Wallis to solve the “bouncing bomb” problem.
(WWII 1943, operation “Chastise” = bombing of Ruhr dams,)

Differential analyser (3)

disc integrators (here the large discs move, the absolute position of the friction wheels does not change)



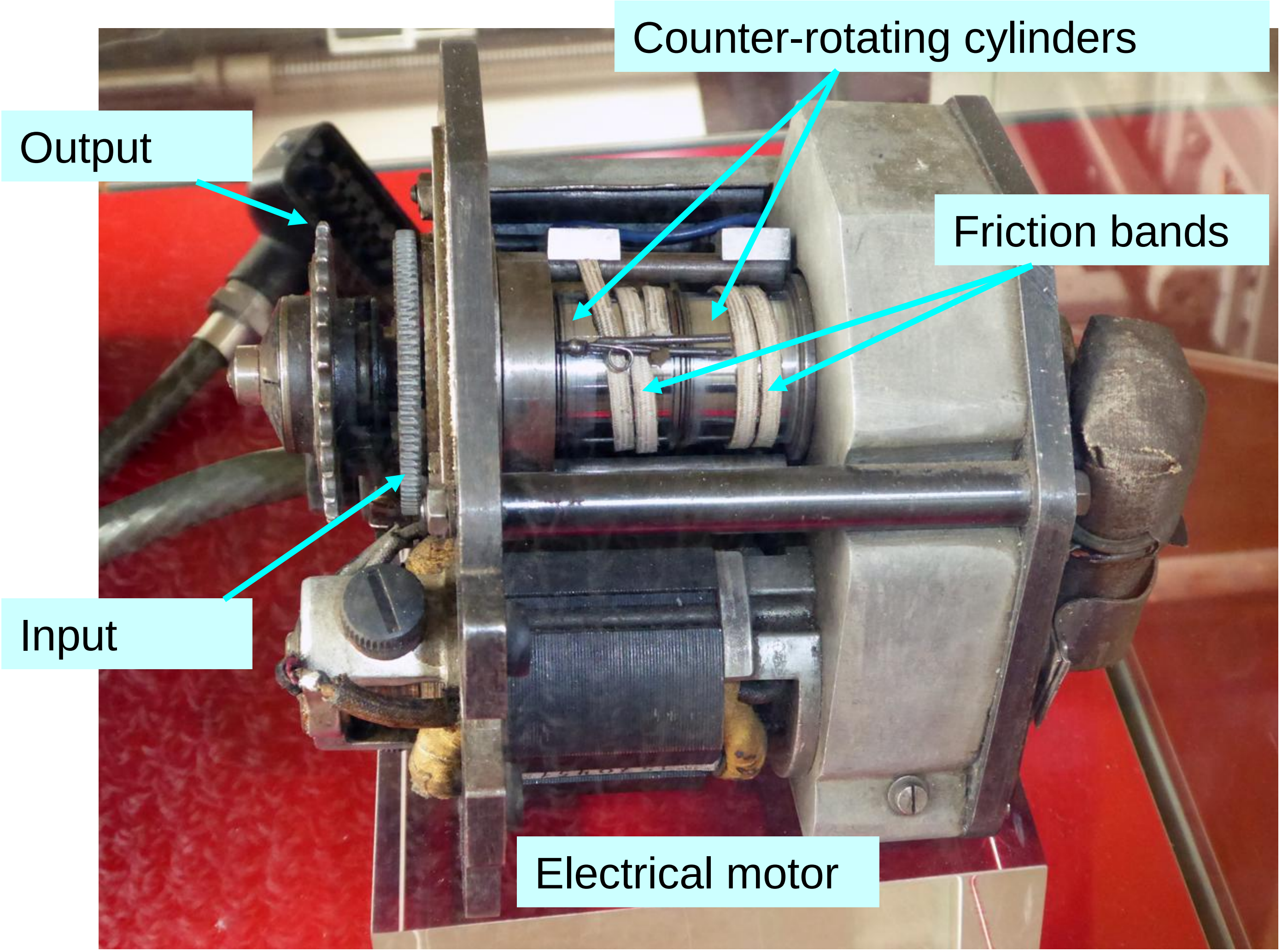
torque amplifier

J.E.Kaspar thesis 1955

Iowa State University

Differential analyser (4)

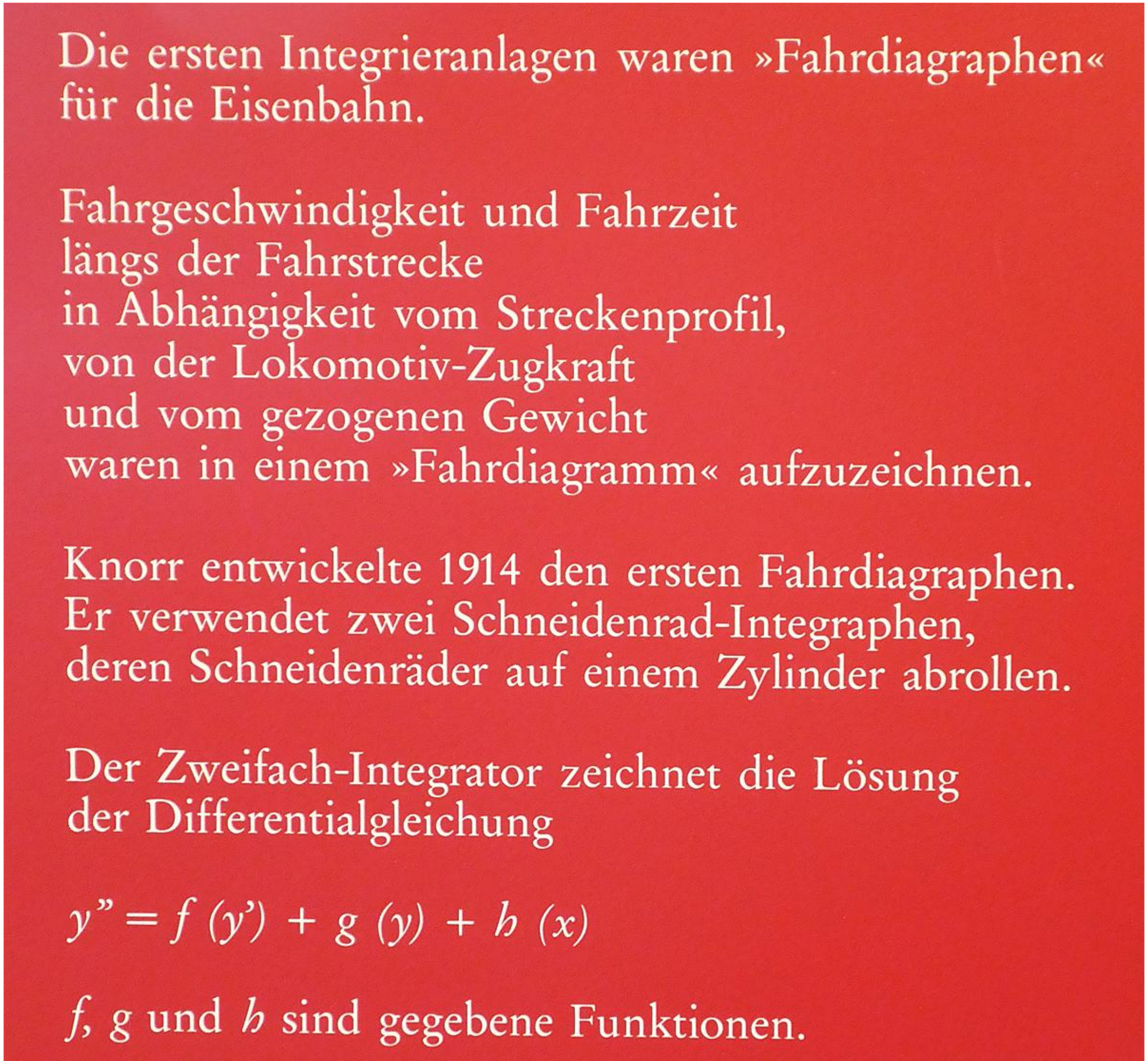
Torque amplifier (Drehmoment-Verstärker)



Invented by H.W.Nieman, 1925

Photo from Deutsches Museum

Application: train graphs



Die ersten Integrieranlagen waren »Fahrdiagraphen« für die Eisenbahn.

Fahrgeschwindigkeit und Fahrzeit
längs der Fahrstrecke
in Abhängigkeit vom Streckenprofil,
von der Lokomotiv-Zugkraft
und vom gezogenen Gewicht
waren in einem »Fahrdiagramm« aufzuzeichnen.

Knorr entwickelte 1914 den ersten Fahrdiagraphen.
Er verwendet zwei Schneidenrad-Integraphen,
deren Schneidenräder auf einem Zylinder abrollen.

Der Zweifach-Integrator zeichnet die Lösung
der Differentialgleichung

$$y'' = f(y') + g(y) + h(x)$$

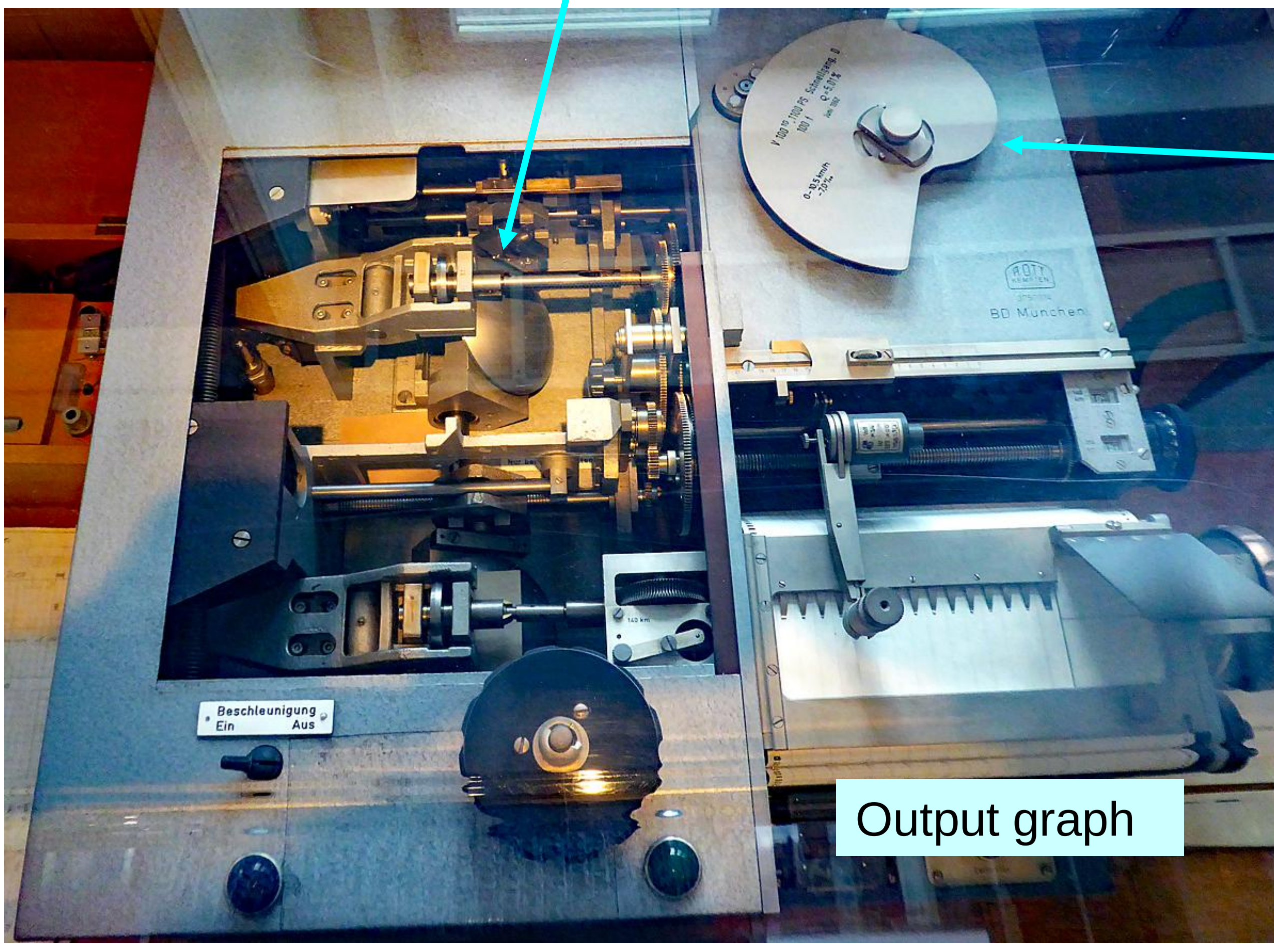
f, g und h sind gegebene Funktionen.

From
Deutsches Museum

Conzen-Ott “Fahrzeitrechner”

Spherical calotte integrator

Function-
generator h(x)

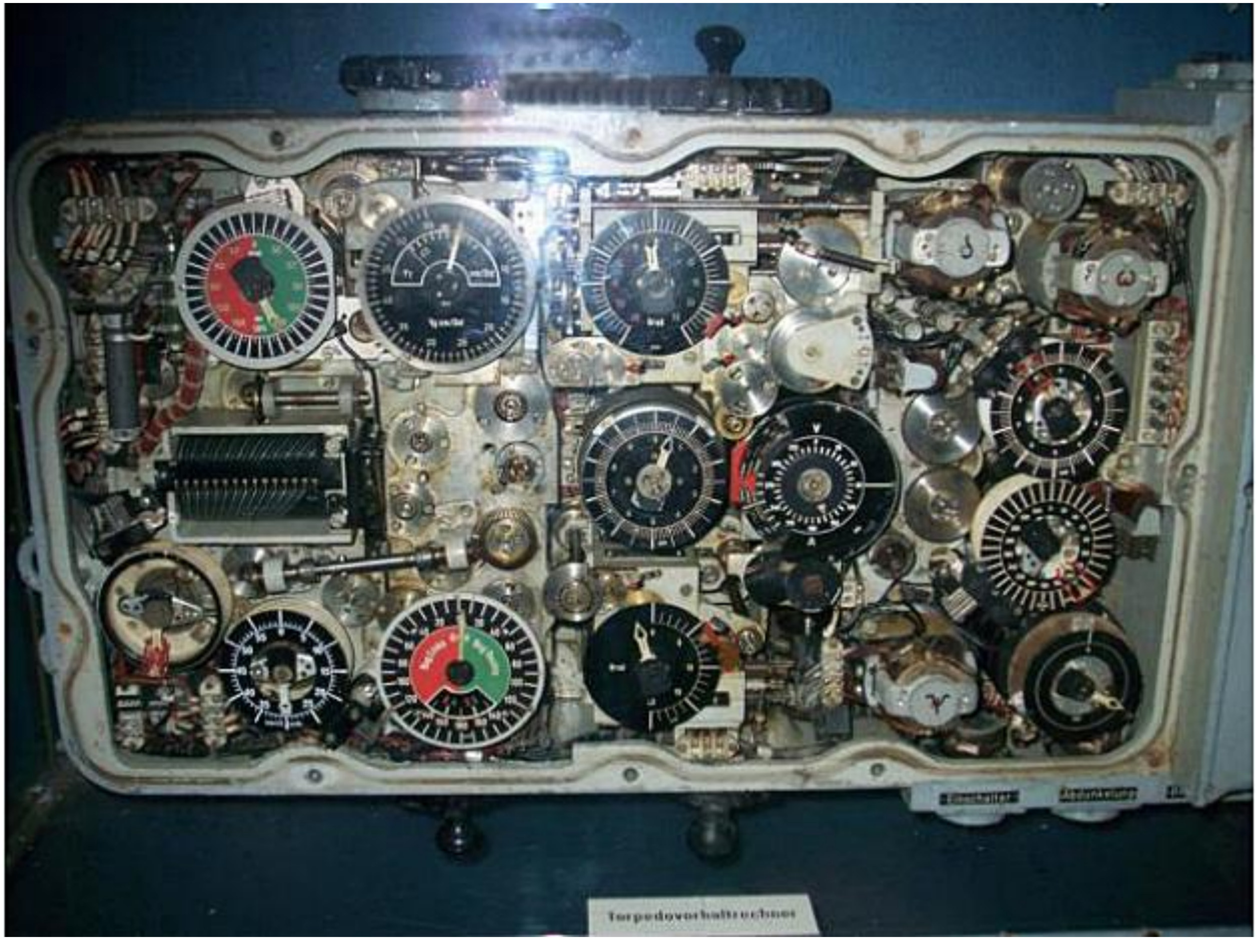


Output graph

Introduced in 1943.
In use at the
Deutsche Bahn
up into the 1980’s.

Photo from
Deutsches Museum

Torpedovorhaltrechner U-995



Thomas Müller: Analogrechner auf deutschen U-Booten des Zweiten Weltkrieges (Dissertation und Taschenbuch, 2015)

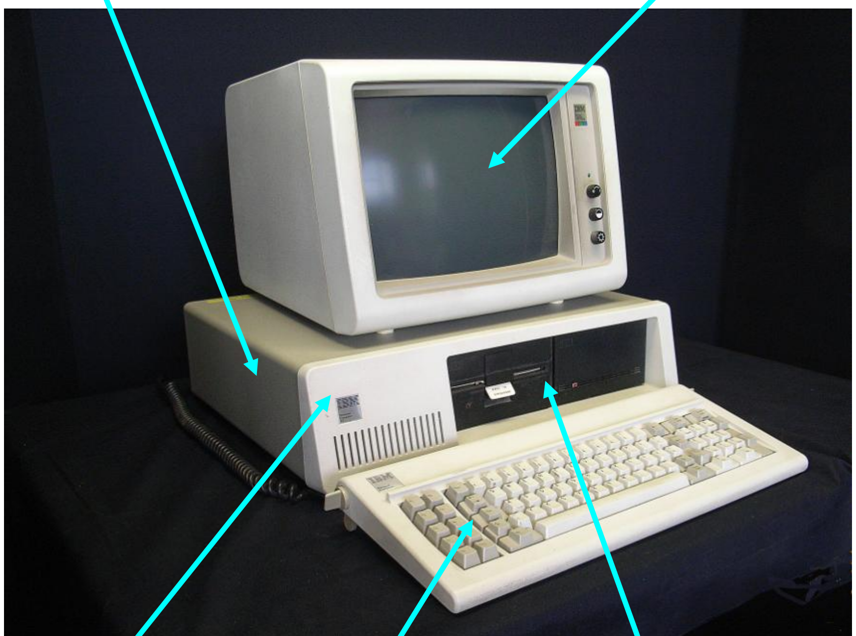
Mark III Torpeda Data Computer

The Mark III was the standard analog computer for torpedo firing and guidance on US submarines in WWII
Google YouTube for
"Torpedo Data Computer (TDC)"

Electronic analog computers

microprocessor

display

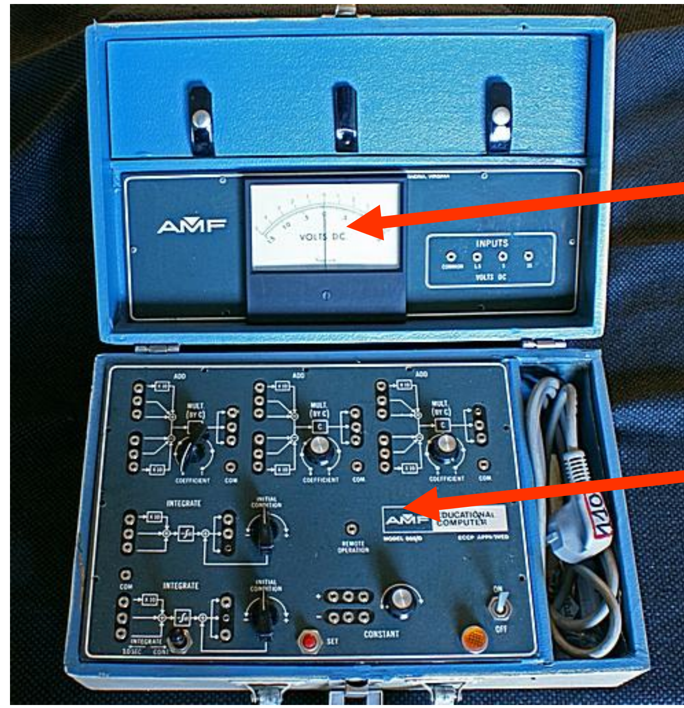


memory

keyboard

storage

Digital computer (IBM XT, 1981)



output

input

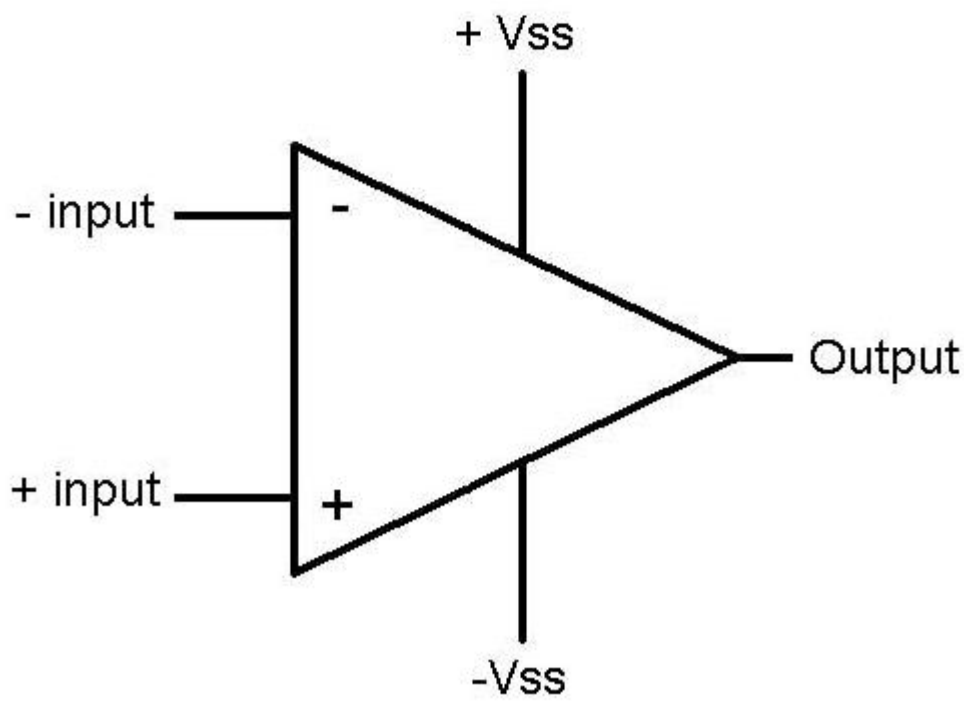
no microprocessor, **no** display

no memory, **no** keyboard,

no storage

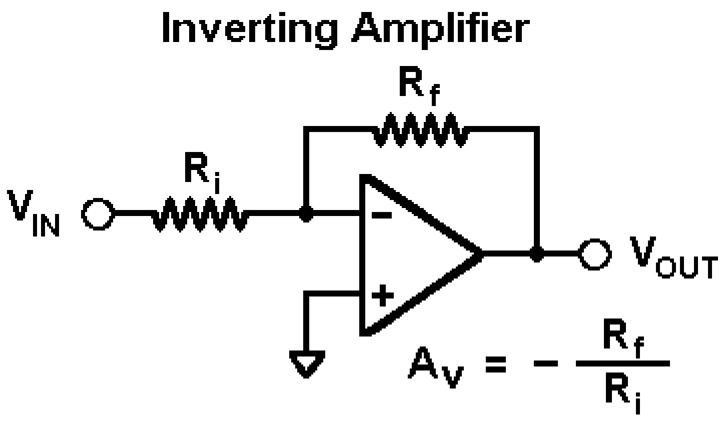
Analog computer (AMF, 1970)

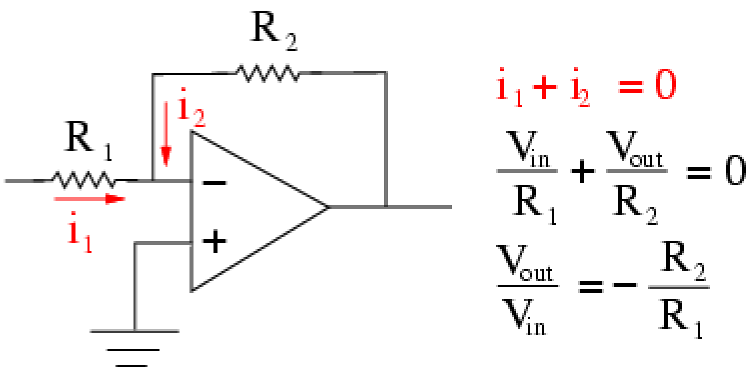
One fundamental component: the Operation Amplifier (OA)



- **Voltage amplifier** with very high gain (typ. 100000 to 1000000)
- usually –input is used, output voltage is inverted
- input current virtually 0
- two supply voltages Vss, typical +15 and -15 VDC

OA is an inverting amplifier



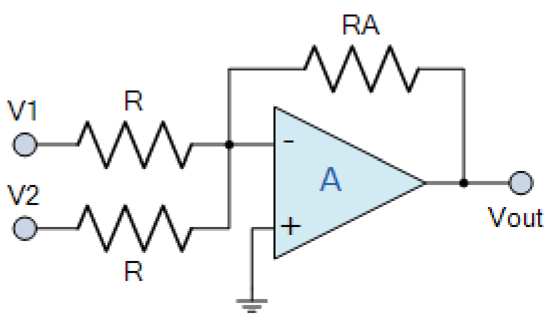


Vout = -k*Vin

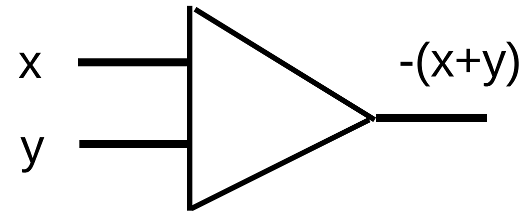
Current i_i ~0 mA

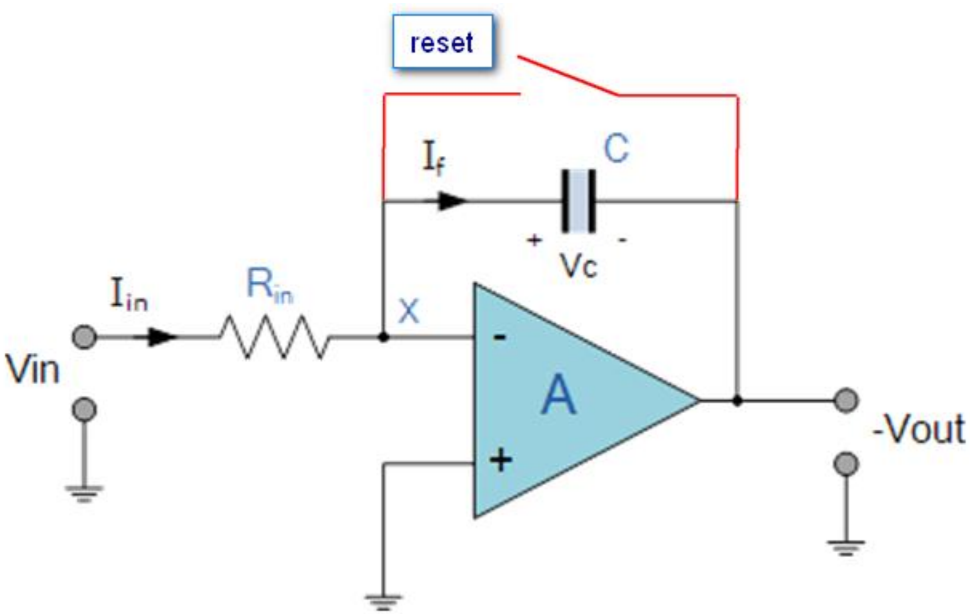
OA circuits: adder, integrator

Vout = -k*(V1+V2)



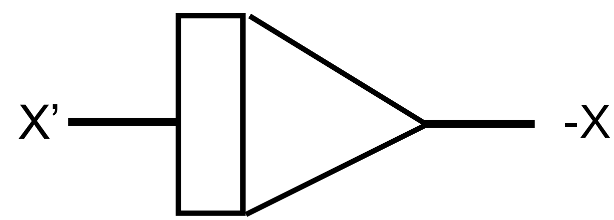
$$\text{Vout} = -\frac{RA}{R}(V1 + V2)$$



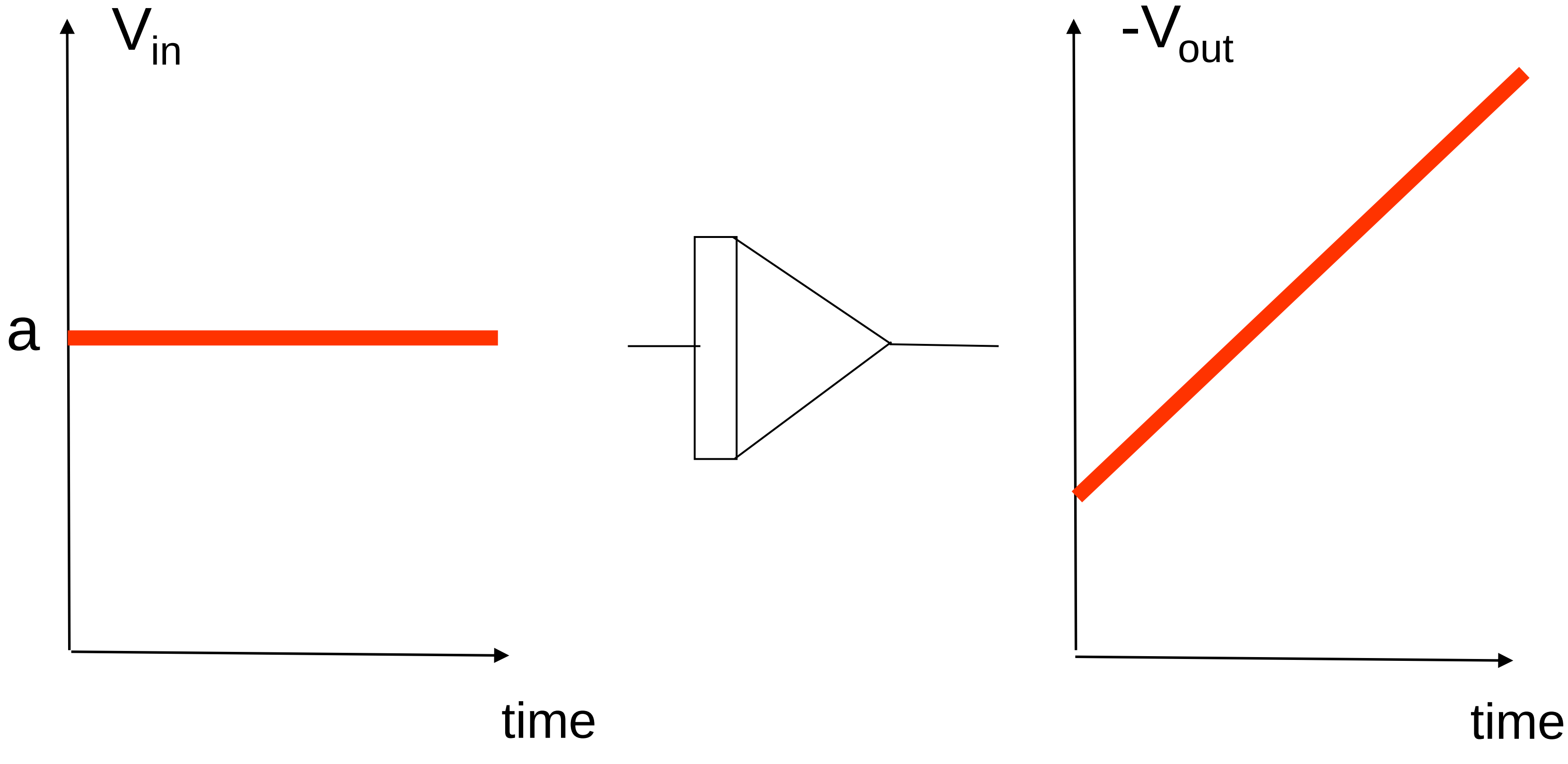


$$V_{out} = -k * \int_0^t V_{in} * dt$$

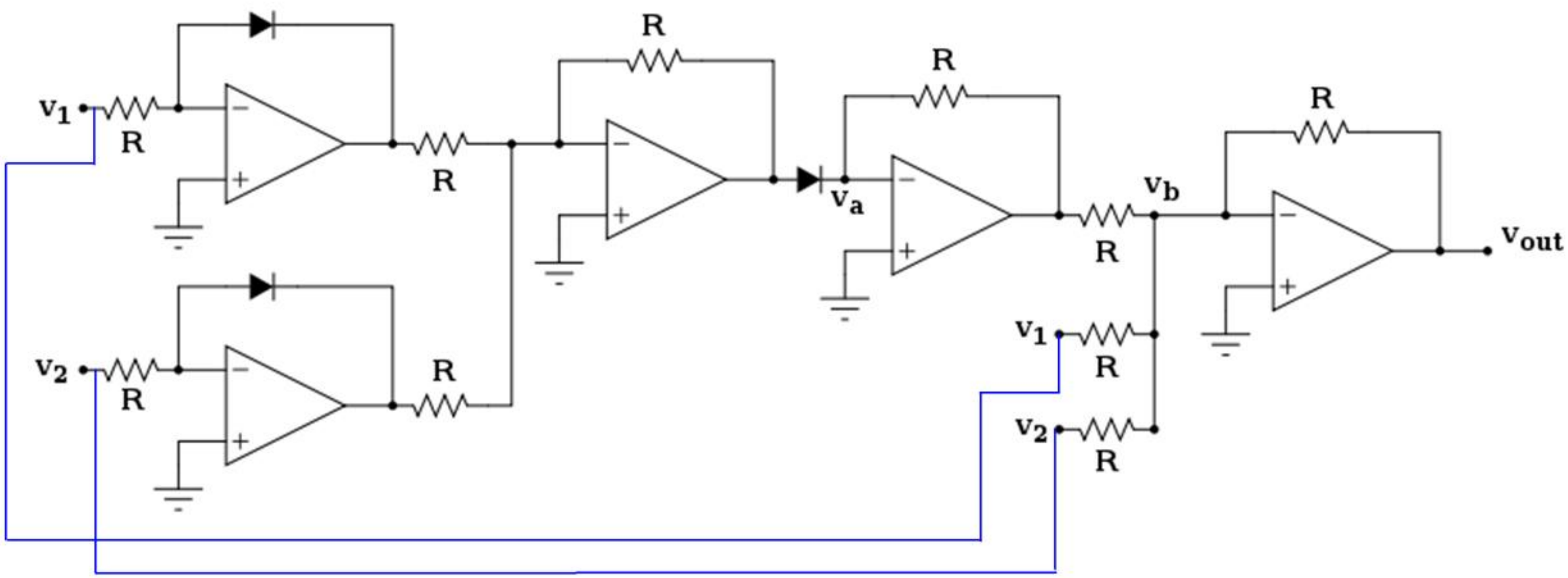
k =1/ (R_{in}*C)



Example of integration

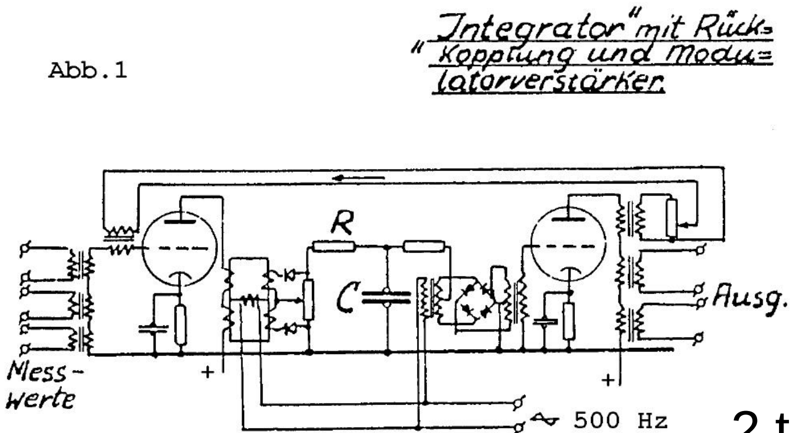


OA circuits: multiplier

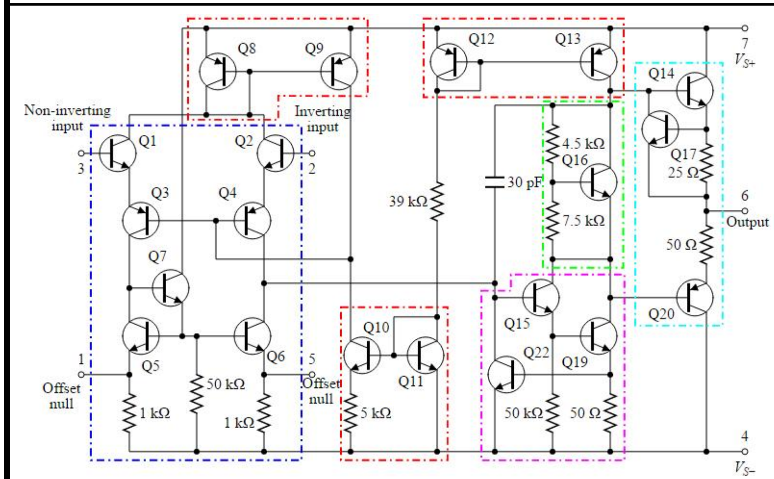
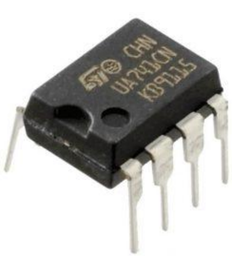


$$V_{out} = -k*(V_1*V_2)$$

History of OA's (1)

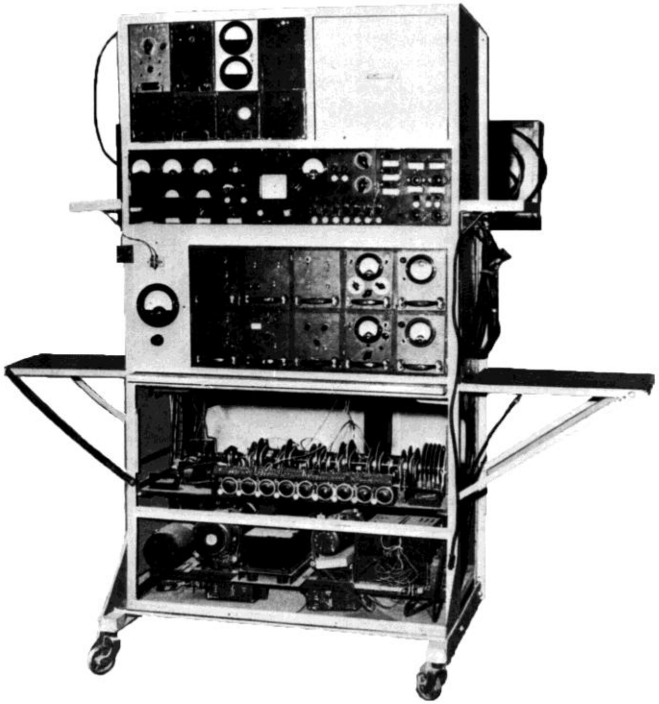
 2 triodes	Helmut Hoelzer, Peenemünde, 1941 Germany
 1 dual triode 1 pentode/triode	K2-GW first commercial OA G.A. Philbrick, 1952 USA

History of OA's (2)

uA702 Fairchild Semiconductors 1964, USA first IC Opamp	uA709 Fairchild Semiconductors 1965, USA uA741 Fairchild Semiconductors 1965, USA
	uA741 most successful OA of all times! 

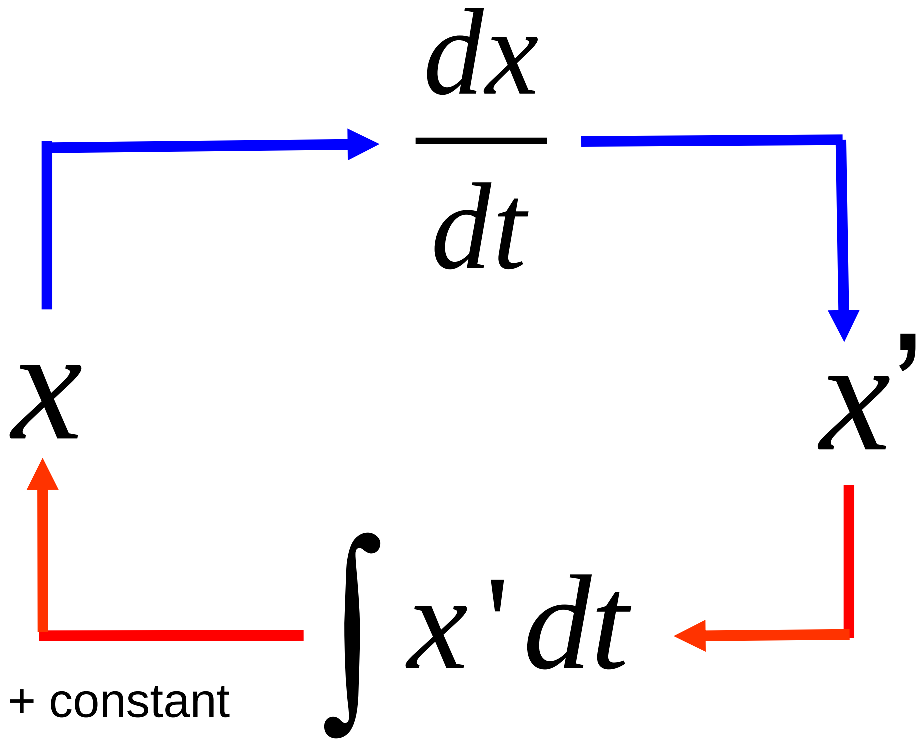
Helmut Hoelzer (1912-1996)

- Works at Peenemünde with Wernher von Braun on the A-4 rocket (V2 = “Vergeltungswaffe” 2)
- Invented and built in 1941 the first electronic analog computer
- Invented and built the “Mischgerät” for guiding the V2
- After WWII emigrated to the USA; worked on rockets and related mathematics (Marshall Space Flight Center).



Remember:

Differentiation (derivation) and integration are inverse operations



One of the V2 problems

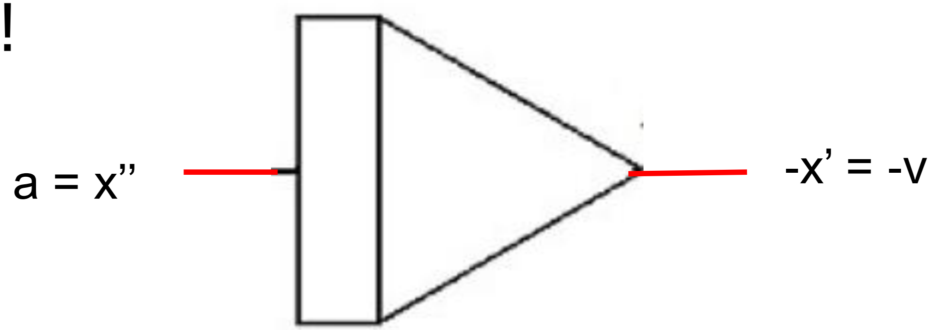
- How to measure the absolute speed?

- Hoelzer's idea: acceleration is easy to measure; speed is the integral of acceleration, so invent an integrator!

$$v = \frac{dx}{dt} = x'$$

$$a = \frac{d^2x}{dt^2} = \frac{dx'}{dt} = \frac{dv}{dt}$$

$$v = \int a * dt$$



Another V2 problem: steering

	Jet spoilers (“Strahlruder”, graphite pads) used during lift-off when speed is low or later outside the atmosphere.
	Fin spoilers (“Flügelruder”) used at higher speeds in lower atmosphere.

V2: gyro and Mischgerät

	One of the two gyroscopes of the V2 (pitch and roll control for lateral stabilization)
	Hoelzer’s “Mischgerät” = analog guidance computer of the V2; located in the head of the rocket. It takes signals from the gyroscopes and acceleration sensors, commands the two types of spoilers and stops the engine at speed v.
	V2 at White Sands Proving Grounds Museum (New Mexico). The rocket has a length of ~14m. The engine runs for about 1 minute (ethanol and oxygen), the top of the trajectory is ~90 km.

V2 launch at White Sands

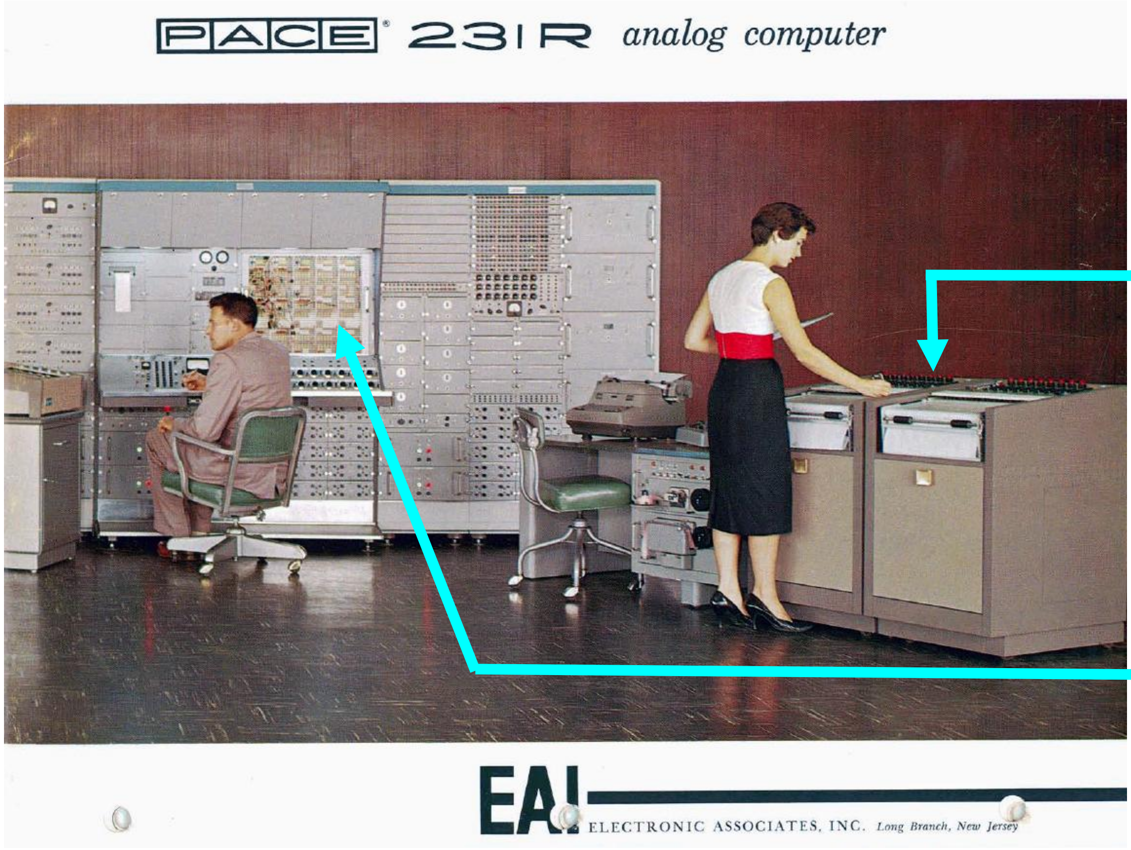
Launch at White Sands of one of the many V2 taken back to the USA. Probably ~1946.

Analog (electronic) computer

- Uses a model of the process to be solved. Variable structure, depending on program!
- Application: process control and simulation: chemical and nuclear reactors, flight, fluid flow, epidemics…
- Mostly used from 1950 to about 1970's
- Works in real time and in parallel, up to 100000 times faster than the first digital computers

Some examples of analog computer manufacturers

EAI (Electronic Associates Incorporated, New Jersey, USA, *1945)
European headquarter in Brussels. First analog computer in 1952.



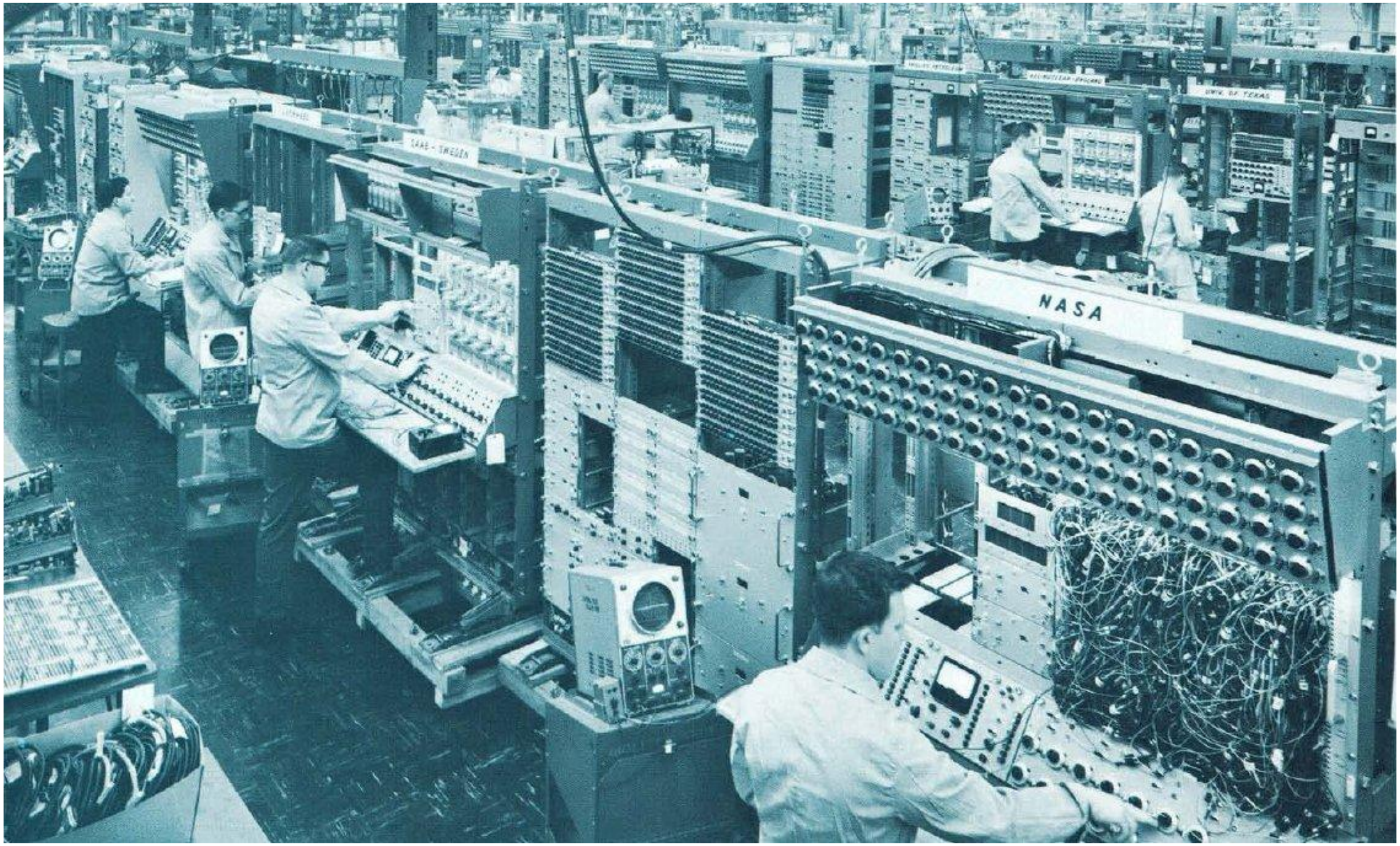
EAI (Pace) 231R Computer, 1961

Plotter for output

Pierre DAVID, a former LCD student, worked at EAI, Brussels.

Patch panel for programming

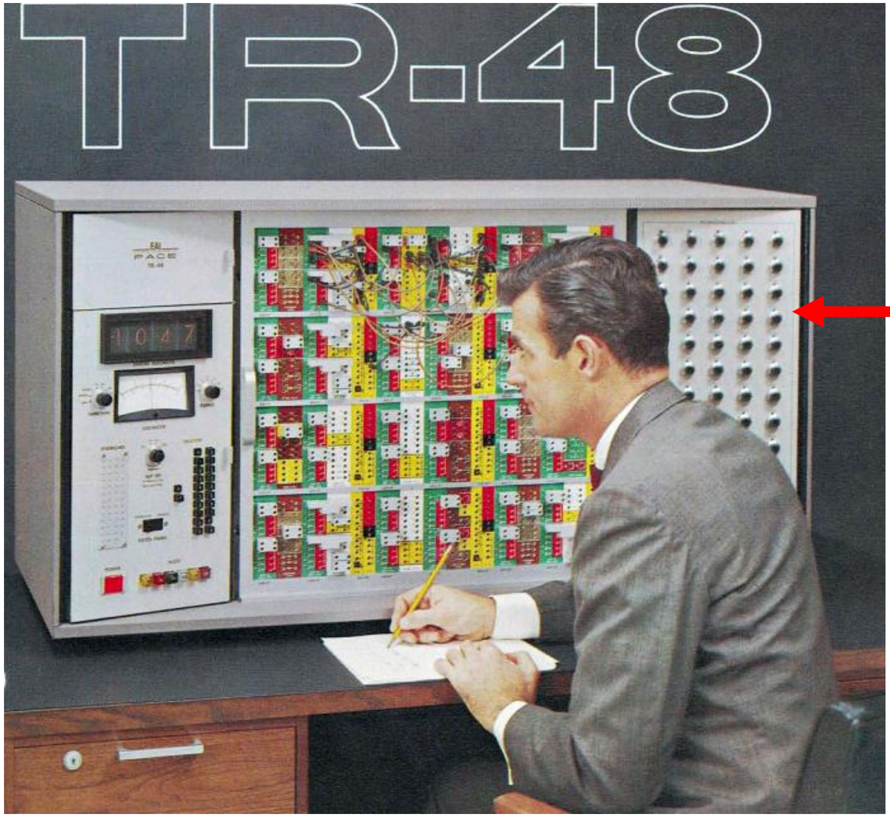
EAI analog computers (2)



Assembly line

http://www.joostrekveld.net

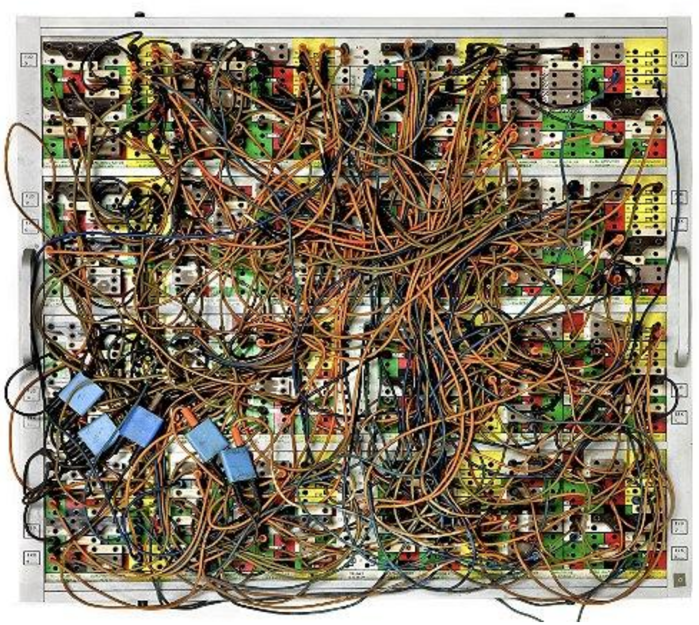
EAI analog computers (3)

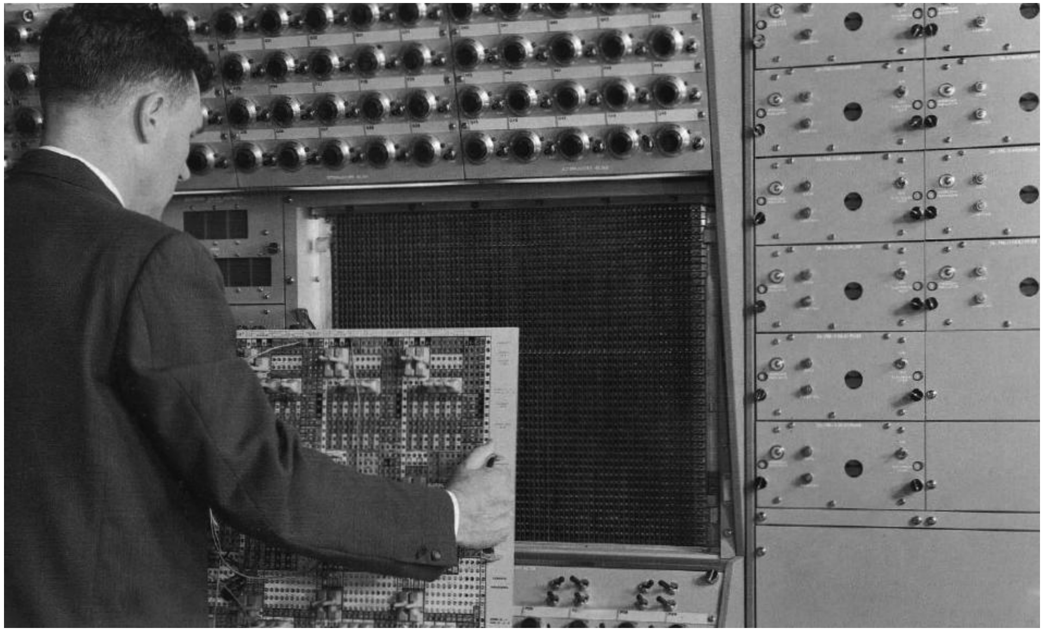


EAI (Pace) TR-48
desktop computer
1962

The potentiometers are used to define the various parameters of the model. Correctly calculating the settings was one of the big difficulties of the analog computers.

EAI analog computers (4)





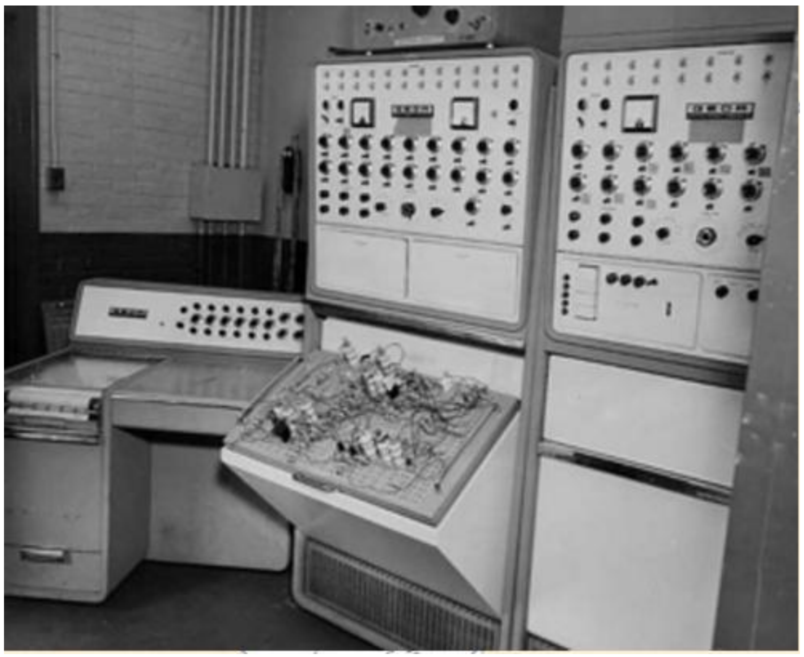
The spaghetti wiring of a patch panel. Bigger computers often had removable panels for storing the wired programs (right: EAI Pace 231R)

EAI analog computers (5)

EAI HIDAC2400
Hybrid computer, 1963.

Analog hybrid computers were a mix of both worlds. The digital part allowed for instance to calculate the setting of the potentiometers and often to set them automatically by servo-motors.

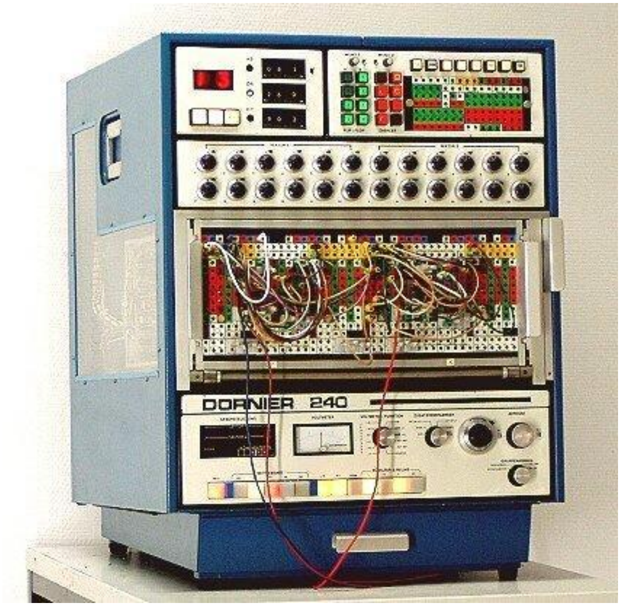
Goodyear analog computers



Goodyear Aerospace Corp. developed a range of analog computers called GEDA =
Goodyear **E**lectronic **D**ifferential **A**nalyzer

This model is from 1953.

Dornier analog computers



The aircraft constructor DORNIER (DE) started building analog computers to solve the problems related to VTOL planes (DO-31 E3, first flight 1967)

Dornier DO-240
analog computer (~1970)

(www.technikum29.de)

Telefunken analog computers (1)

Two oscilloscopes to visualize the results

Telefunken RA-1
First analog computer built by Telefunken in 1955.

(photo Prof. Bernd Ulmann)

Telefunken analog computers (2)

Telefunken RA-770

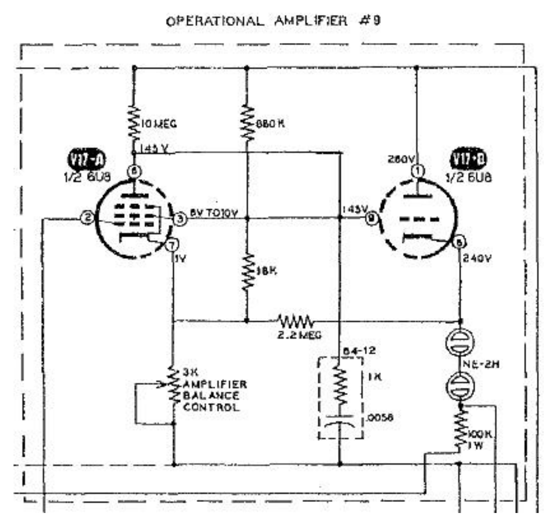
A very precise analog computer (precision 10^{-4}, weight 550 kg).

Used at the Forschungs-zentrum Jülich for nuclear research.

(photo Prof. Bernd Ulmann)

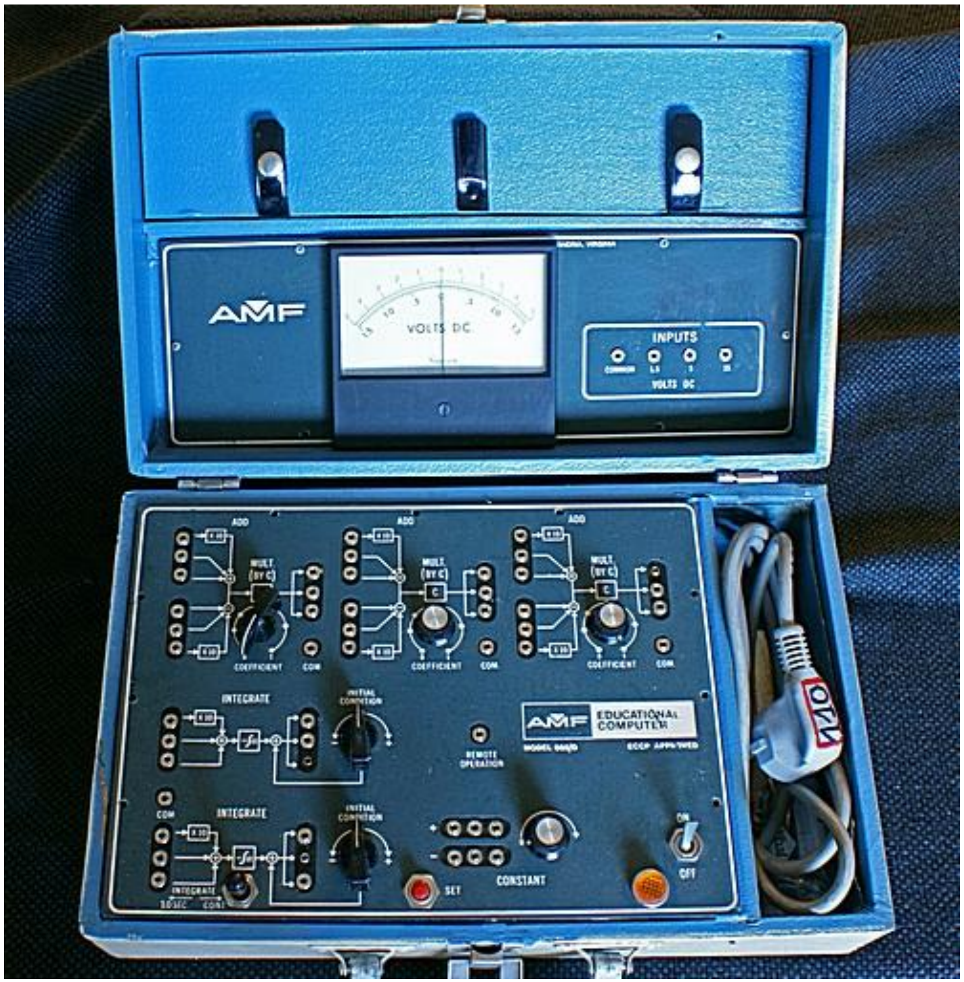
analog computers (1)

Heathkit EC-1
Educational computer
1961, 9 OA with tubes



The R,C components to define the function (adder, integrator,…) must be added on the front-plane. Precision and stability are modest.

analog computers (2)



AMF
(American Machine and Foundry: bowling, bicycles, tennis rackets, nuclear reactors for research…)

AMF 665/D educational computer from 1970.

OA = u741

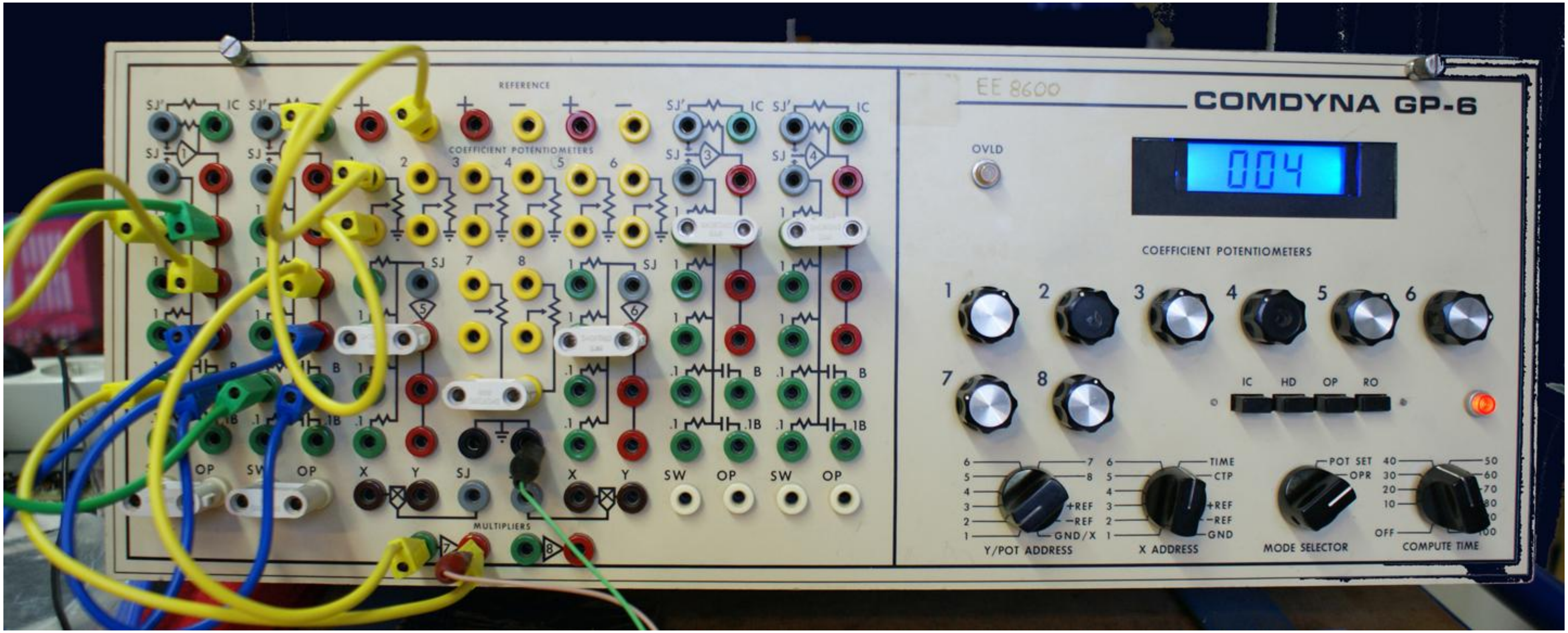
2 integrators, 3 adders

(donated by AALCD).

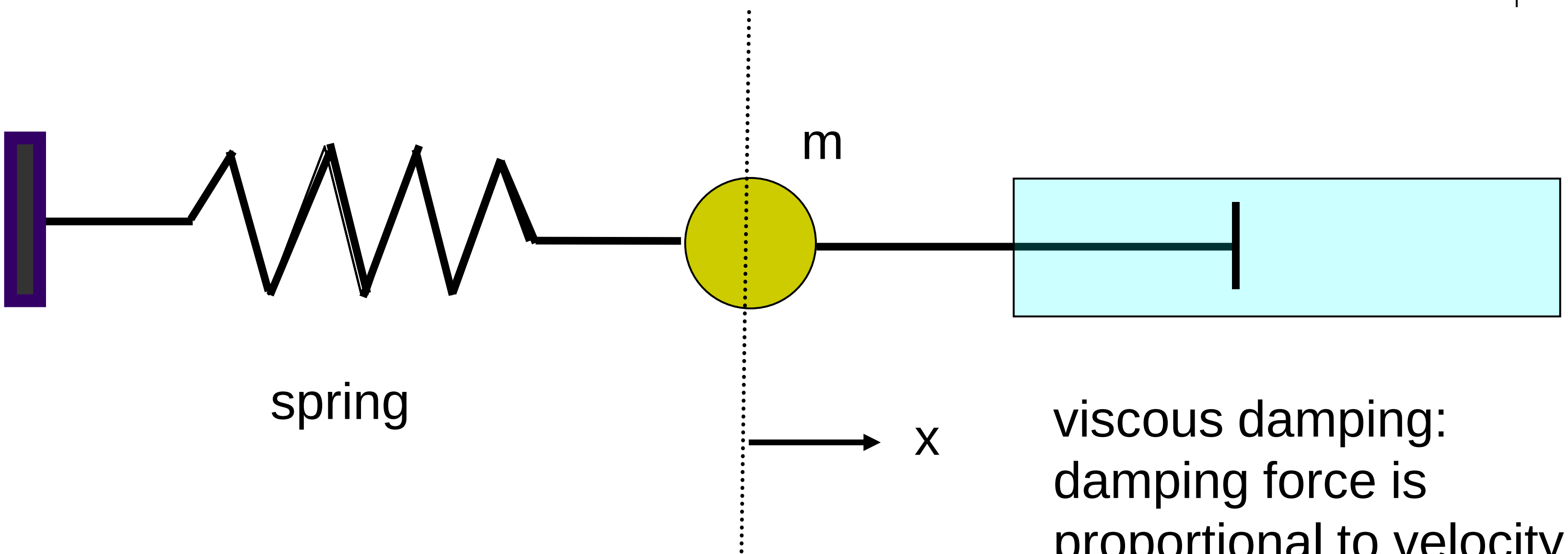
analog computers (3)

COMDYNA GP-6

6 integrators, 2 multipliers, 2 inverters. Built from 1968 to 2004. OA = u741.
Comdyna founder is Ray Spiess, a former EAI engineer.
This specimen comes from the University of Wisconsin (donated by AALCD).



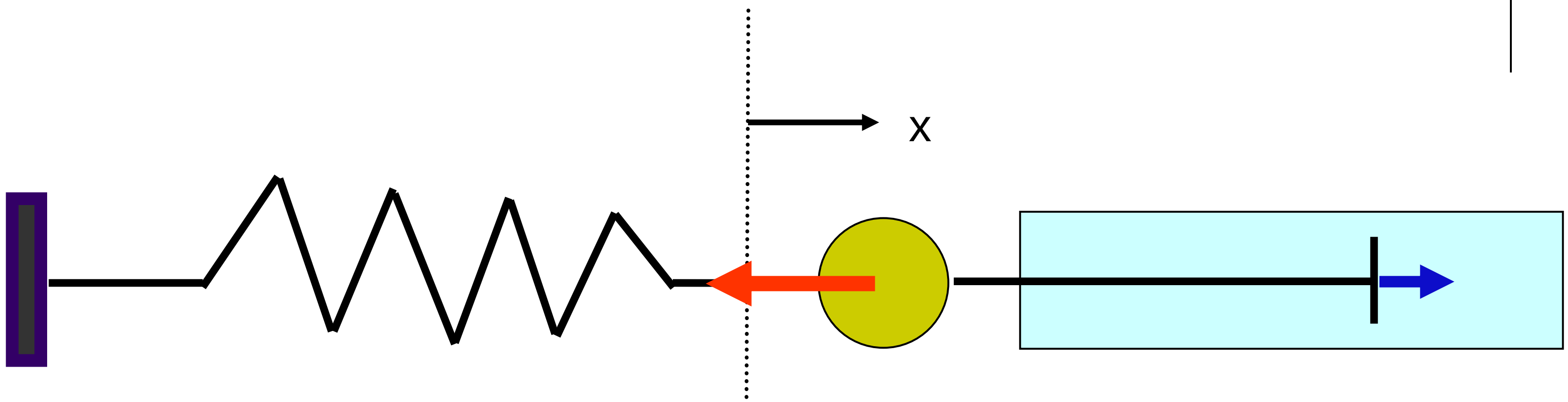
Solving the damped oscillator problem (1)



viscous damping: damping force is proportional to velocity

To solve this problem we need a model!

Solving the damped oscillator problem (2)



Spring force = $-k*x$ damping force = $-d*v = -d*x'$

Total force = $-k*x - d*x'$

Newton: Total force = $m*a = m*x''$ → $m*x'' = -d*x' - k*x$

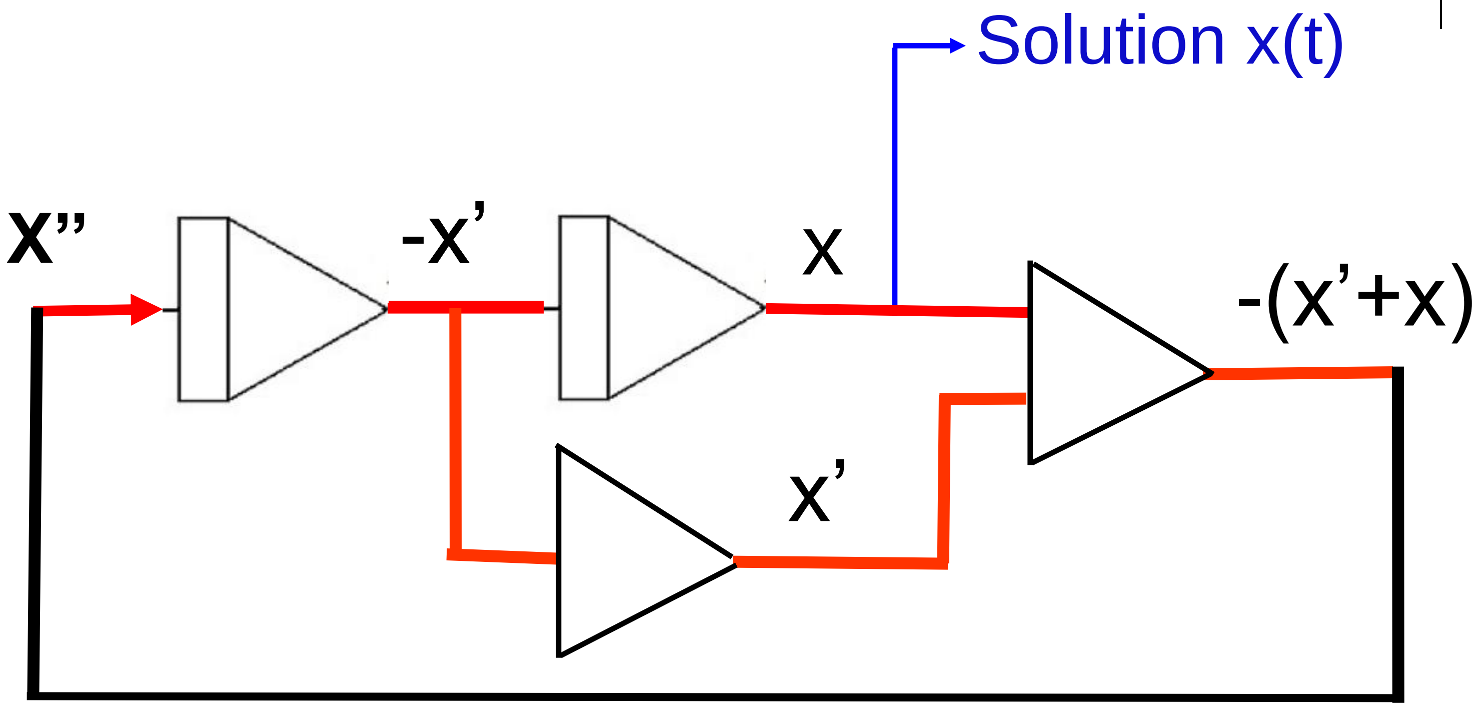
For simplicity: $m = d = k = 1$: $\boxed{x'' = -x' - x}$

this is the model!

x(t) is the solution to find…

Wiring for analog computer

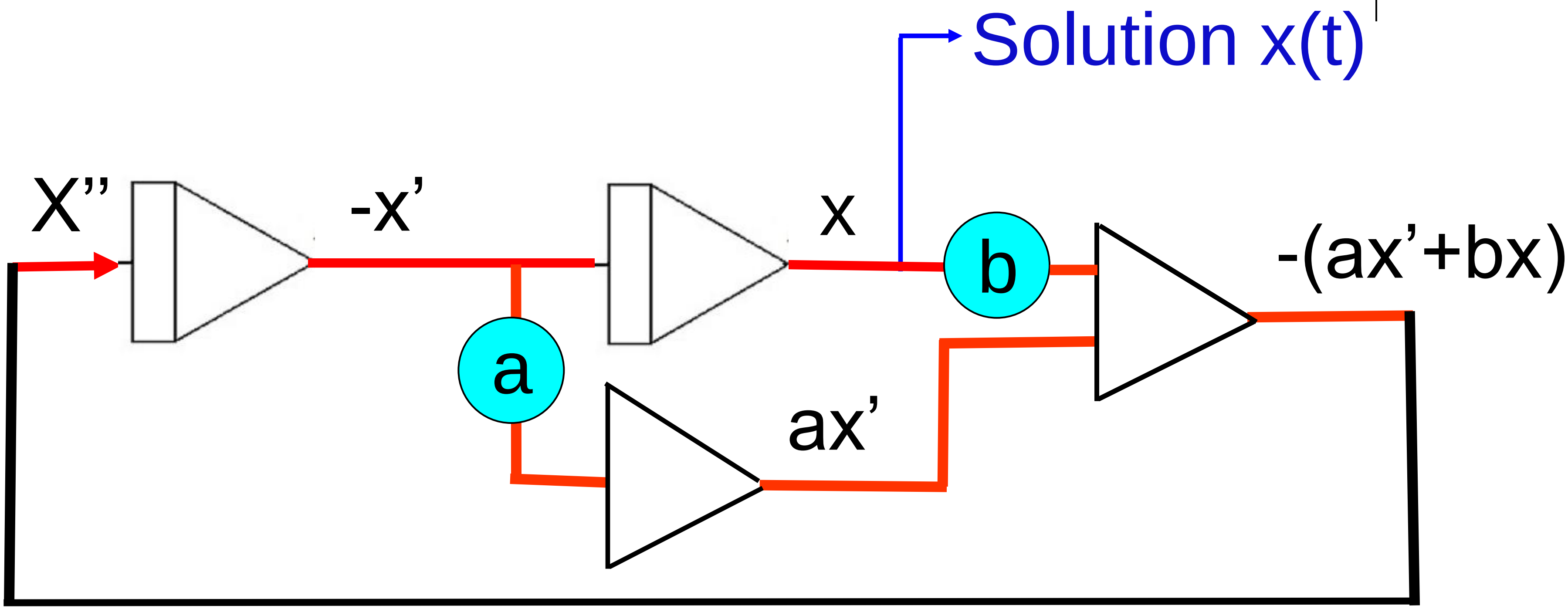
$$x'' = -x' - x = -(x' + x)$$



The feedback of the output to the input was first suggested by Lord Kelvin (William Thomson) in 1876

Wiring for analog computer

$$x'' = -ax' - bx = -(ax'+bx)$$

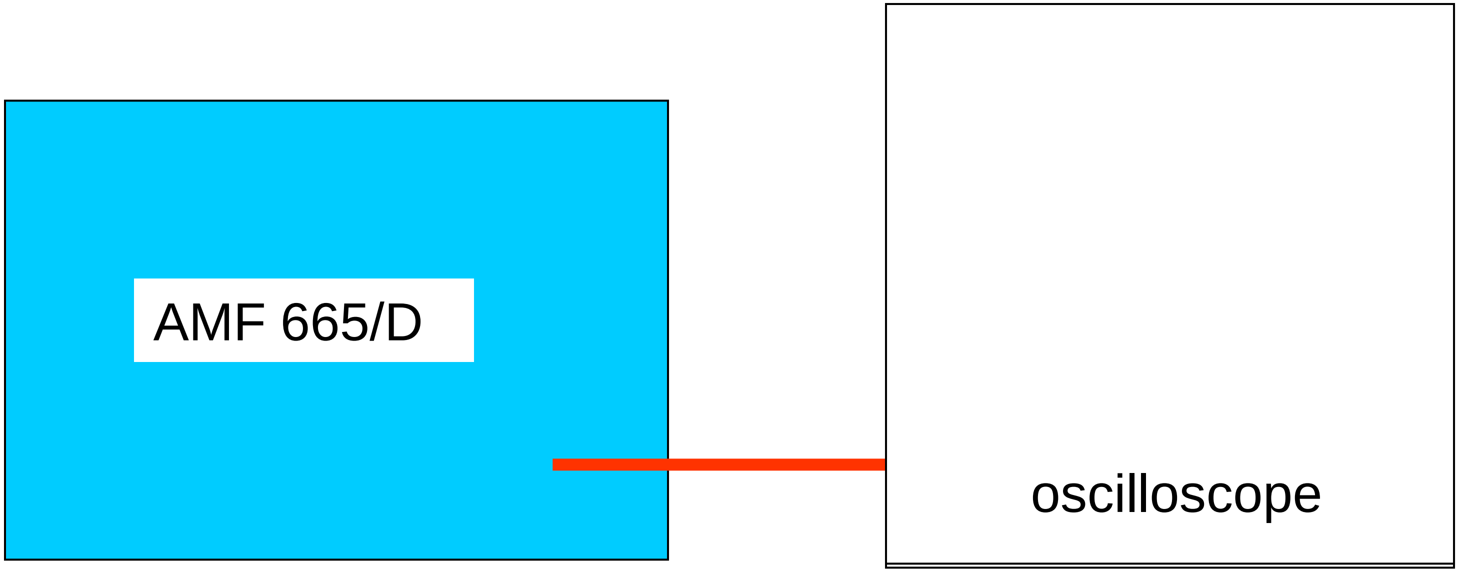


a Pontentiometer related to viscous damping

b Pontentiometer related to stiffness of spring

The potentiometer can be changed during the running "program" !

Demonstration with AMF analog computer



An "infectious problem" (1)

- Town has population of 1000
- Initially: 10 are sick (y)
  900 may be become sick (x)
  90 are immune (z)
- Contact rate between sick and not yet sick people = 1/1000 (per day)
- 1/14 of the sick become immune every day
- How do x, y, z evolve in time?

An “infectious problem” (2)

- Contact rate between sick and not yet sick people = 1/1000 (per day):

x’ = - 1/1000*(x*y)   [change per day of not yet sick people]

new infections per day

An "infectious problem" (3)

- 1/14 of the sick people become immune every day:

$$y' = + 1/1000*(x*y) - 1/14*y$$

[change of sick people per day]

new infections per day

new immunizations per day

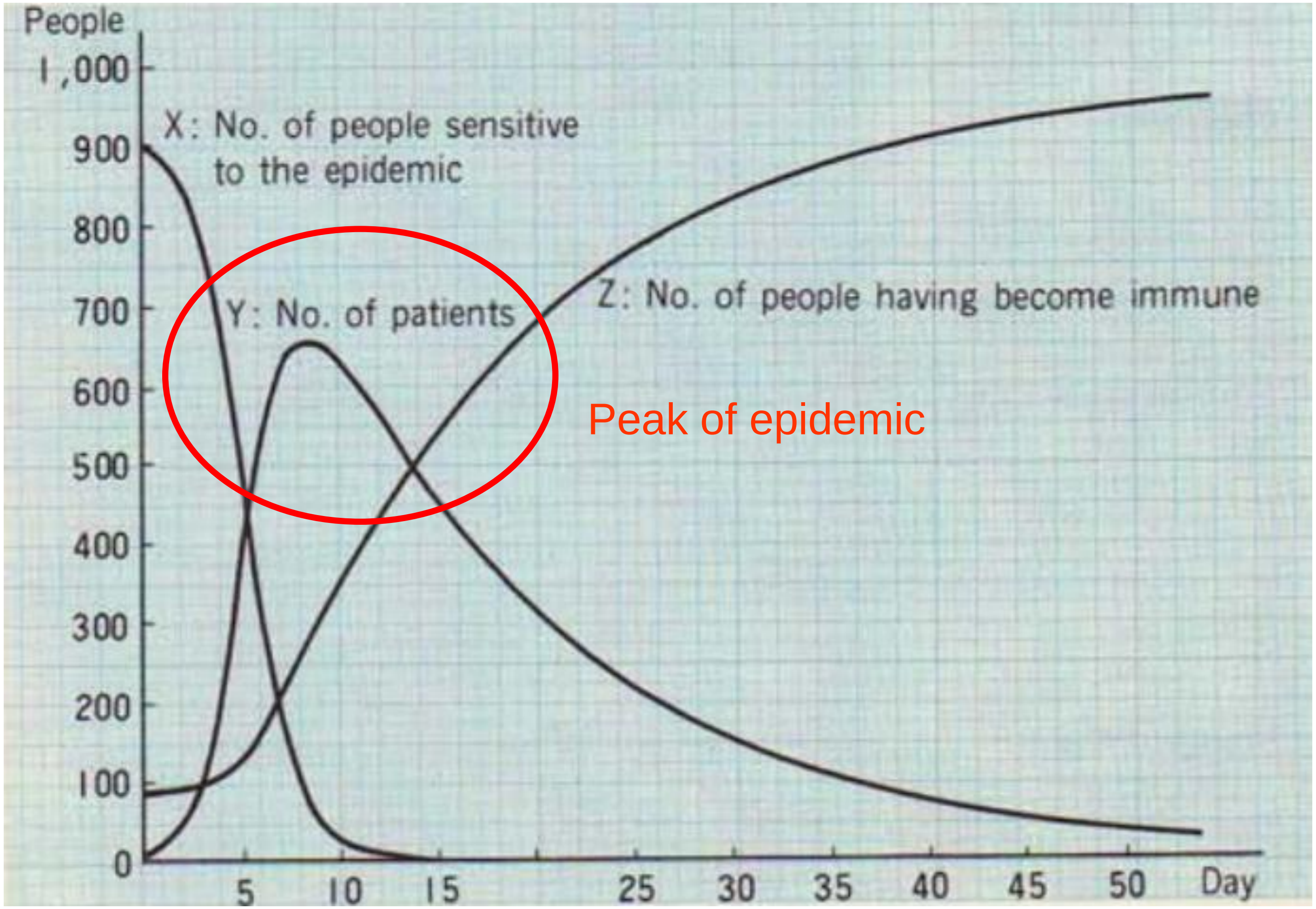
An “infectious problem” (4)

- z’ = 1/14 *y [change of people having recovered per day, now immune]

Model:

x’ = - 1/1000*(x*y) change not yet infected/day
y’ = + 1/1000*(x*y) – 1/14*y change of sick/day
z’ = 1/14 *y change of immunized/day

An “infectious problem” (end)



Lorenz strange attractor (1)

- In 1963 Edward Lorenz developed a simplified model of the atmospheric convection:

$$x' = a*(y-x)$$
$$y' = b*x - y - z$$
$$z' = x*y - c*z$$

x(t), y(t), z(t) are variables which describe the state of the atmosphere: e.g. x ~ convective movement of air

Lorenz strange attractor (2)

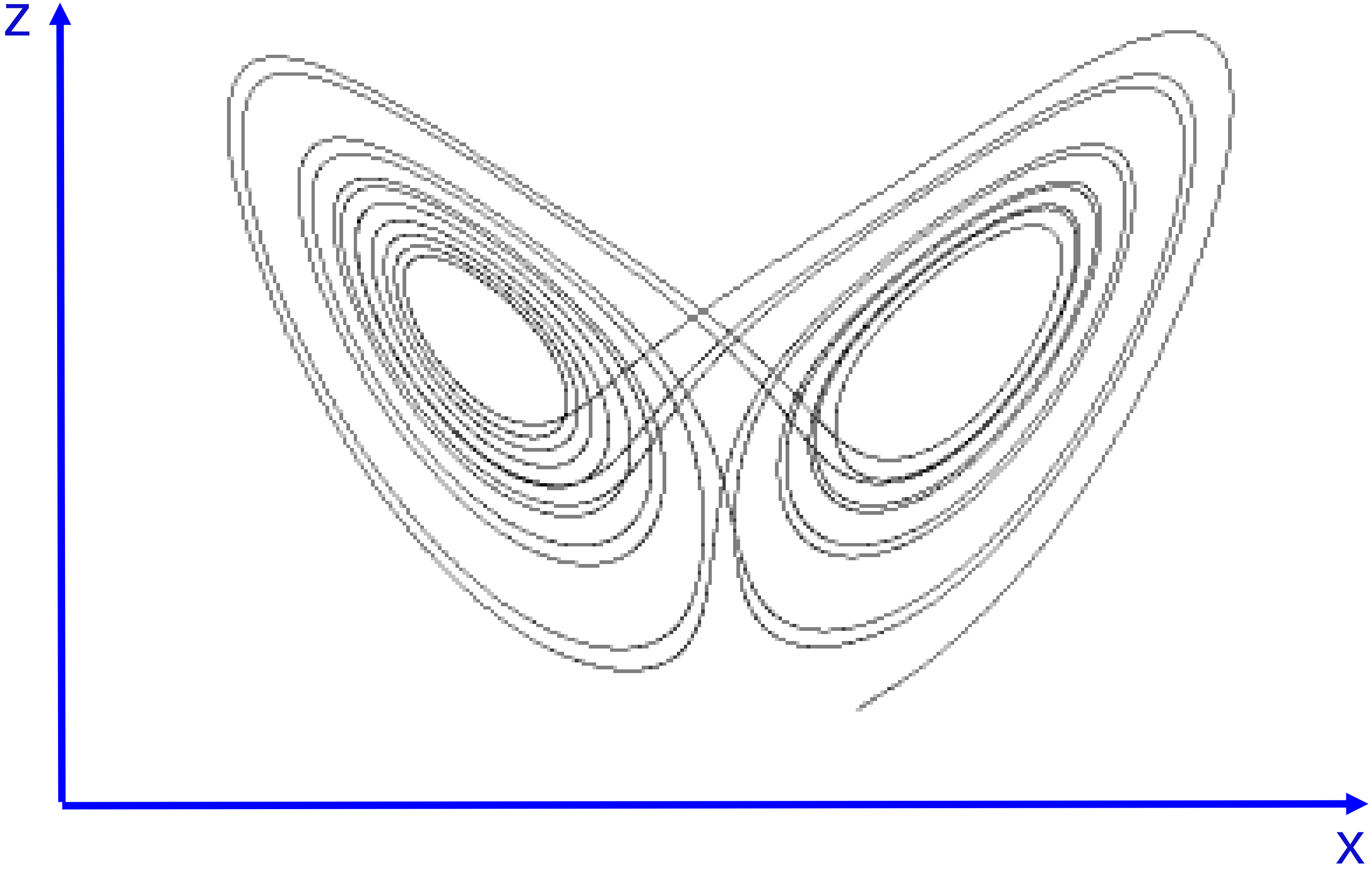
Lorenz found that for the particular values

$a = 10$, $b = 8/3$ and $c = 28$

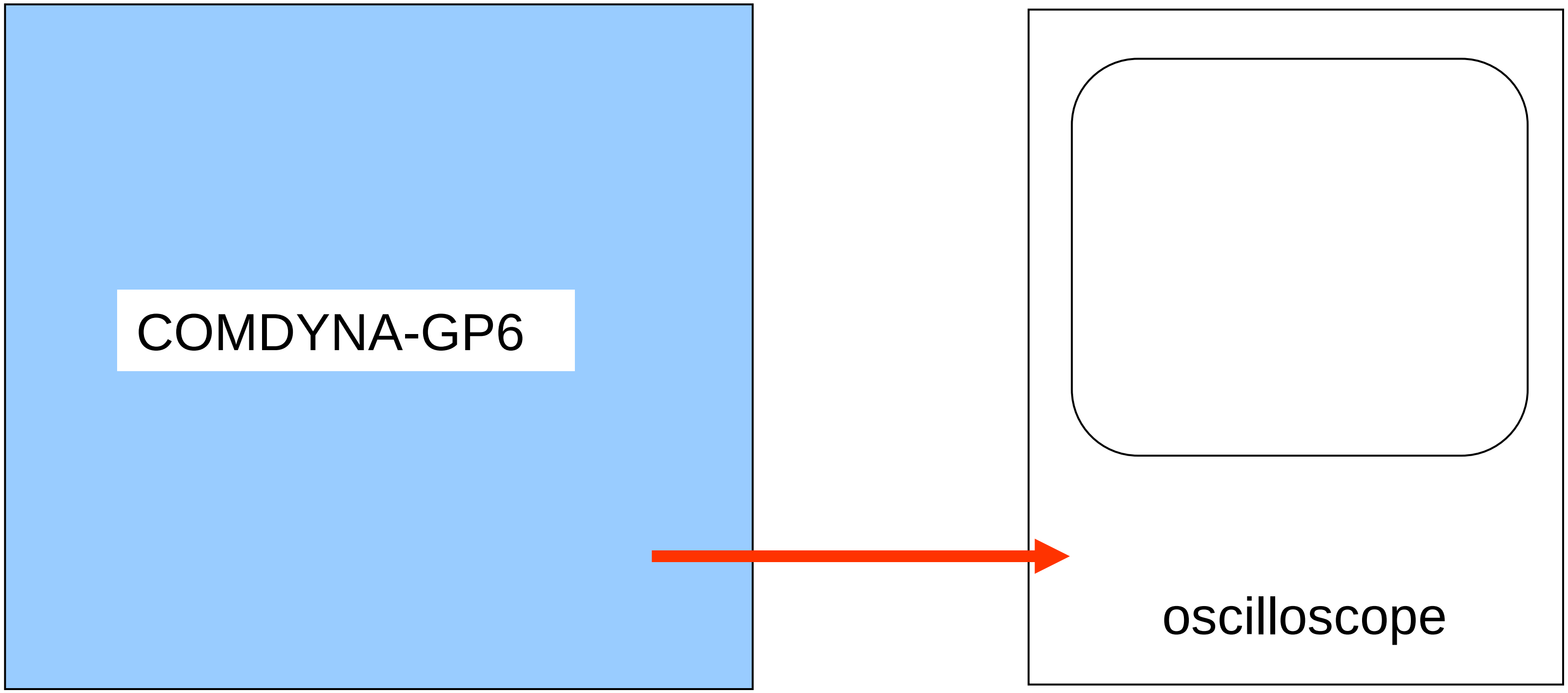
the solutions x(t), y(t), z(t) become chaotic when the variable time (t) cycles through a range of values.

This was the start of the "**chaos theory**" and its related theory of **fractals**.

Lorenz strange attractor (3)



Demonstration with COMDYNA-GP6 analog computer

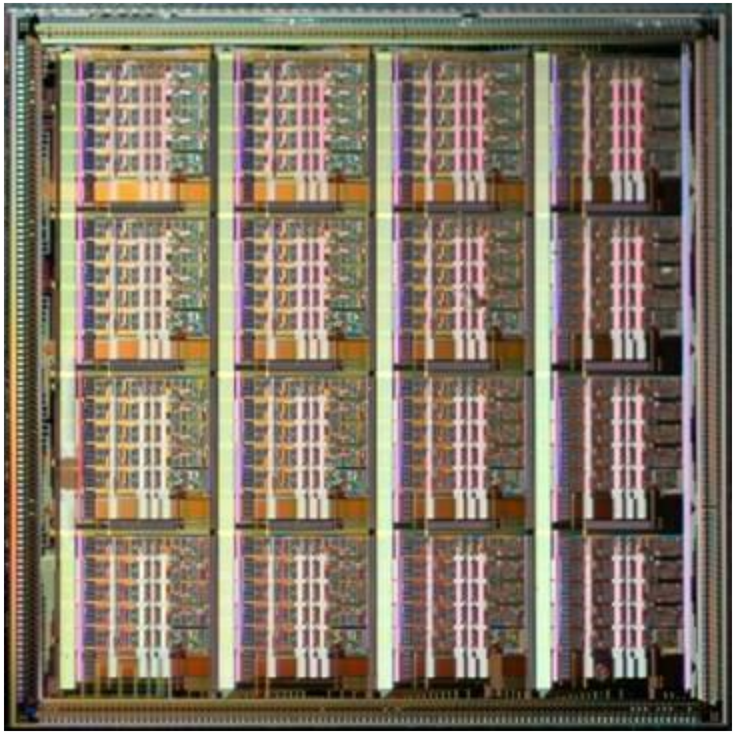


A possible come-back of the analog computer ? (1)

- G.E.R. Cowan (Concordia University, Montréal) developed in 2005 a single-chip VLSI analog computer (= a coprocessor) having 80 integrators and 336 other programmable linear and nonlinear circuits.

- The chip can be used to accelerate a digital computer's numerical routines to 23 Gflops*. The IC is 1 cm^2 and consumes 300 mW, still the lowest energy use of the world.

*[Intel Core-i7: 95 Gflops, 57 W]

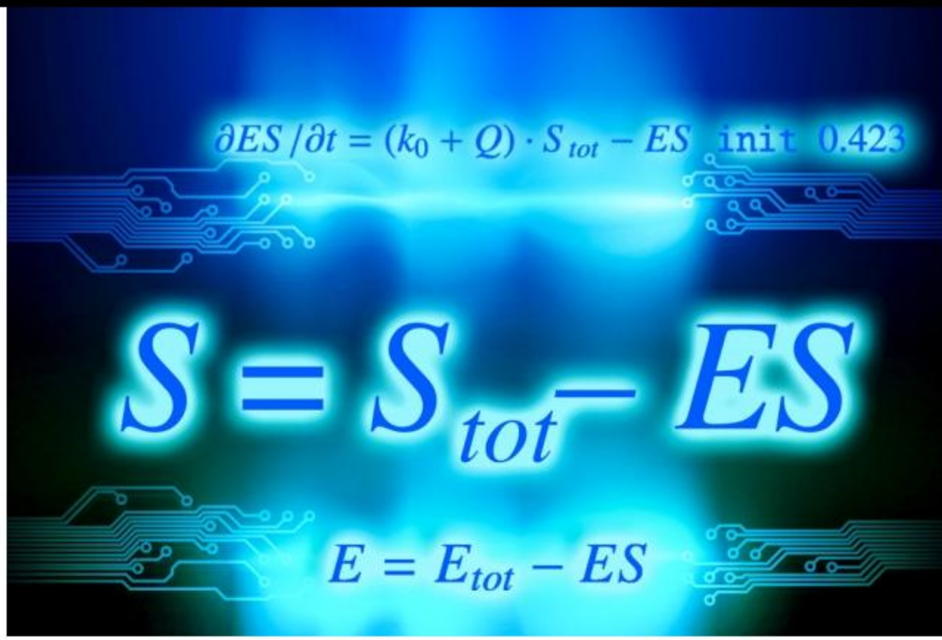


Come-back (2)

MIT News

ON CAMPUS AND AROUND THE WORLD

Browse or Search



FULL SCREEN

The researchers' compiler takes as input differential equations and translates them into voltages and current flows across an analog chip.

Illustration: Jose-Luis Olivares/MIT

Analog computing returns

New analog compiler could help enable simulation of whole organs and even organisms.

Larry Hardesty | MIT News Office
June 20, 2016

Press Inquiries

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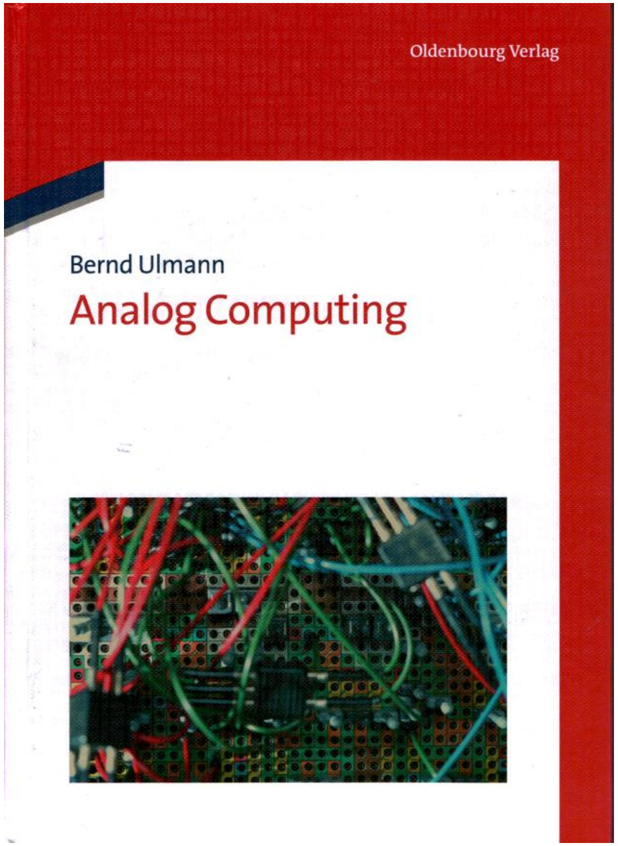

*Prof. für Wirtschaftsinformatik FOM, Hochschule f. Ökonomie und Management, Frankfurt/Main

Bernd Ulmann*: http://www.analogmuseum.org/
Joost Rekveld: http://www.joostrekveld.net/?p=1409 (Analog Art)

http://computarium.lcd.lu: Historic Computing Links and Library/PDF’s

COMPUTARIUM

LCD

Lycée classique de Diekirch

Merci fir d'Nolauschteren!

Slides sinn op
http://computarium.lcd.lu/news.html