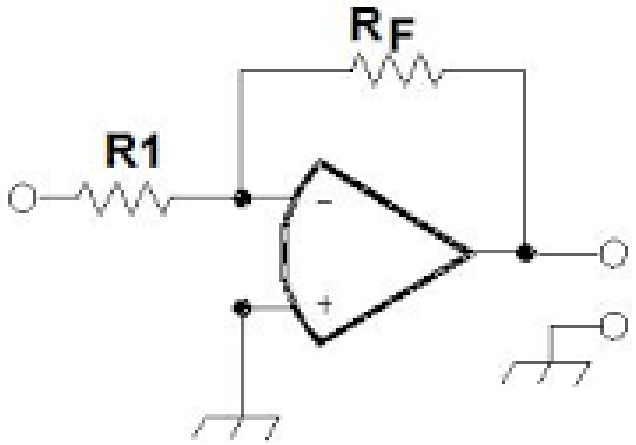
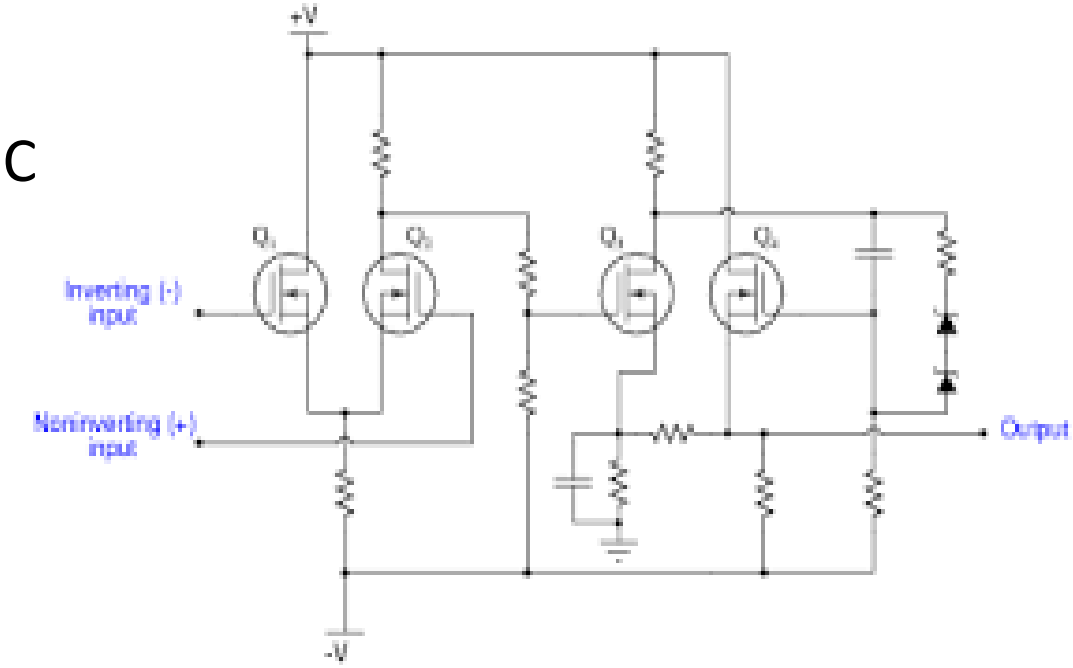
The Operational Amplifier When, Why, What, Who ?

Emil Novakov

UGA / IMEP-LAHC

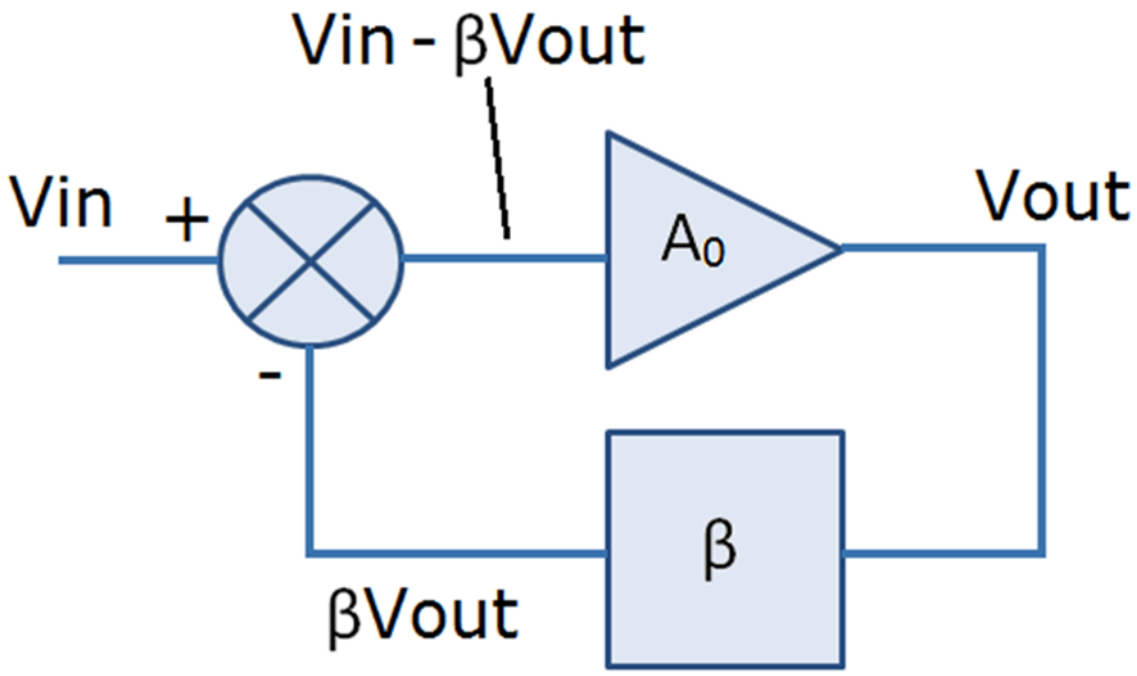




Milestones

- Feed Back Electronic circuits – H. Black, 1928, Bell Labs, Philips
- « Long-tailed-pair » - differential amplifier, J. Toennies, 1938
- First Op Amp, Loebb Julie, 1941 (gun director - military applications)
- Birth of the term “Operational Amplifier”, J. Ragazzini, 1947
- OP Amp Model K2-W, G. A. Philbrick, GAP/R, 1952
- Model 130, the world’s first transistorized op-amp, Burr Brown, 1958
- P45, transistorized Op Amp, Bob Peace, GAP/R, 1961
- Firs monolithic Op Amp µA 702, B. Widlar, Fairchild, 1963, (µA 709 – 1965)
- World standard µA741, D. Fulagar, Fairchild, 1968
- Model 45, high speed JFET Op Amp, J. Cadigan, Analog Devices, 1970
- CA3130, the first CMOS Op Amp, O. Schade, RCA, 1974

The feedback problem



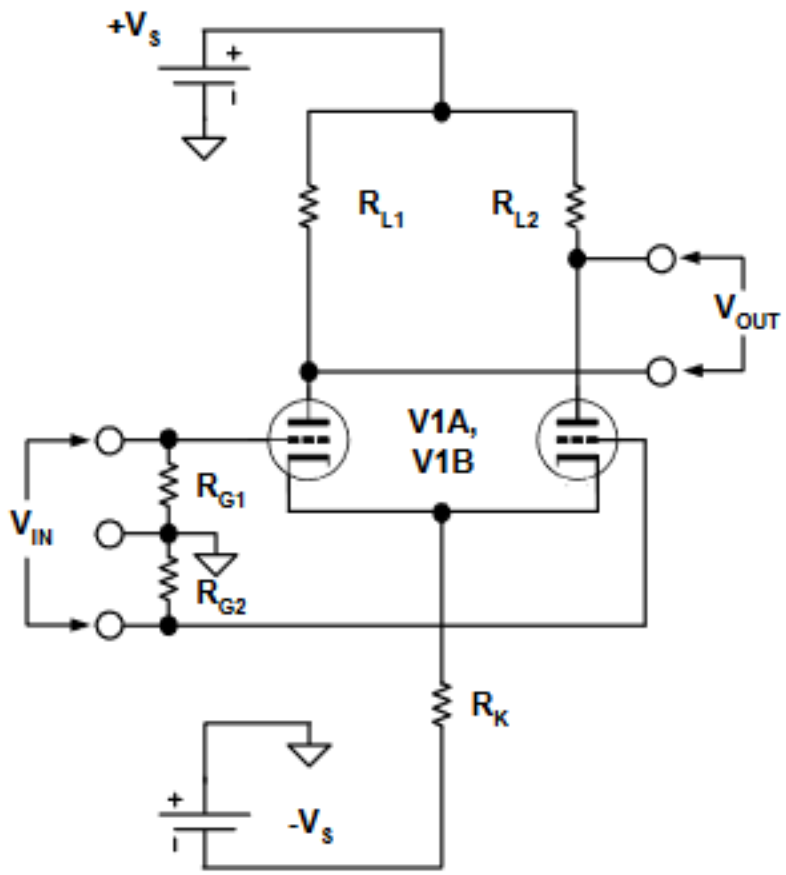
Paul Voigt : mid-1920s
Alan Blumlein (GB) - 1930s
A research group at Philips (Netherlands)

H. Black - late 20s to early 30s.

B. D. H. Tellegen 1937

Karl Dale Swartzel filed a patent for the 'summing amplifier', 1941, Bell Labs

The basic electronic circuit

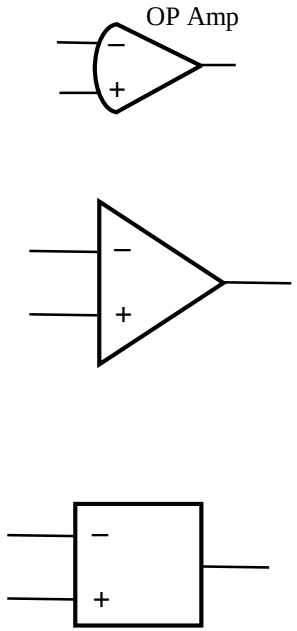


Cathode-coupled long-tailed differential pair
1938 J. F. Toennies

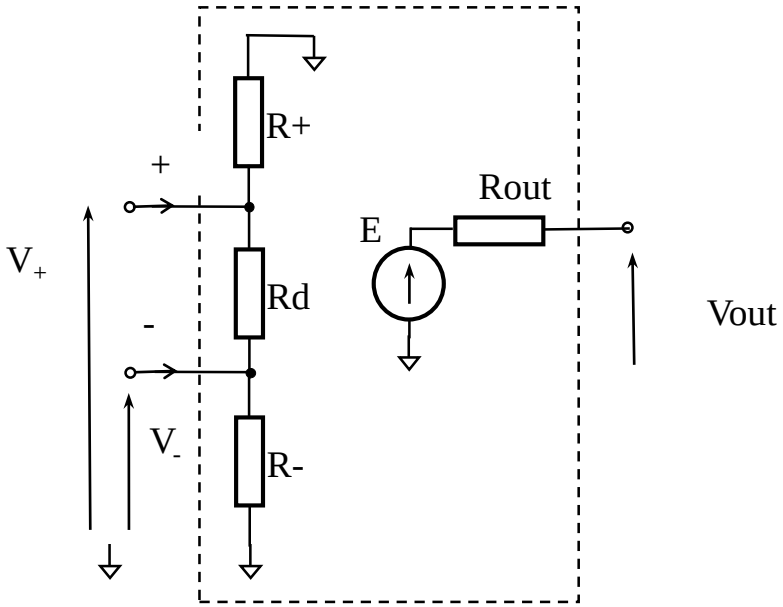
Bell Labs 1941, Division 7 - M9 project
Under George A. Philbrick supervision, Julie Loebb completed a two-tube op amp design, using a pair of dual triodes in a full differential-in / differential-out arrangement. The first operational amplifier.

Two inputs amplifier

Symbol

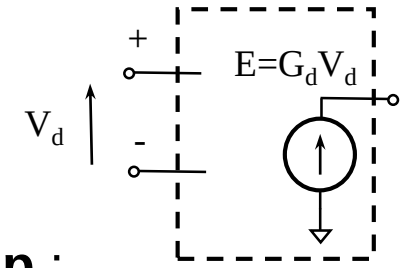


Model



$$E = G_d(V_+ - V_-) + G_{cm}\left(\frac{V_+ + V_-}{2}\right)$$

Ideal Model



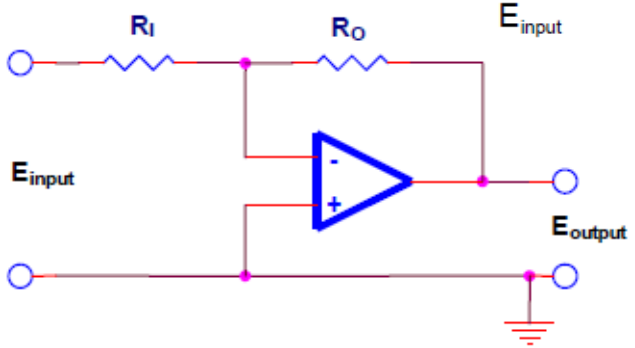
Ideal Op Amp :

Voltage controlled voltage source with :

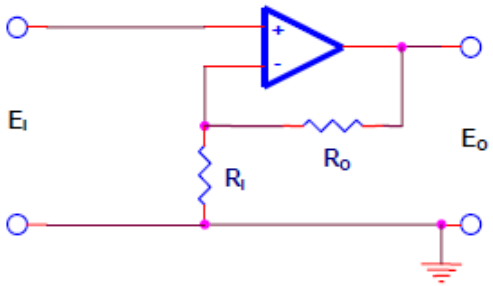
- infinite differential gain (G_d) ,
- zero common mode gain (G_{cm}),
- infinite input impedances (R_+, R_-, R_d),
- zero output impedance (R_{out}),
- infinite bandwidth
- zero offset ($V_+ - V_-$) = 0 → E = 0

Basic circuits - arithmetic operations

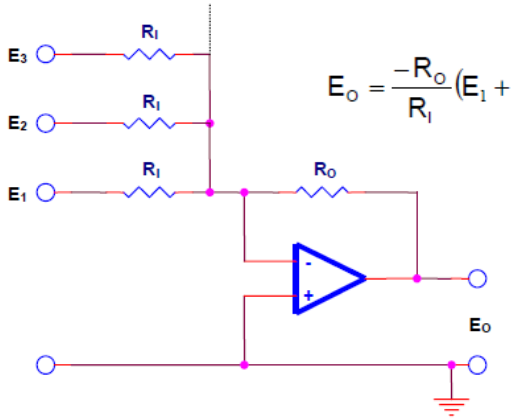
$$\frac{E_{output}}{E_{input}} = -\frac{R_O}{R_I}$$



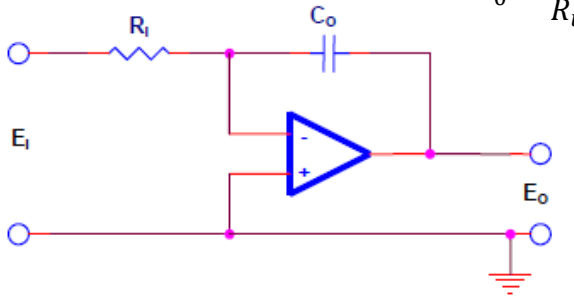
$$E_O = \left(1 + \frac{R_O}{R_I}\right) \cdot E_I$$



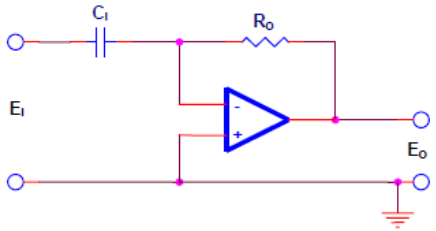
$$E_O = \frac{-R_O}{R_I}(E_1 + E_2 + E_3 + \ldots)$$



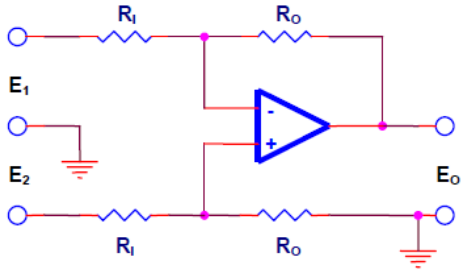
$$E_0 = \frac{-1}{R_i\, C_0} \int E_i dt$$



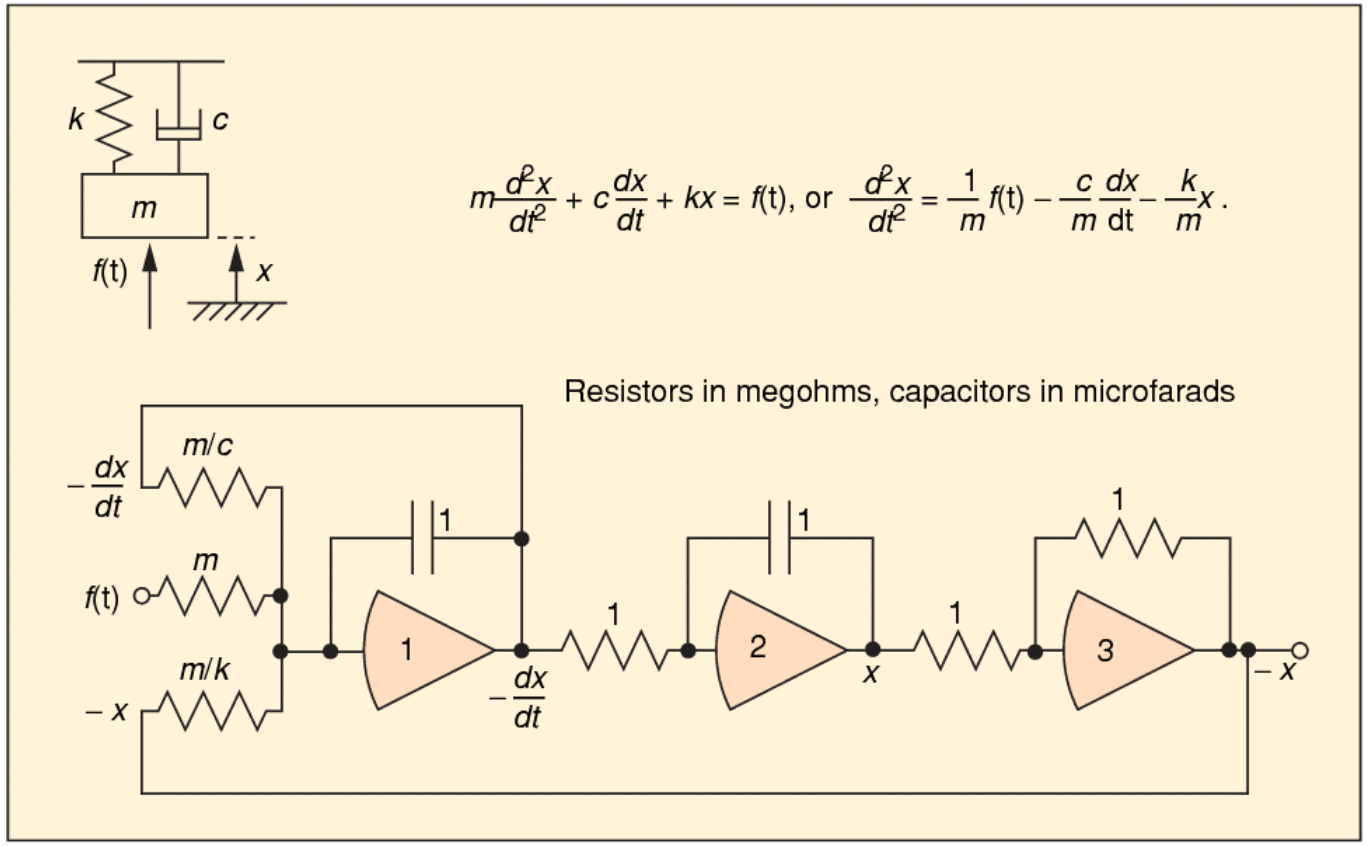
$$E_O = -R_O C_I \frac{dE_1}{dt}$$



$$E_O = \frac{R_O}{R_I}(E_2 - E_1)$$



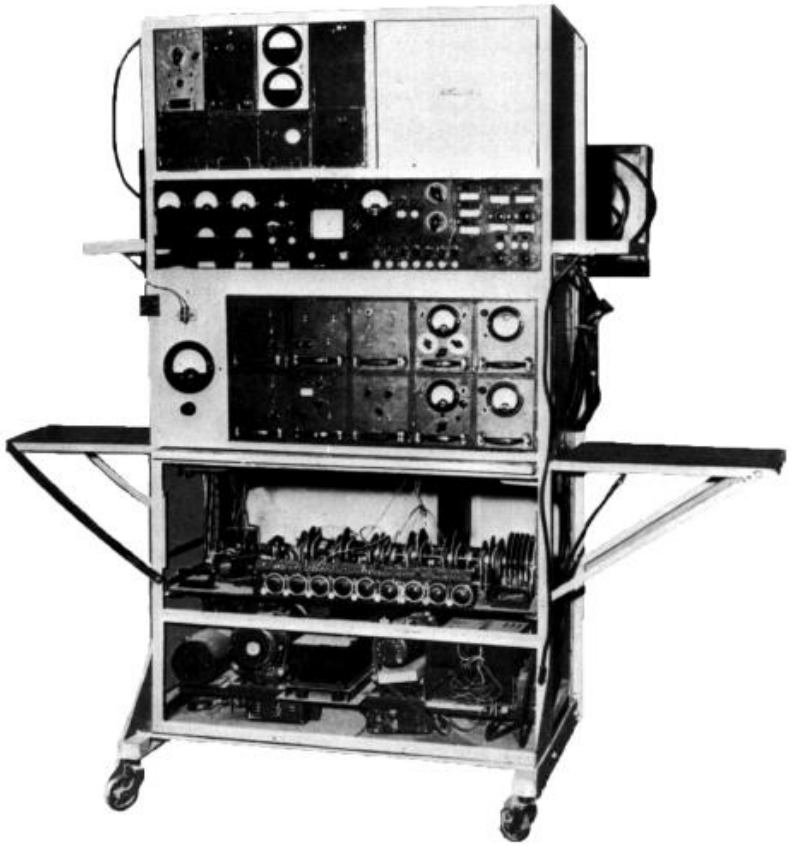
Differential equation resolution



John Ragazzini (1947)
Columbia University of New York

"As an amplifier so connected can perform the mathematical operations of arithmetic and calculus on the voltages applied to its input, it is hereafter termed an '**operational amplifier**'."

The analog computer – V2 rocket



1941, Hoelzer analog computer (Peenemunde, Germany):
- V2 rocket dynamics simulation,
- Calculate and simulate V2 trajectories.

The computer was based on an electronic integrator and differentiator conceived by Hoelzer in 1935.

Mischgeraet : the world's first on-board computer,
guidance section of V2 rocket.

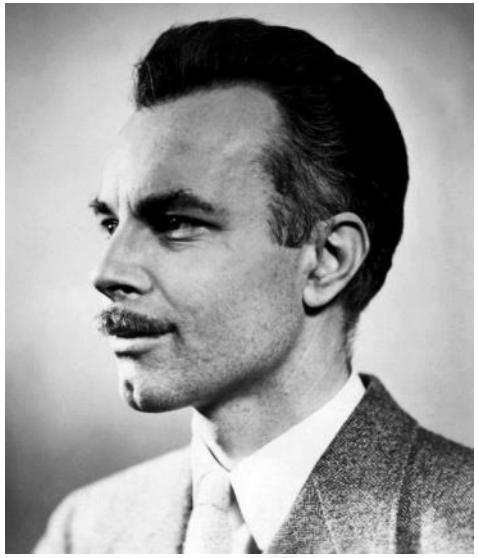
The analog computer – M9 Gun Director

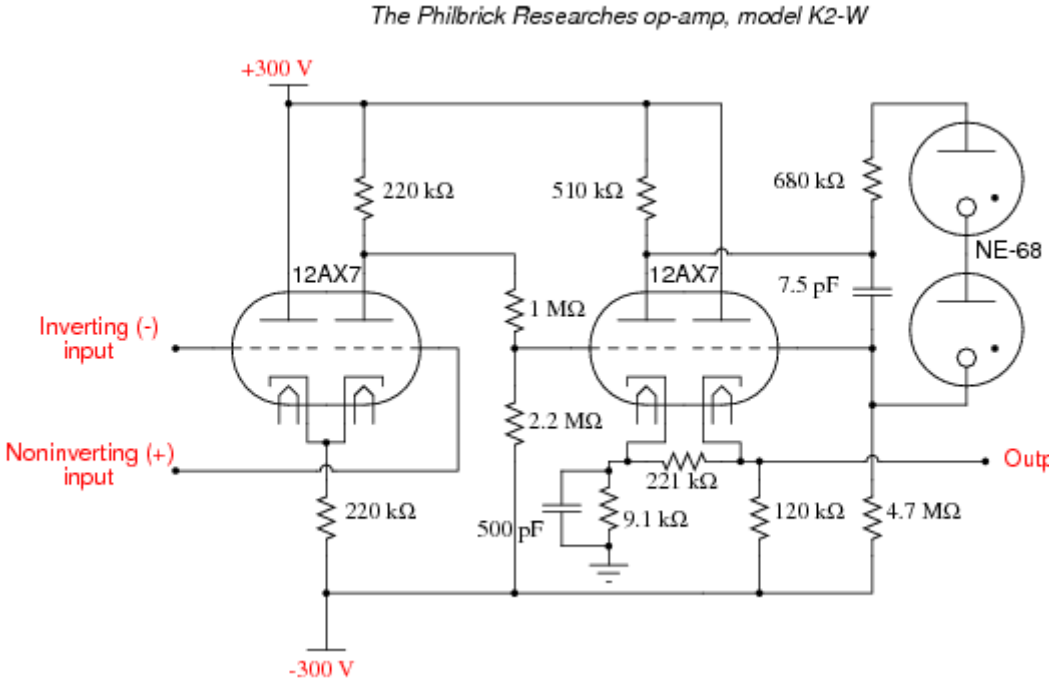
M9 Gun Director - D. Parkinson, Bell Labs, 1943.

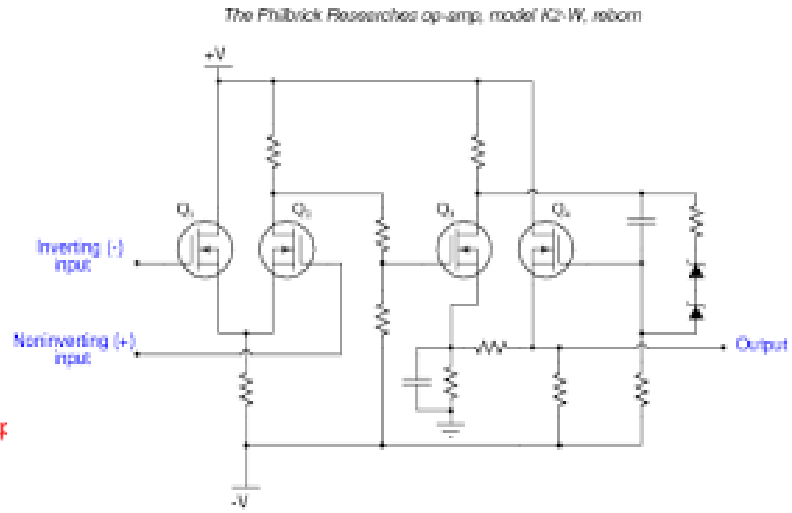
A revolutionary instrument !

M9's radar tracked incoming enemy aircraft, determined their speed, altitude and direction and then relayed the information to an analog computer that calculated the anti-aircraft gun's trajectory and fuse setting. During one week in August 1944, M9s destroyed 89 of 91 V1 !

G. A. Philbrick Research (GAP/R): K2-W Op Amp







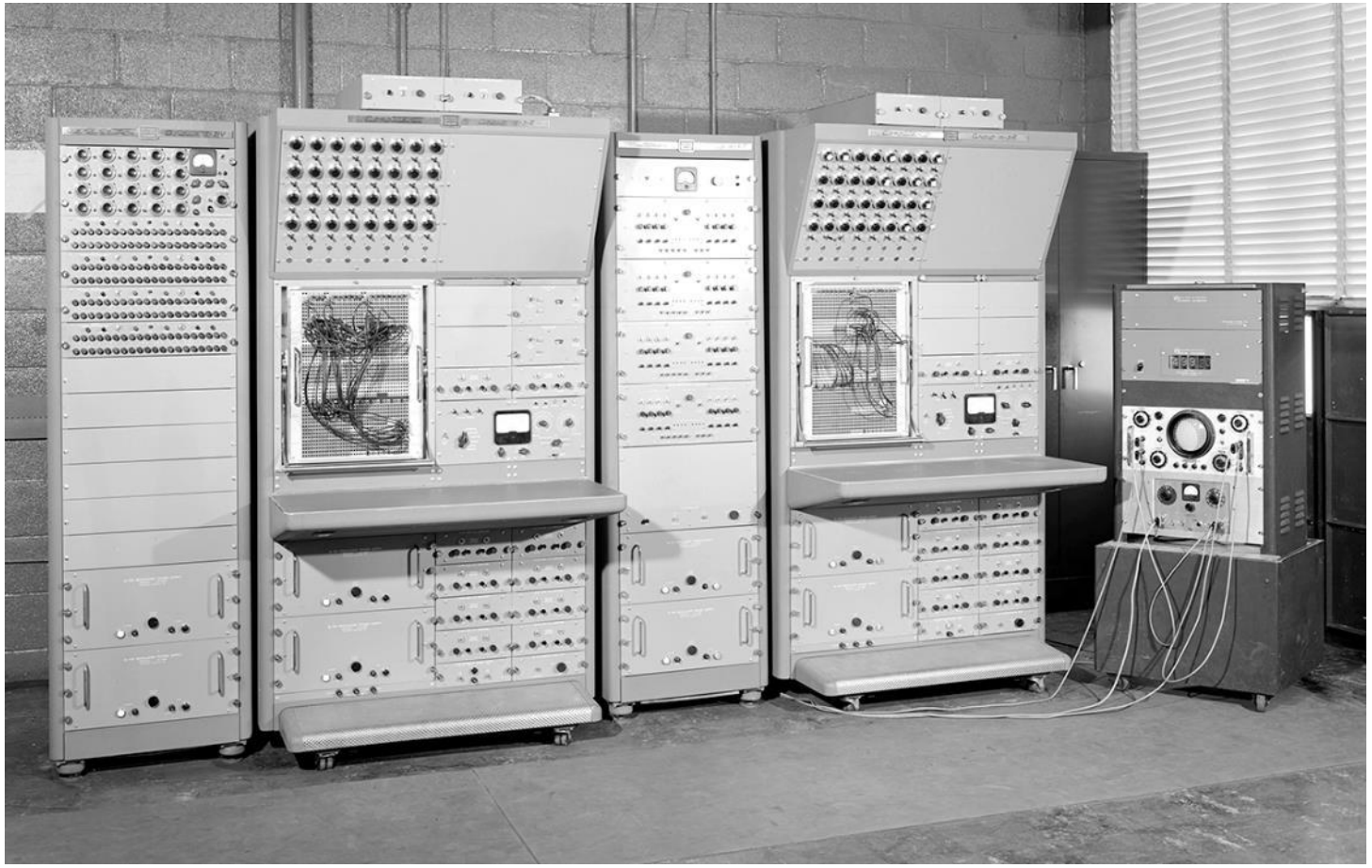
Equivalent MOS implementation

1946, G. A. Philbrick started GAP/R - Analog Computers Company

K2-W, 1952 commercial use of the Operational Amplifier, Price US$ 20

K2-W was last manufactured in 1971

The analog computer



PACE 16-31R, 1950s

Electronic analog computer,

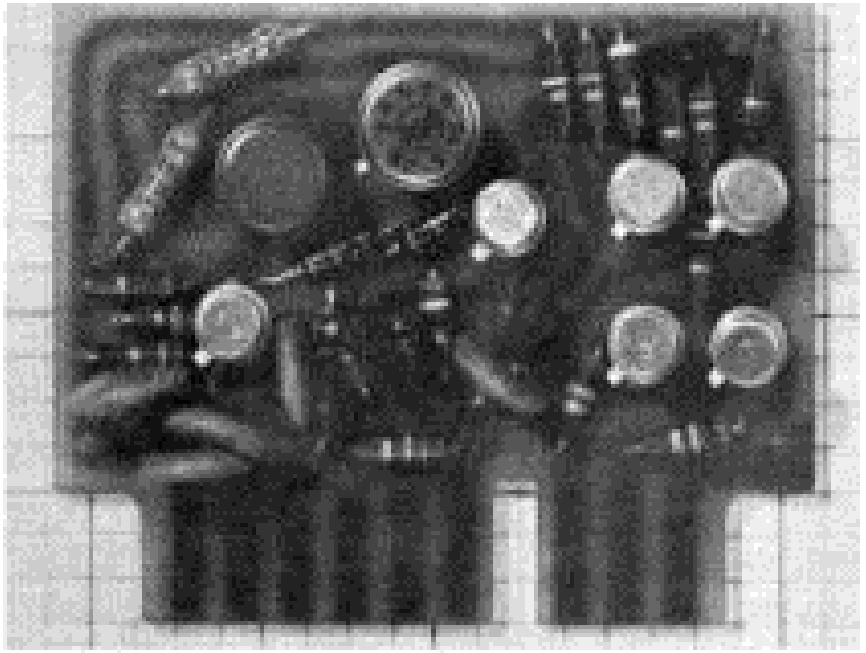
Electronic Associates Inc.,

NASA’s Lewis Flight Propulsion Laboratory,

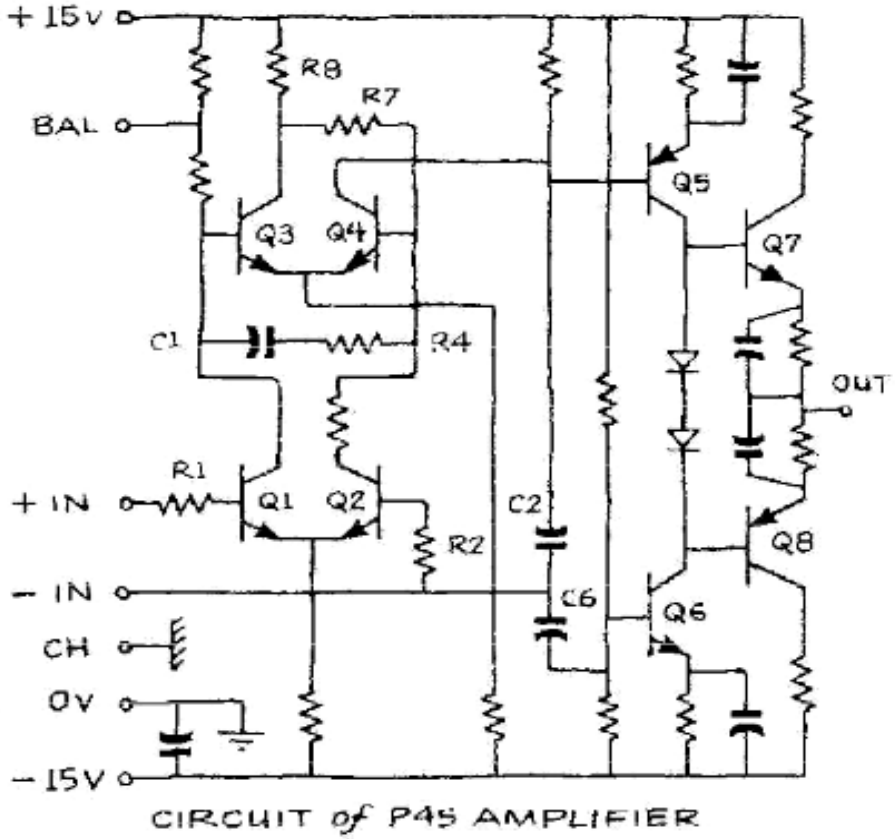
Used in Mercury, Gemini, and Apollo programs.

Solid state modular and hybrid amplifiers

- 1947, J. Bardeen, W. Brattain, W. Shockley, Bell Labs - The transistor
- 1954, G. Teal, Texas Instruments : grown - junction silicon transistor

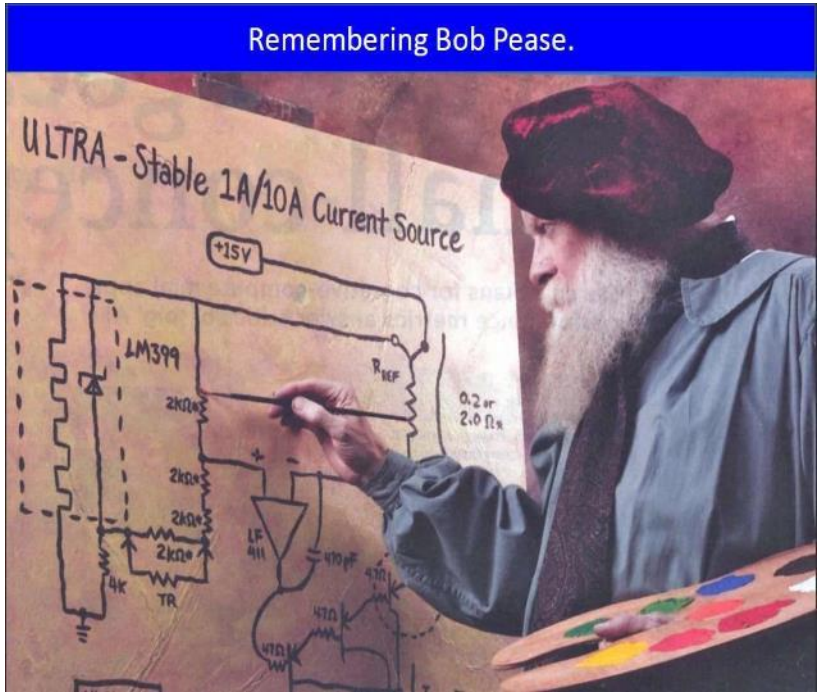


1961, P45, Bob Pease, GAP/R First transistorized op amp



CIRCUIT of P45 AMPLIFIER

Bob Pease - GAP/R, National Semiconductor

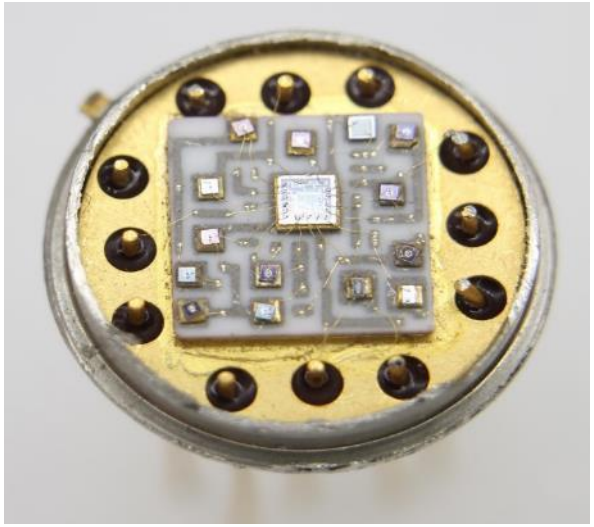


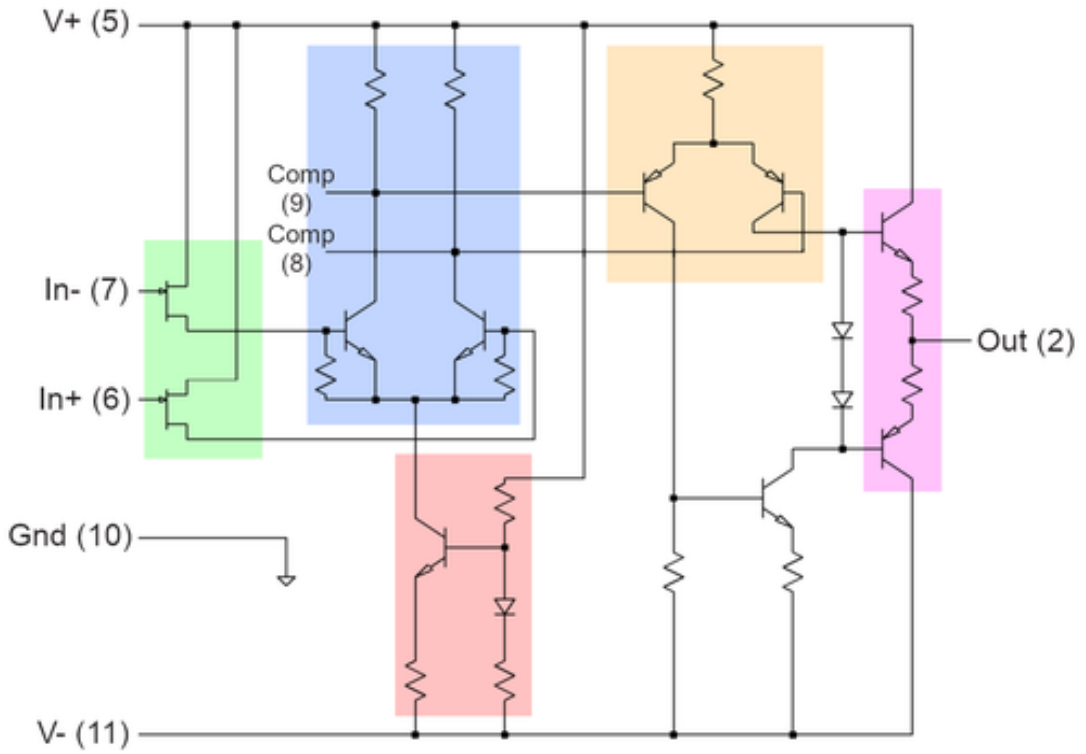
What's All This …. Stuff, Anyhow?

P45A could deliver ±10 V at ±20 mA to the load.
Gain was rated a minimum of 50,000 at into a load of 500 Ω.
Gain-bandwidth product of 100 MHz!
In 1966, P45A cost $118.
P45 ran on ±15 V, the new power standard.
Input / output signals ranges of ±10 V.

Bob Peace : Analog guru at National Semiconductor !
Band-gap Reference Circuit Tsar
LM337 regulator designer
LM331 V-F converter and many other circuits …
Famous columnist at Electronic Design.

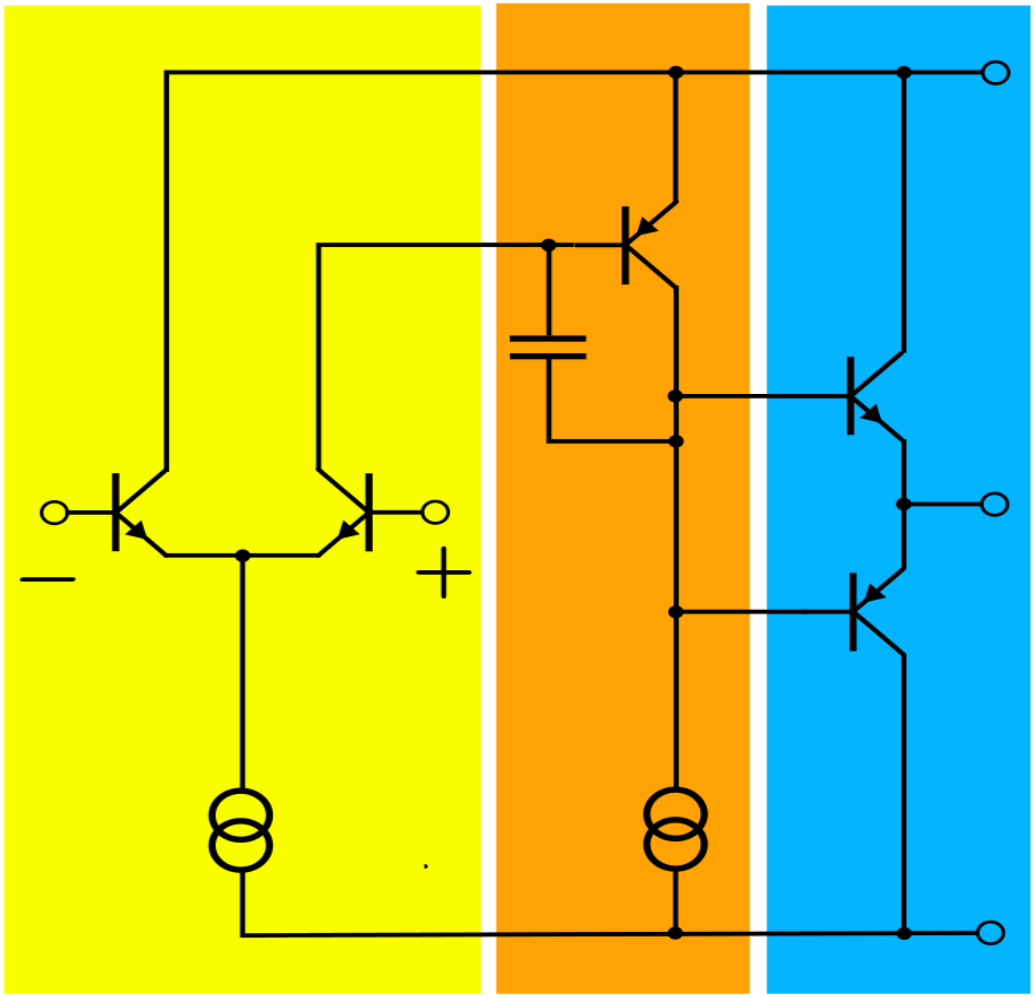
NASA Op Amp's





- 2404BG, 1969, Amelco, designed by Bob Peace 58,50 $ (today 300 $).
- 1966, Amelco + GAP/R → Teledyne Philbrick Nexus
- Apollo 12 on the Moon

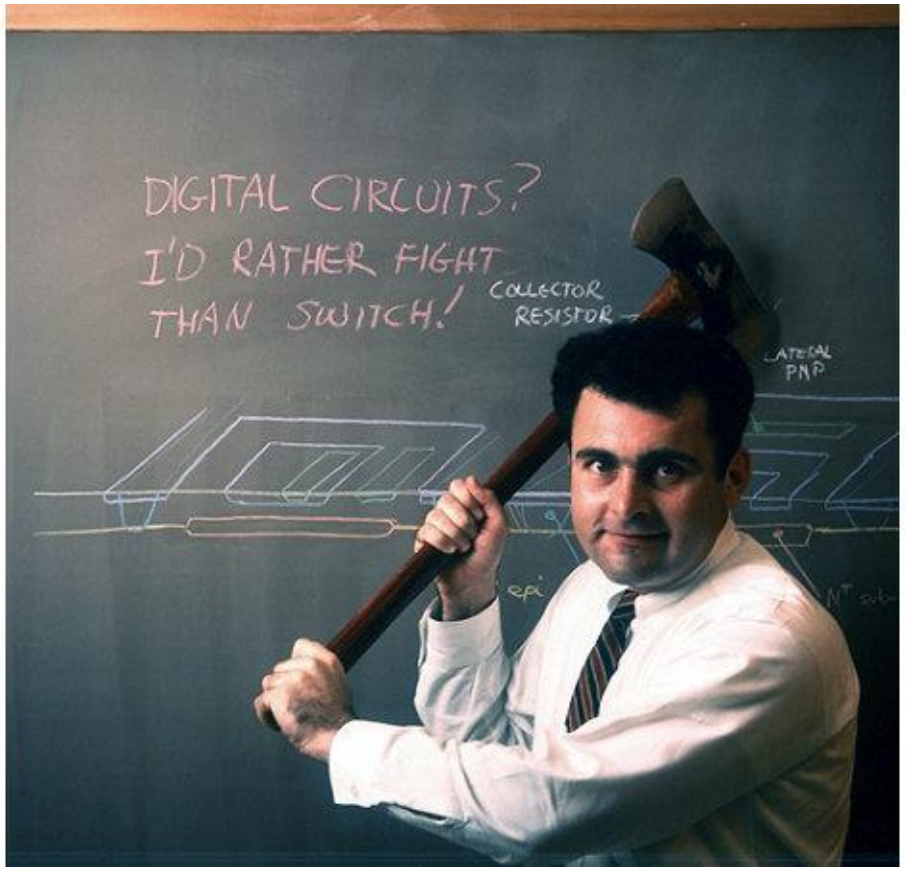
Transistorized OP Amp – Basic structure

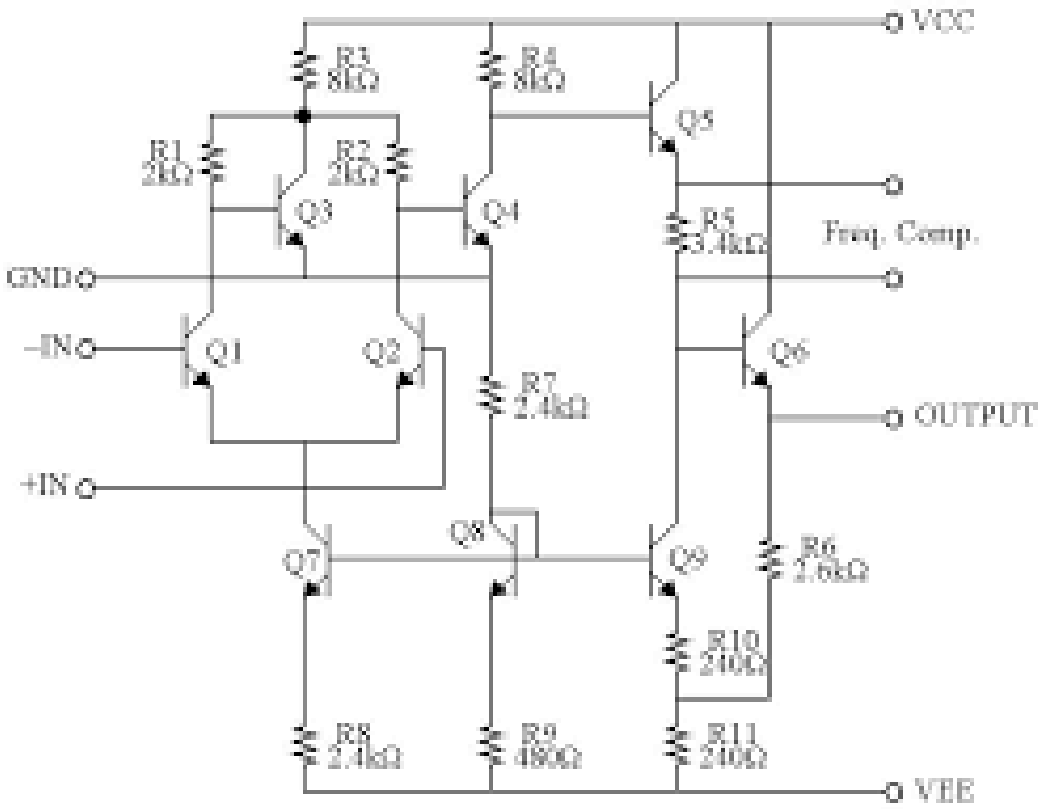


3 stages:

1. Differential input & gain
2. Gain and offset shift
3. Output stage

The monolithic Op Amp



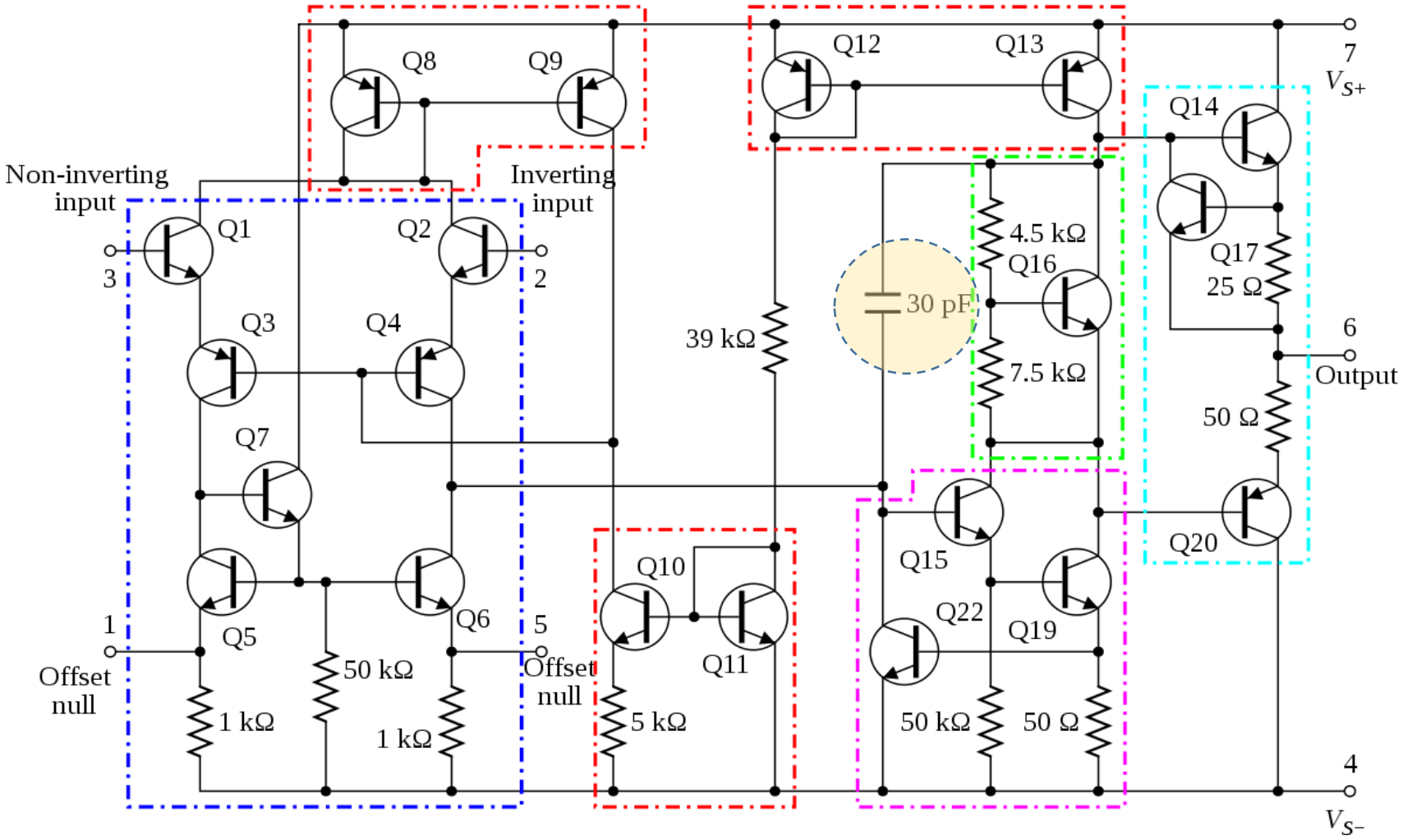


First monolithic Op Amp : µA702, Bob Widlar, 1963, 300 US$!

Bob Widlar – the analog IC genius. “Digital? Every Idiot Can Count to One”

- 1963, Bob Widlar, Fairchild Semiconductor,
- First monolithic op Amp: µA702
- 1965, µA709, first commercial success.
- LM10, National Semiconductor, brilliant Op Amp designs, in production for over three decades
- Design of countless analog IC!

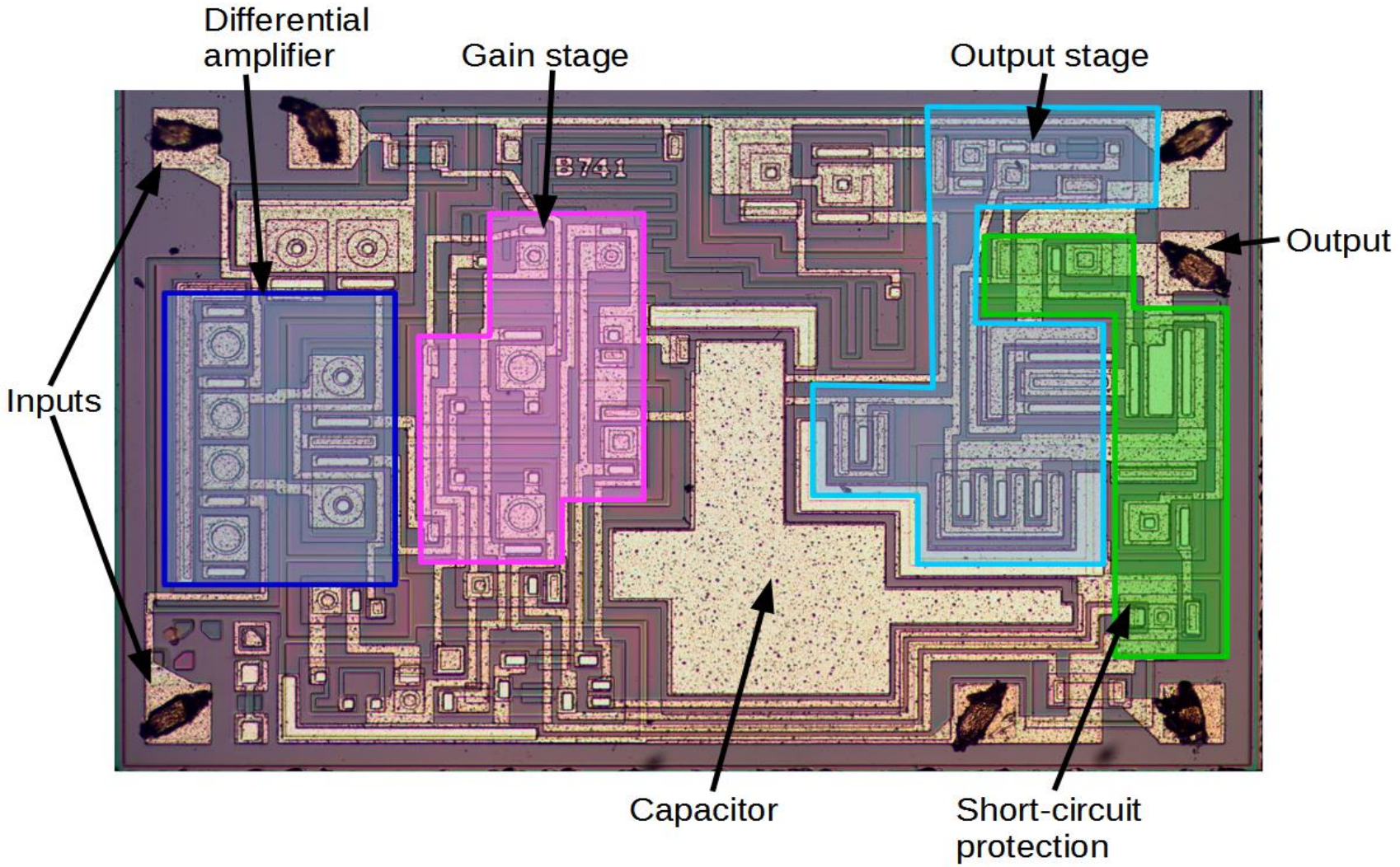
µA 741 – The legend (D. Fulagar, Fairchild, 1968)



Internal frequency compensation

Short circuit output protection

µA 741 - Layout



µA 741 today (2020) – still alive, 52 years later!

2020, Price (per 1000) :

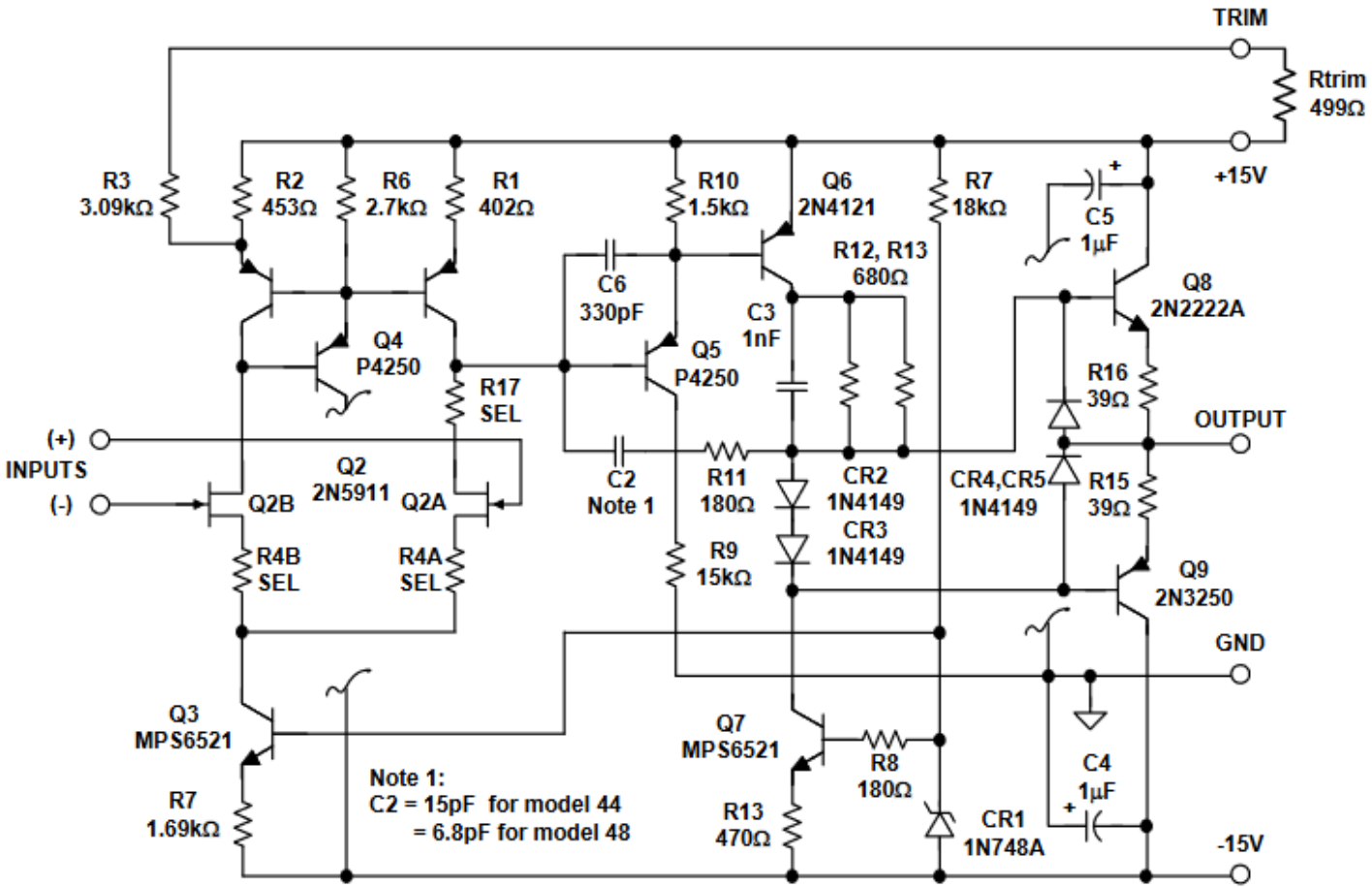
0.12 EUR

µA 741 Estimated sales:

≈ US$ 10 billion

≈ 20 billion circuits

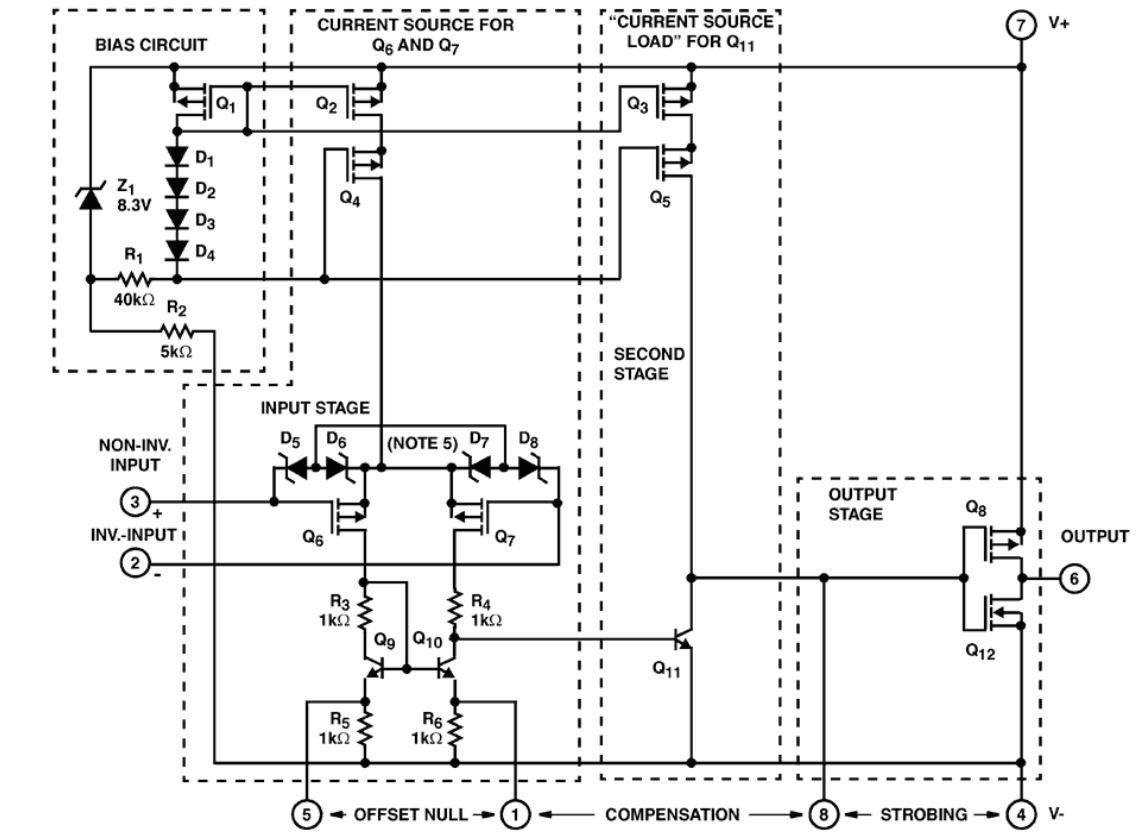
Model 44 high speed JFET 110 V/µs



J. Cadigan,
Analog Devices, 1970
Very-low input currents

CA3130 first CMOS Op Amp (pMOS input)

Schematic Diagram



NOTE:

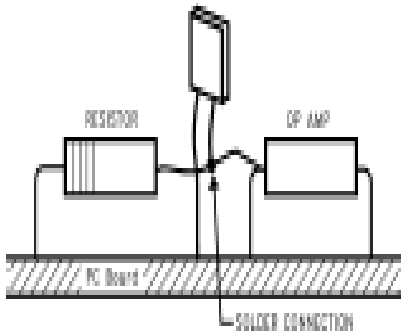
5. Diodes D_5 through D_8 provide gate-oxide protection for MOSFET input stage.

O. Schade, RCA, 1974

- Very High Z_{Input} , 1.5 TΩ (1.5 x 10^{12}Ω) !
- Very Low I_{Input} , 2pA at 5V Operation

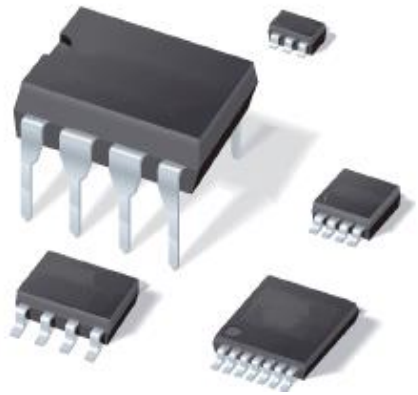
CMOS OP Amps are most frequently used as sub-circuits within larger systems : on-chip applications (ADC, DAC, Audio, voice …)

Air-wiring to avoid leaks !



Companies : merger & acquisition (and dead …)

- GAP/R - George A. Philbrick Research, Philbrick - Nexus (+Amelco), Teledyne Philbrick, Teledyne semiconductor (E2V), Microchip.
- Fairchild (acquired by National Semiconductor)
- National Semiconductor (NS), acquired by Texas Instruments (TI) , 2011
- Analog Devices 5AD) (Ray Sata, 1965)
- Burr Brown (BB), acquired by Texas Instruments, 2000
- Maxim
- Linear Technology (LT), acquired by Analog Devices, 2016

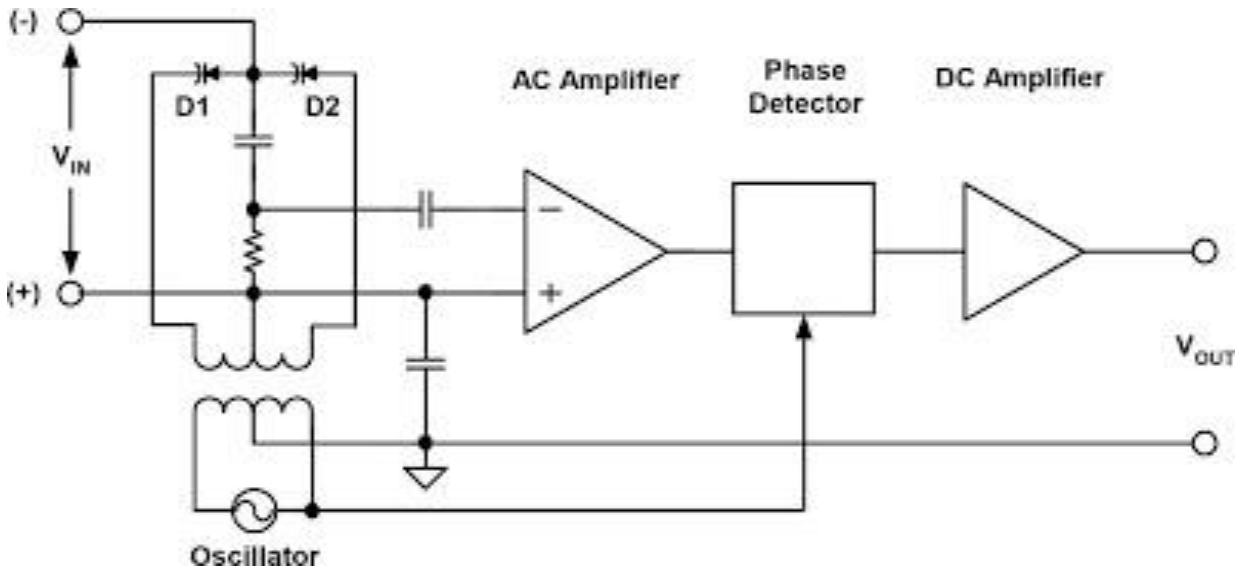


2020: Main players: AD (+LT), Maxim, TI (+NS), Microchip, STMicroelectronics

Op Amp: a good business !

- STMicroelectronics, 2019, “Analog, MEMS and Sensor group (AMS)”, US$ 3.3 billion revenue (30%!), ST – US$ 9.5 billions revenue.

Case Study 1: Varactor bridge amplifier P2



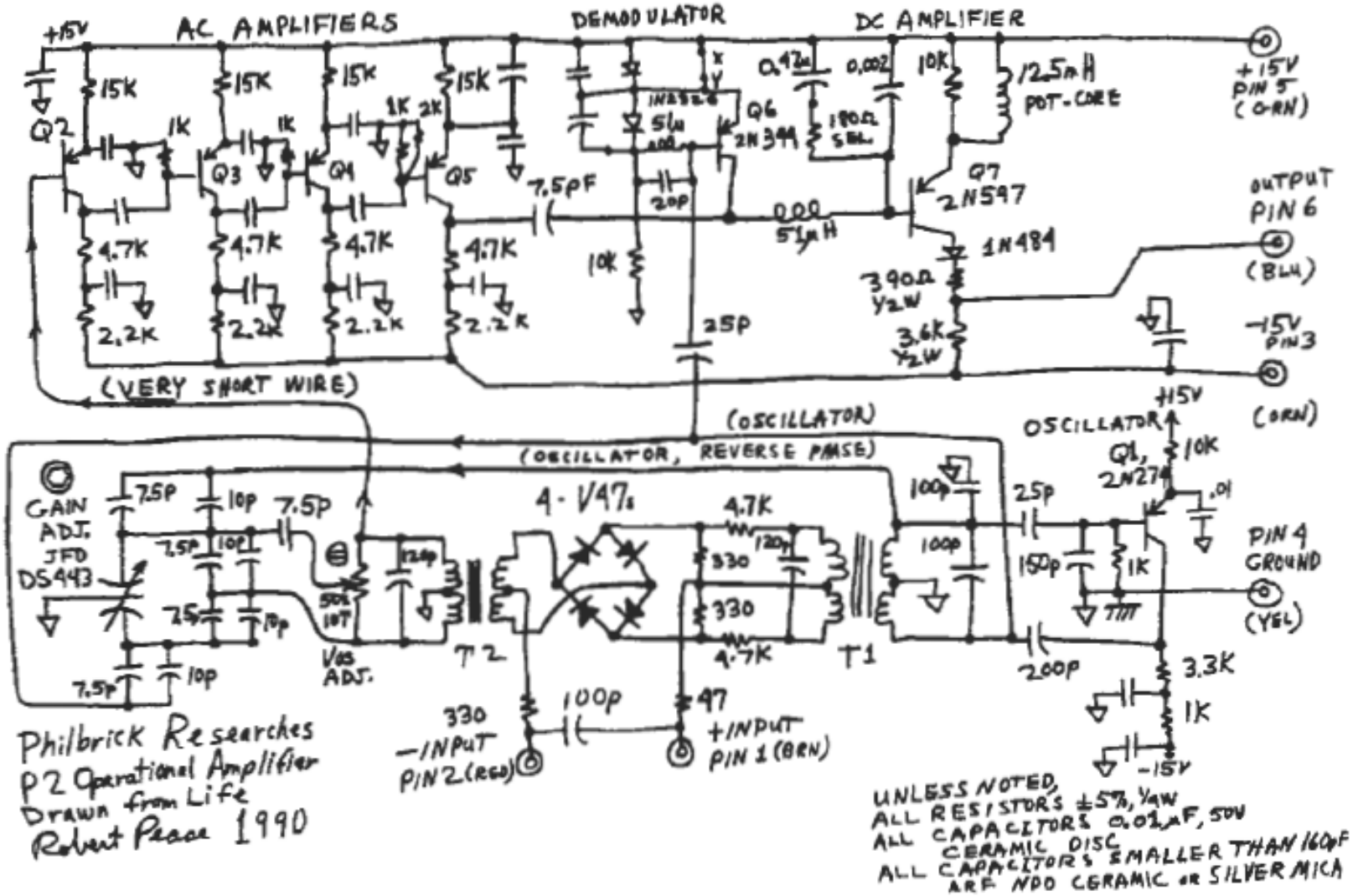
An idea of G. Philbrick

P2 Pico-ampere Input Current (Transducers signal processing)

Bob Malter, GAP/R , 1960 5-10 pA input, gain 10000, US$ 227 dollars (average price of a car US$ 2500)

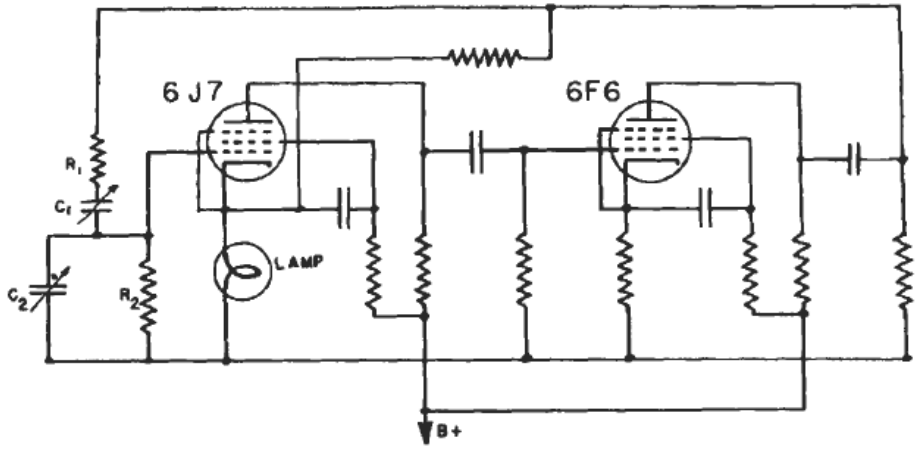
P2 dominated for 30 years, becoming obsolete only after the release of the LMC660, I_{input} = 2 fA – 1998!

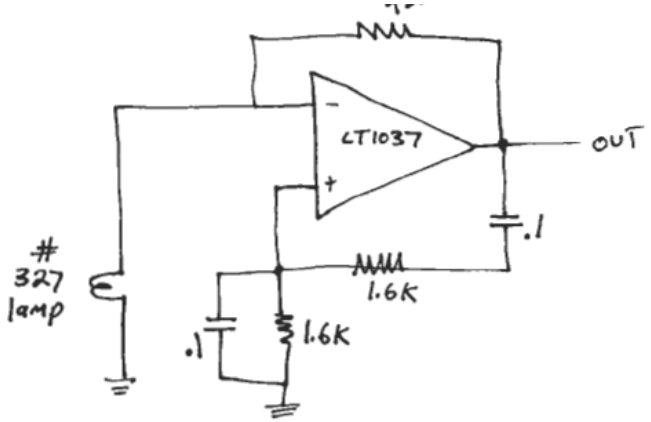
P2 schematics from Bob Peace



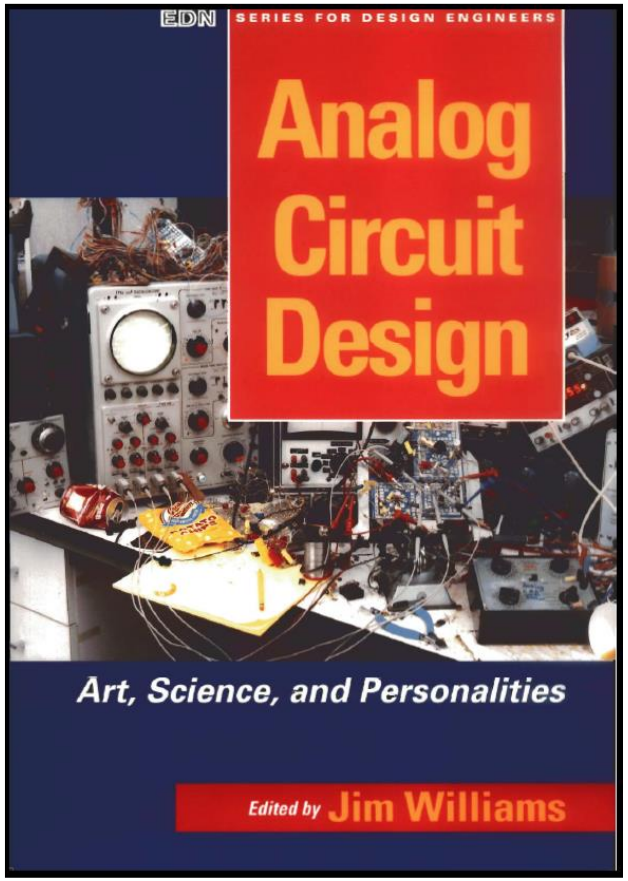
Case study 2 :

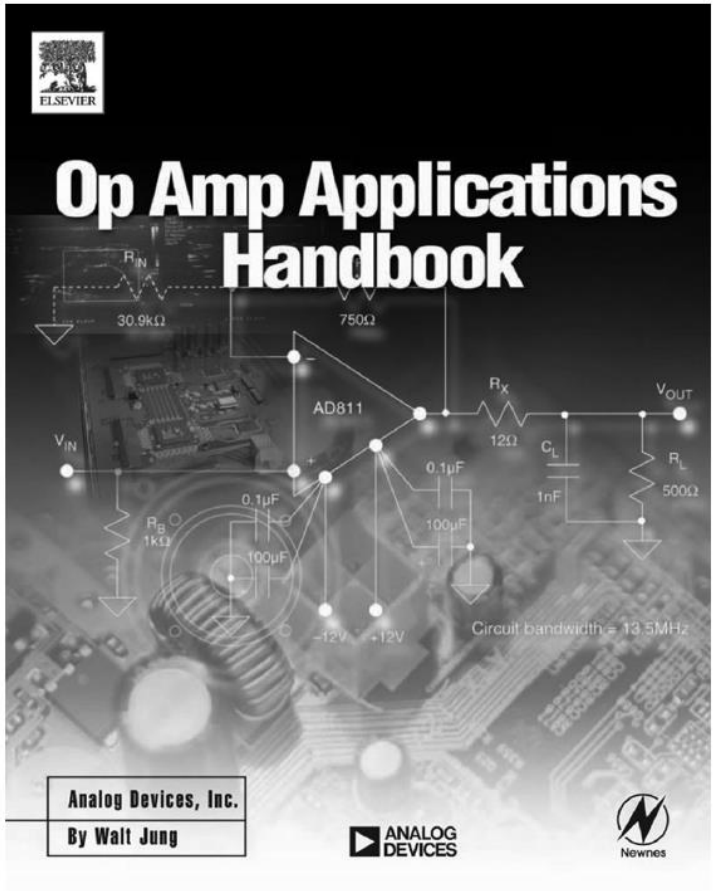
Wien Bridge Oscillator, Bill Hewlett, Ph.D. thesis, 1939

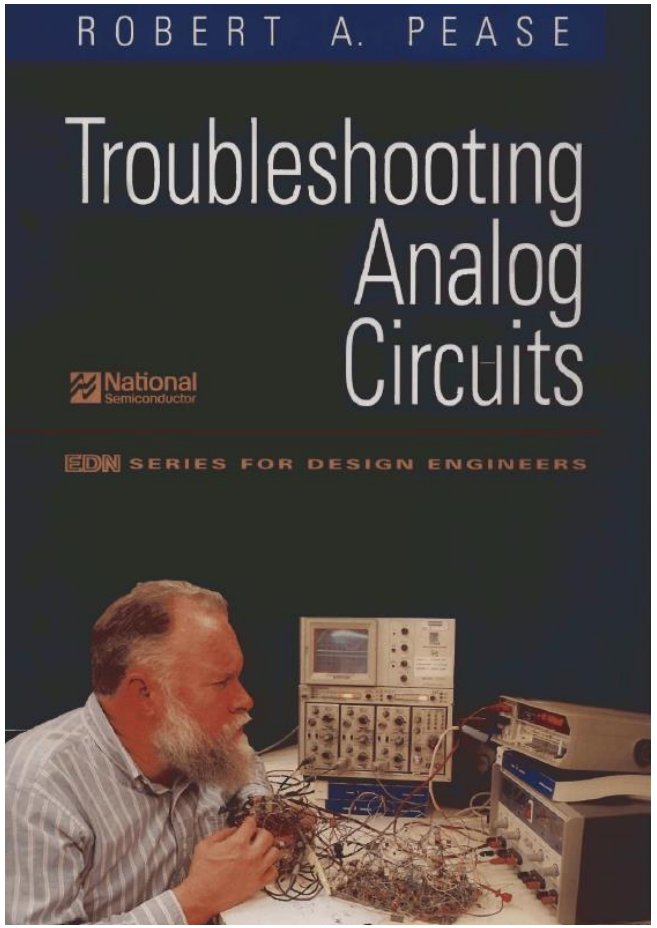


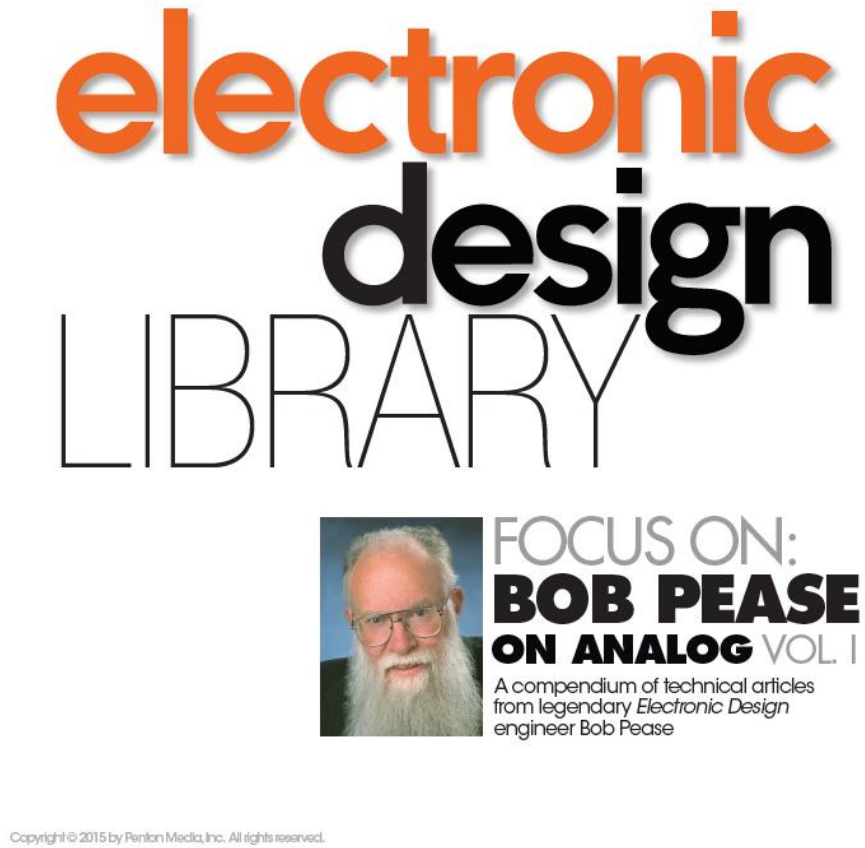


The best reading: the application notes of the circuits. Some are written by the leading industry experts







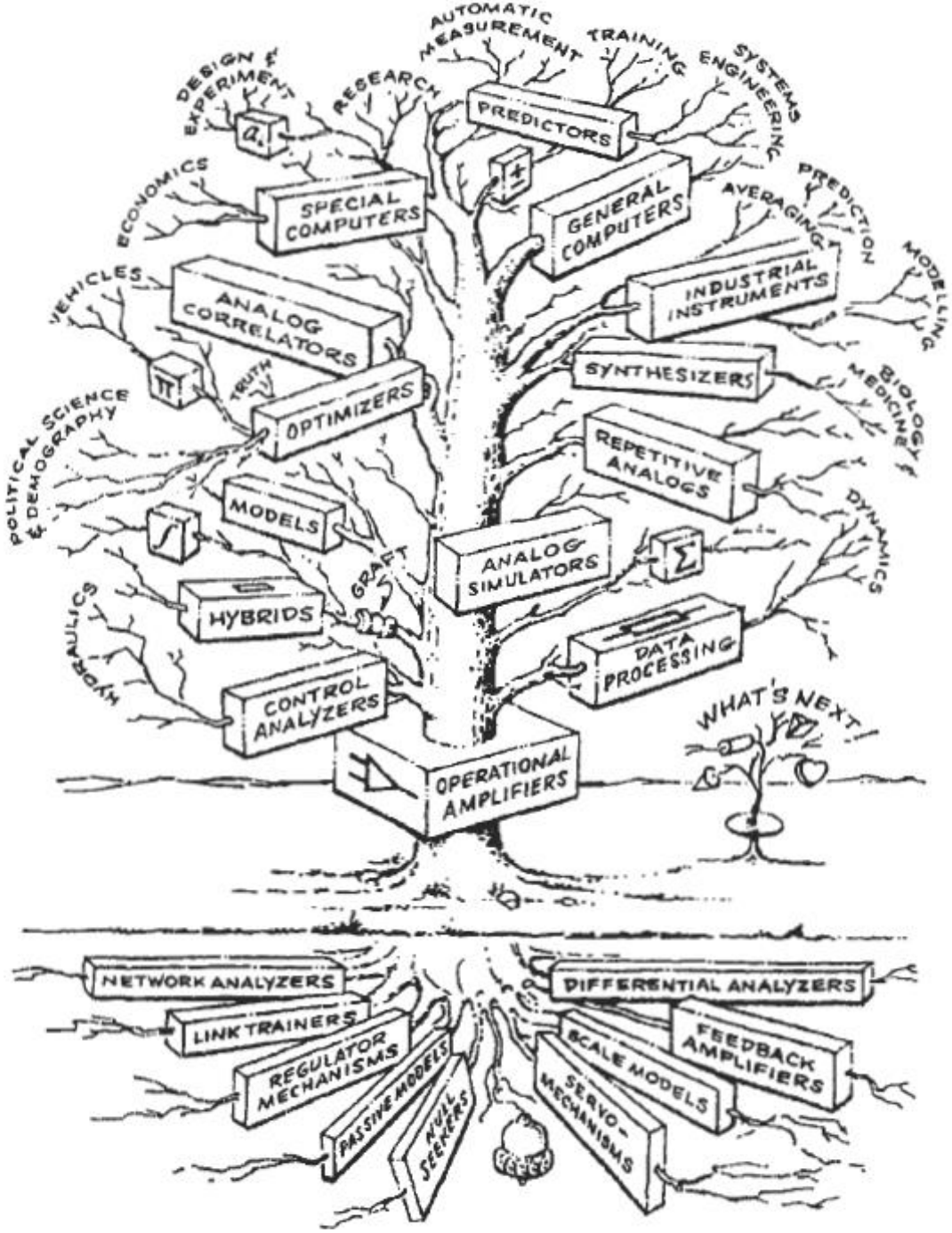


www.electronicdesign.com/home/contact/21809514/bob-pease

www.analog.com/media/en/training-seminars/design-handbooks/Op-Amp-Applications/SectionH.pdf

Analog design : combination of art, science and technology.

The root is the operational amplifier.



The analog tree,
G. Philbrick vision