Lecture 7

Tube and Early Transistor Electronics

Lecture 7

Tube and Early Transistor Electronics

More appropriate dating format

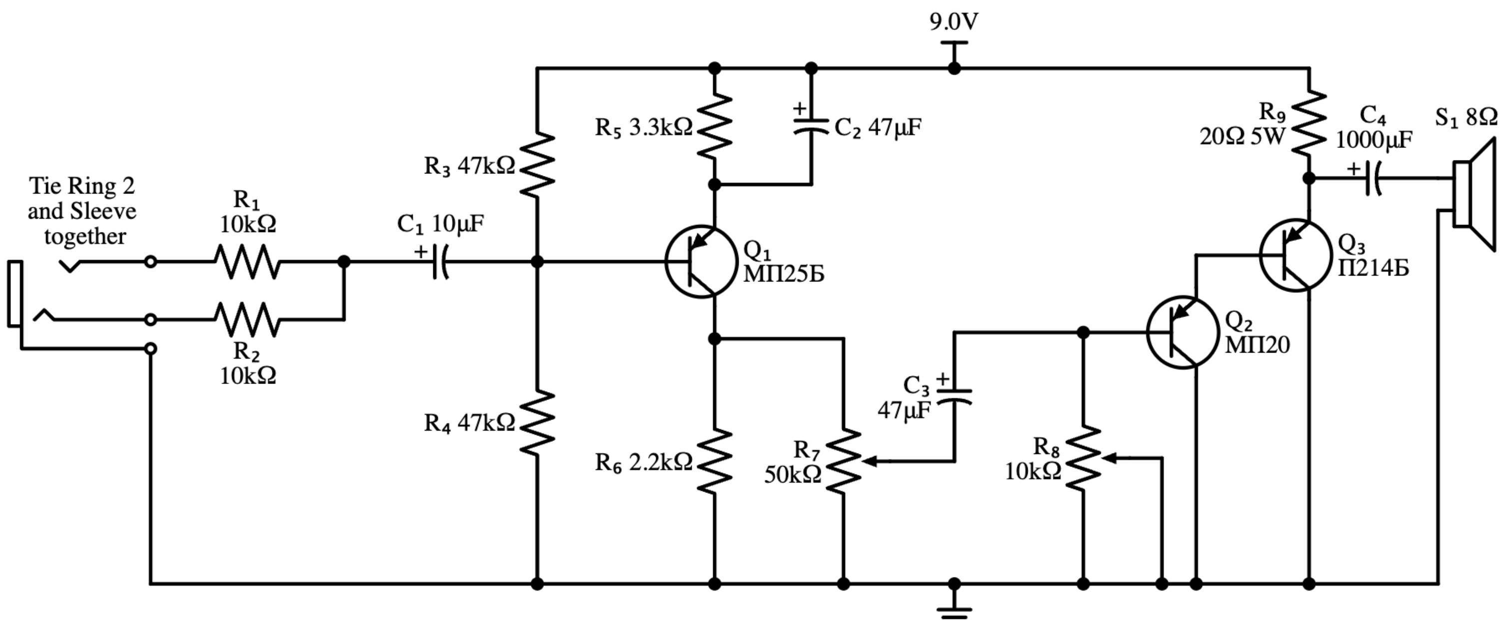
Administrative Stuff

- Today last proper lecture
- Guest lecture on Friday! Phil Erickson from Haystack Observatory coming out. I will get food.
- Lab 07 is out. Stuff will remain in lab through Sunday afternoon (WEATHER-permitting*)
- This will be the last lab...you'll make a transistorized amplifier
  - You can keep it

*I might come in Saturday if snow storm hits on Sunday instead!

Lab 07

- Three transistor amplifier built only using PNP...kind of a weird amplifier



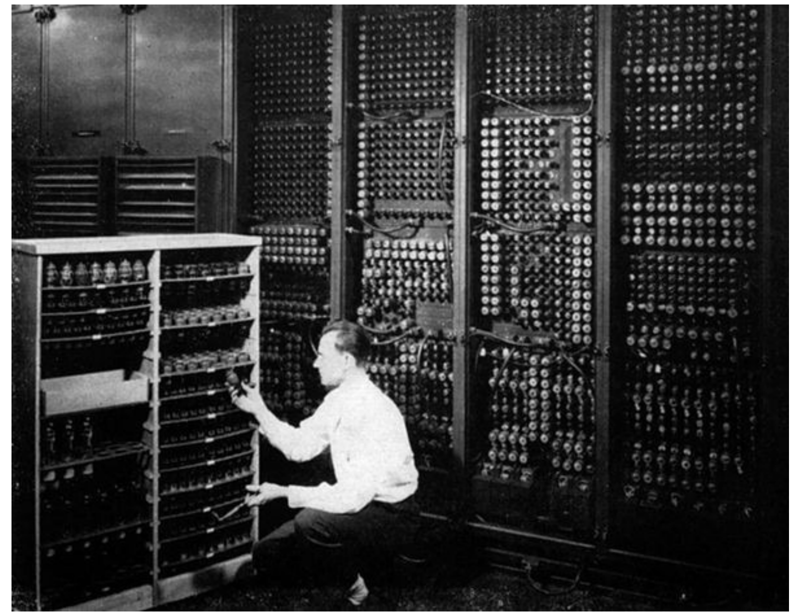
Anywho…

Living with Tubes

- Tubes are really cool tech, but they had their issues:
- Very delicate
- Limited life-time (eventual burnout and then you had to replace)
- Could only be shrunken so far
- Very power hungry
- Needed high voltage…even as they made smaller tubes, these would still need 40, 50, 60V and current consumption would best be measured in Amps (not mA)

Tubes Burned Out A Lot

- Tubes are just like filament lightbulbs...Eventually the filament goes bad
- Or could lose vacuum
- What's worse is it could sometimes be a catastrophic cessation of operatio sometimes gradual fading…very hard to debug then.



Guy Tracking down which tube burned out out of the 18,000 that made up the ENIAC computer

A lot of early debugging techniques were built around tracking down which tubes were going bad.

https://www.computerhistory.org/revolution/birth-of-the-computer/4/78/325

Tubes Consumed A Lot of Power

- ENIAC used something like *170 kW* to run
  - 5,000 additions or 50 multiplications per second
- 2023 M2 Ultra 24-Core CPU & 76-Core GPU, 192GB unified memory uses *330 W maximum (standard is like 49W)*
  - ~50 billion multiplications per second and that's without the GPU and neural cores.

The Problem(s) with Tubes

- A solid-state vacuum tube was dreamt of for decades
- Reliable *semiconductor diodes* were a thing by the 20's but the *semiconductor triode* was elusive
- Julius Lilienfield made and patented an early working (Field Effect Transistor) FET in the 1920s, but this work was largely ignored
  - Semiconductors weren't good quality to take advantage of it
  - Tubes were dominant so seen as more of a curiosity

*also invented/patented the electrolytic capacitor

Thesis advisor was Max Planck!

Transistors

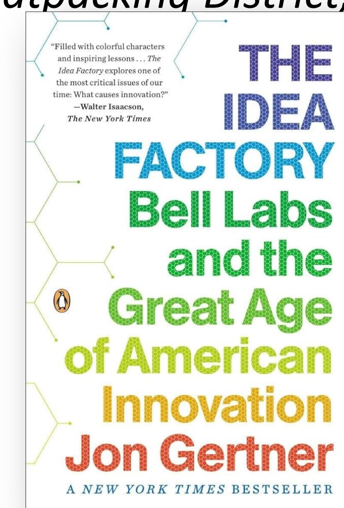
- WW2 motivated a lot of research into a lot of areas.
- One of these was in creating more refined semiconductors for making better mixer diodes which could be better than tube diodes
- During this work people started to wonder if the same pattern could apply to *triodes*, *pentodes*, etc...
- Literature at the time speculated on ”crystalline triodes” and other hypothetical elements
- Multiple groups worked on problem
- The “winners” of the race were them:

ttps://en.wikipedia.org/wiki/History_of_the_transistor

Bell Labs

- Research division of Western Electric which was main subsid/supplier of the Bell System and American Telephone and Telegraph (AT&T) which basically had a monopoly on land-based communication in US
- Did tons of research and had very liberal licensing tendencies so their work was very influential
- Laser, radar, transistor, radio astronomy, UNIX, B, C, C++, solar cells, Charge Coupled Devices, lots of network and information theory...just goes on and on

Old Bell Labs facility in Meatpacking District, NYC



Transistors

- Mid-afternoon on Dec 23, 1947, these three guys demo-ed a working transistor to staff at Bell Labs (PNP-germanium transistor with gain of 18).

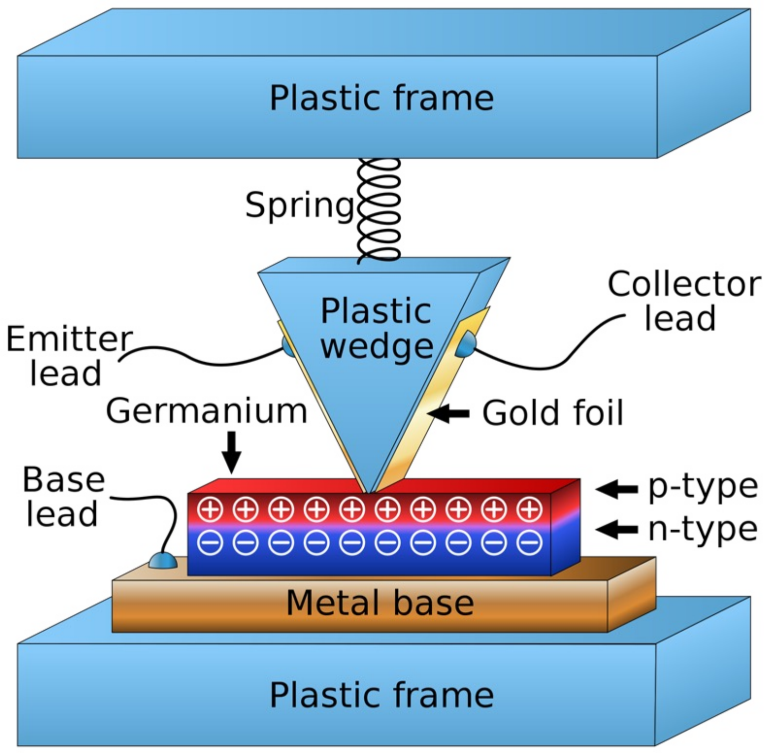
William Shockley
MIT, PhD '36, sadly…

John Bardeen
One of only two people to have won two Nobel Prizes! Marie Curie was other!

Walter Brattain

https://www.computerhistory.org/revolution/digital-logic/12/273

The Point-Contact Transistor



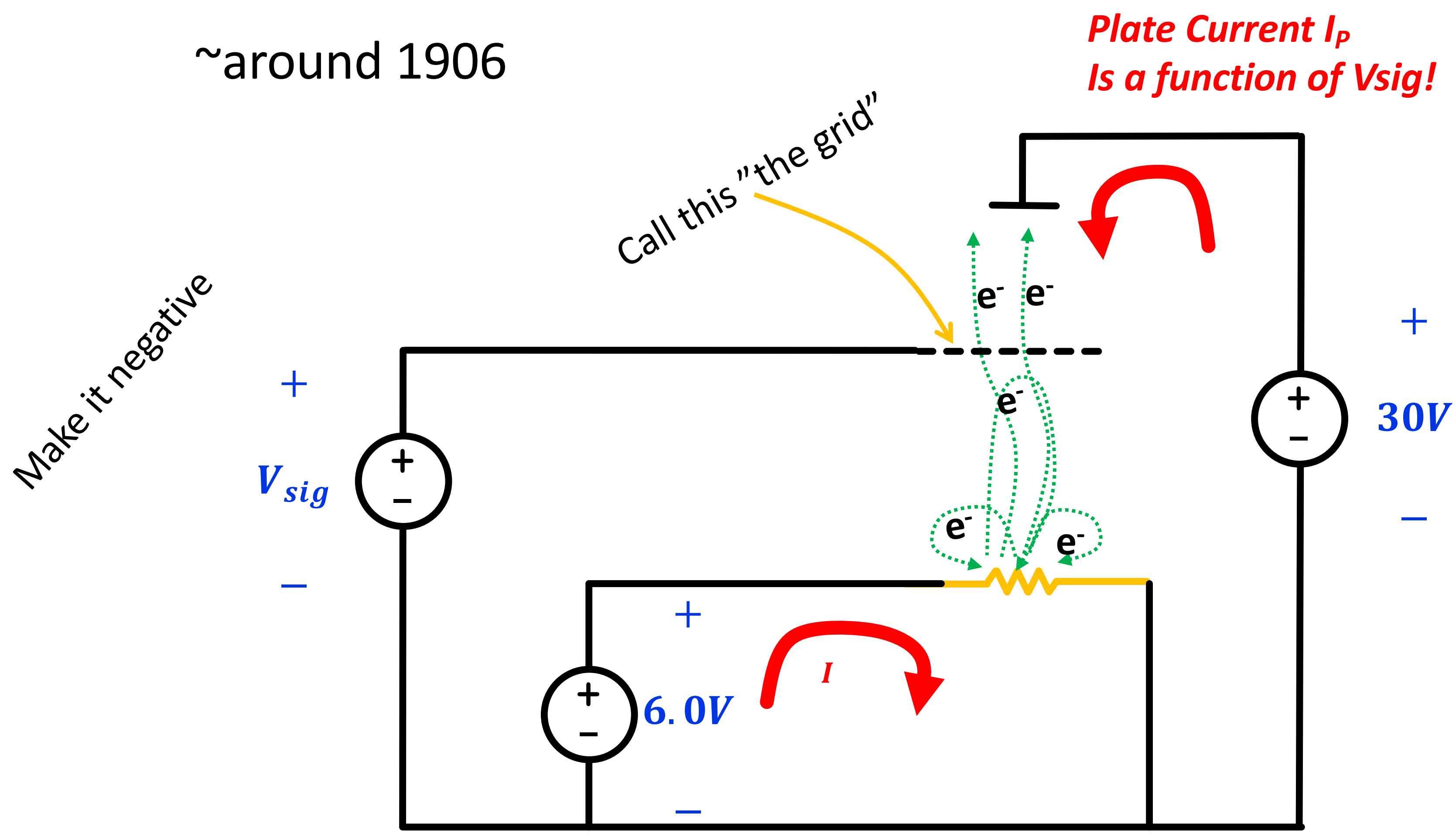
https://www.computerhistory.org/revolution/digital-logic/12/273

Point Contact is weird transistor

- Very hard to manufacture
- Very, very delicate
- Tended to get stuck “on” aka act as latch
- Its size and lower voltage were the only things it had going for it, but the first two issues did not make it very competitive with tubes.
- Shockley kept working and eventually came up with the more “modern” junction transistor comprised of three layers of silicon of different “types”
- In 1951 he patented the Junction transistor which is the first “modern” transistor which we still use today.

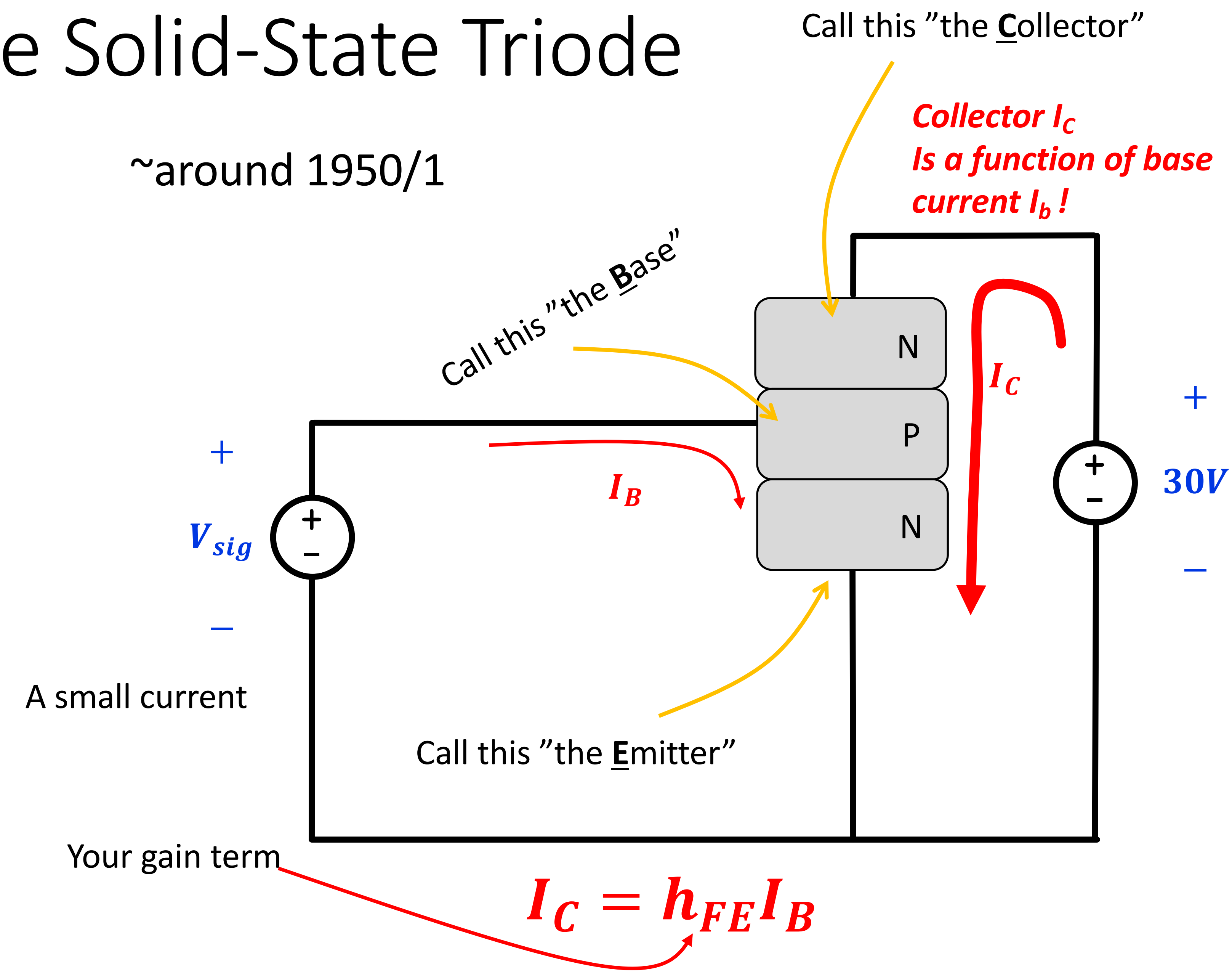
Remember the Triode

~around 1906



The Solid-State Triode

~around 1950/1



$$I_C = h_{FE} I_B$$

First Big Departure from Tubes: How Signal is Controlled!

- Tubes were (largely) devices that used a **voltage** to modulate a **current** (varying grid voltage would vary plate->cathode current)
- Early Transistors were devices that used a **current** to modulate a **current** (varying current from base-to-emitter would vary current from collector-to-emitter)
- ***Big departure!***

Implications

- Since junction transistors relied on putting in an input current and amplifying it that meant that the input impedance of the device was generally lower than that of a tube:
  - Remember, when a triode was operating with a negative grid-cathode voltage, current into the grid was negligible.
- Coupling and connections between stages needed to be done differently

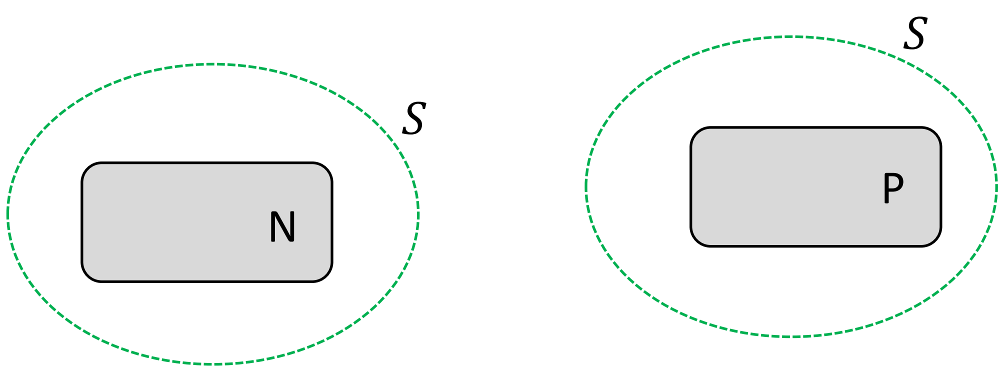
Semiconductors

- Once semiconductor crystals could be made with high purity they decided to ”dope” them with certain atoms to make their crystal structures have either excesses of electrons or lacks of electrons (holes)
- Rarely was “pure” semiconductor used…it was usually doped into two types:
  - “N”-type (had excess of mobile electrons)
  - “P”-type (had excess of mobile “holes”)

N and P type Semiconductors

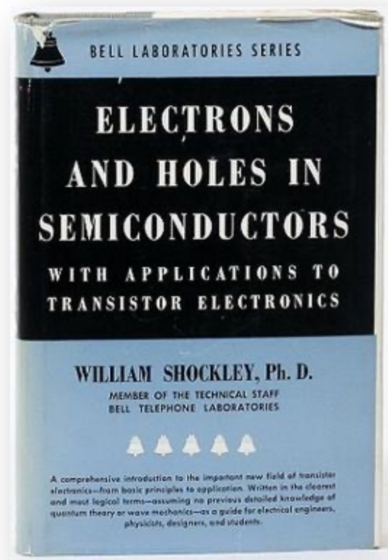
- N-type is ***NOT*** negatively charged…it is electrically neutral…it just has electrons which are "mobile"
- P-type is ***NOT*** positively charged…it is electrically neutral…it just has holes which are "mobile"

$$\oiint_S E\, dS = 0$$

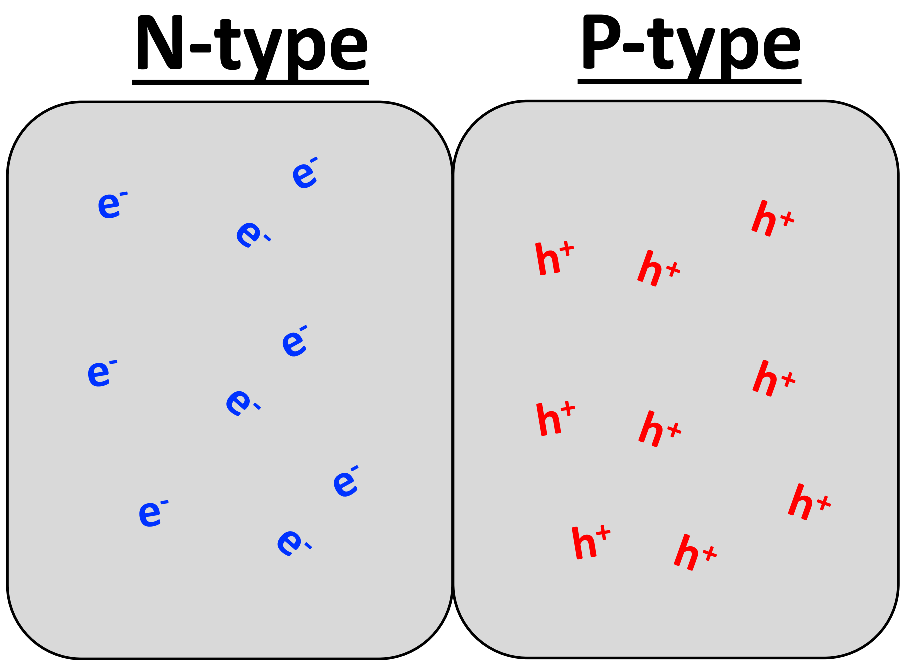


What the Hole you Talking About?

- It is a “quasi-particle”. A missing electron in a crystal lattice can roughly be thought of as a particle of negative e^- in charge.
- One analogy is how “gaps” in a traffic jam will move opposite the flow of traffic and from a distance it looks like “anti-cars” are moving
- Analogy taken from Shockley’s famous book

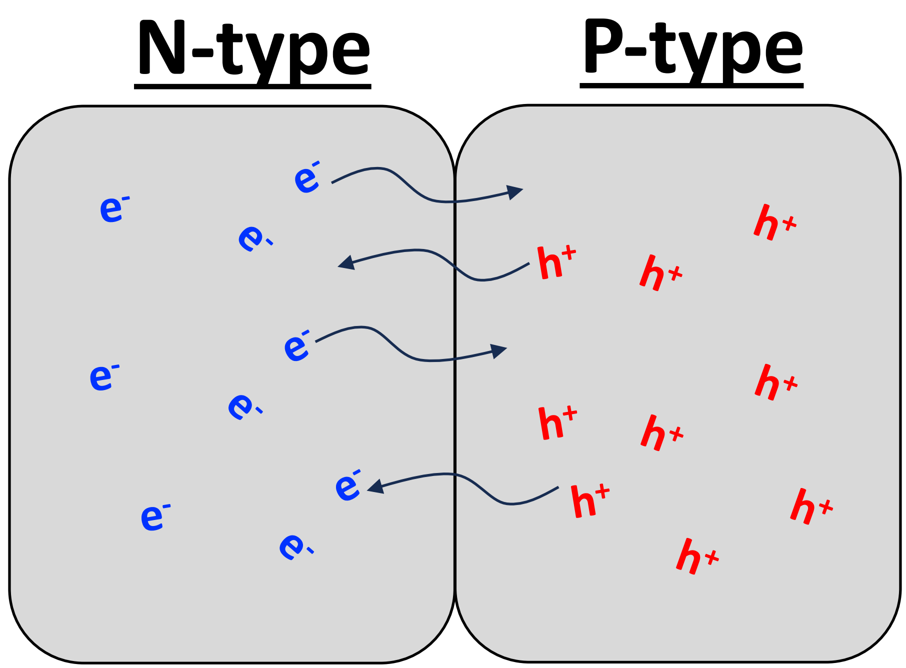


Drift-Diffusion



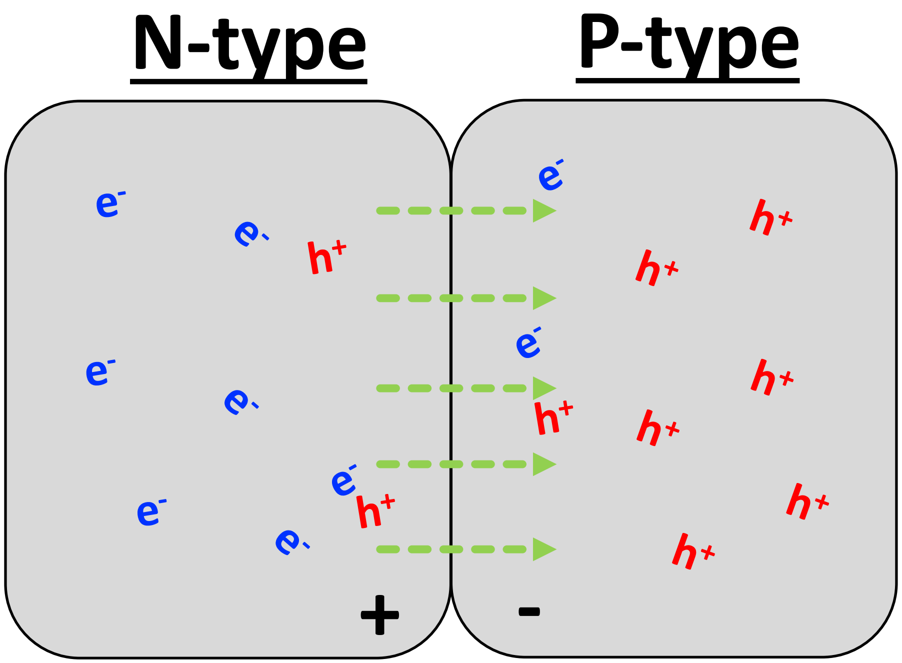
Diffusion

- High Concentrations of anything will always spread out via Brownian motion



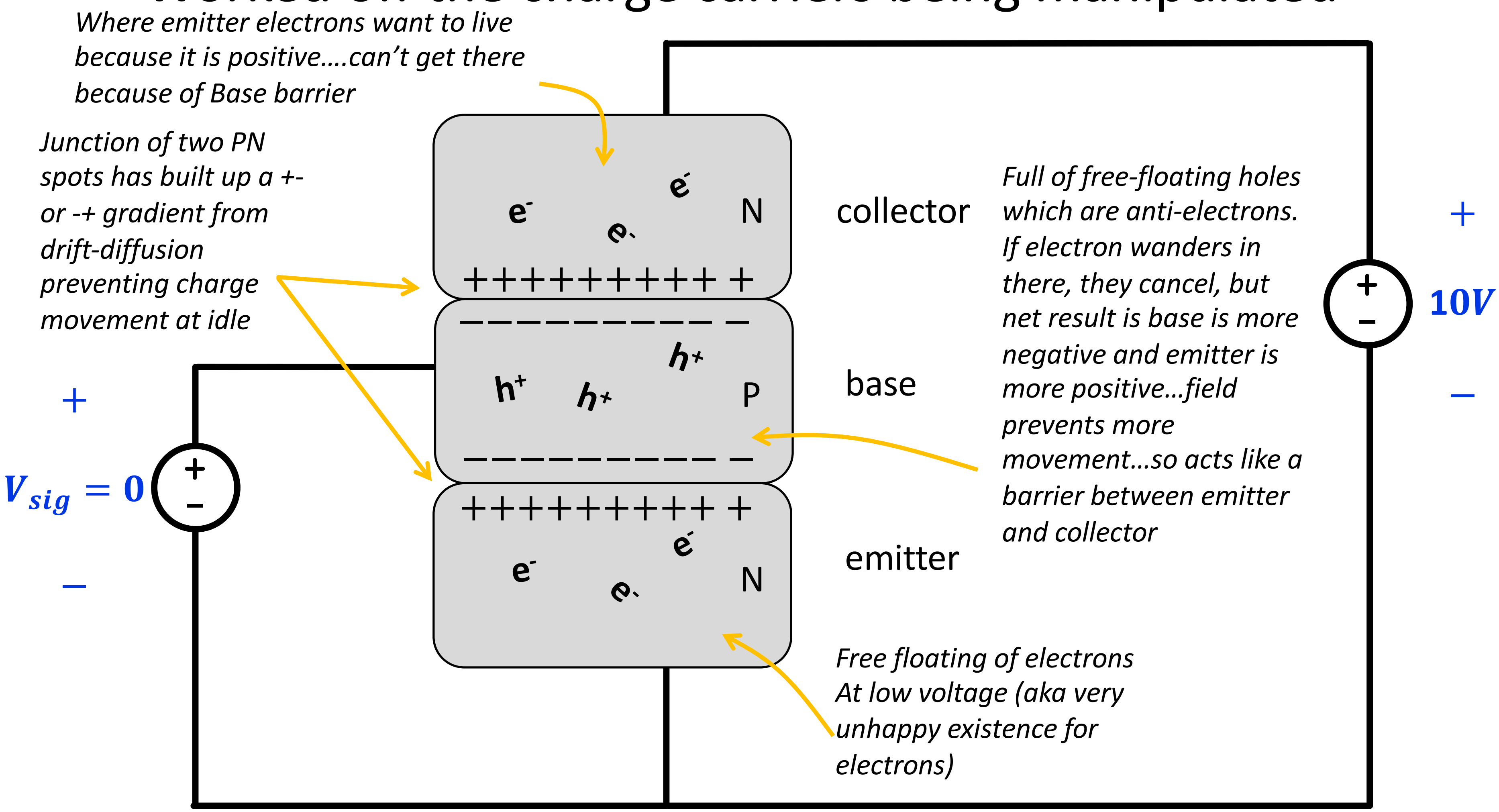
Drift-Diffusion

- Buildup of h^+ in N and e^- in P leads to a charge differential and electric field eventually resulting in a stabilization and cancellation of any further charge movement



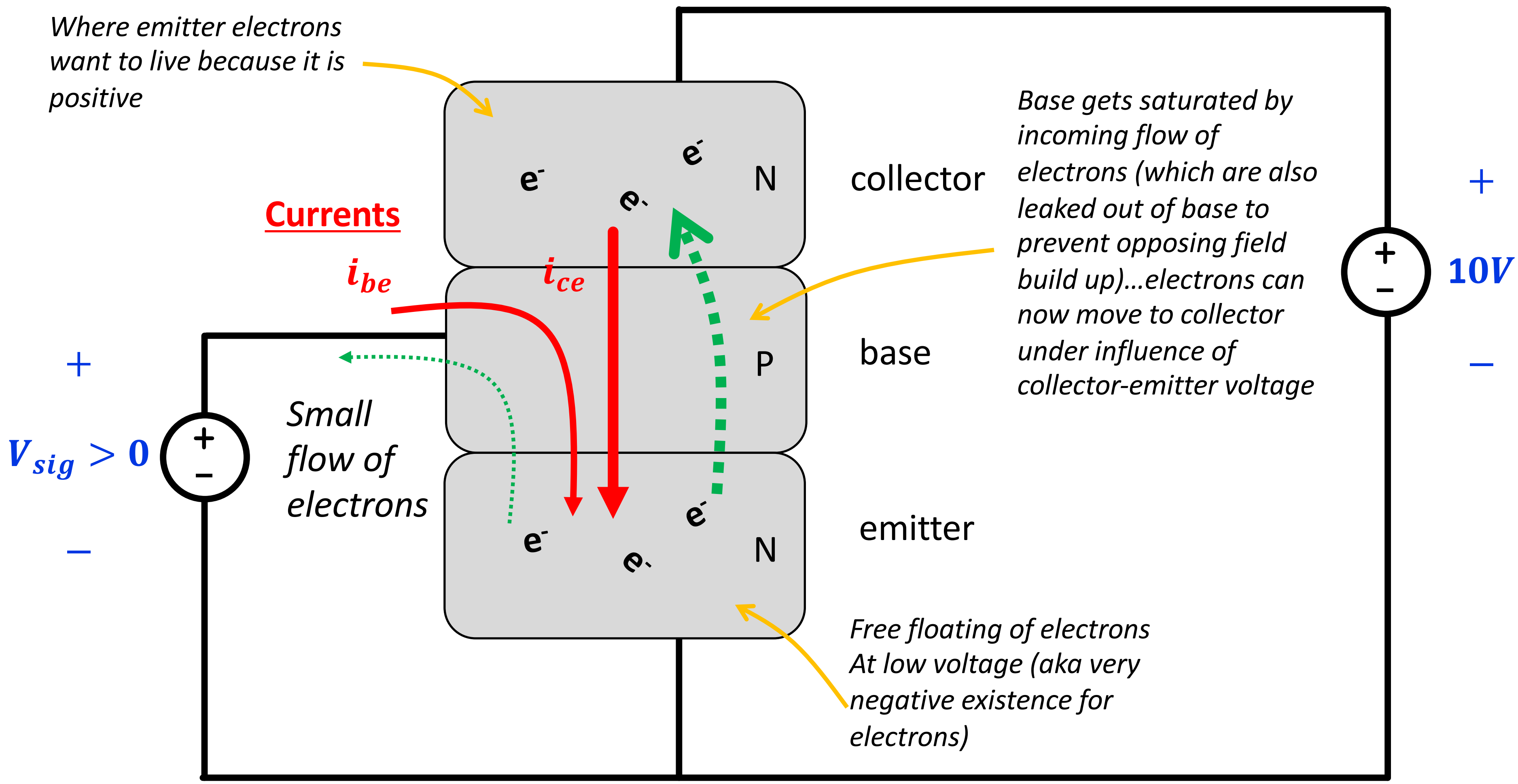
Why this nomenclature?...consider NPN transistor:

- Worked off the charge carriers being manipulated



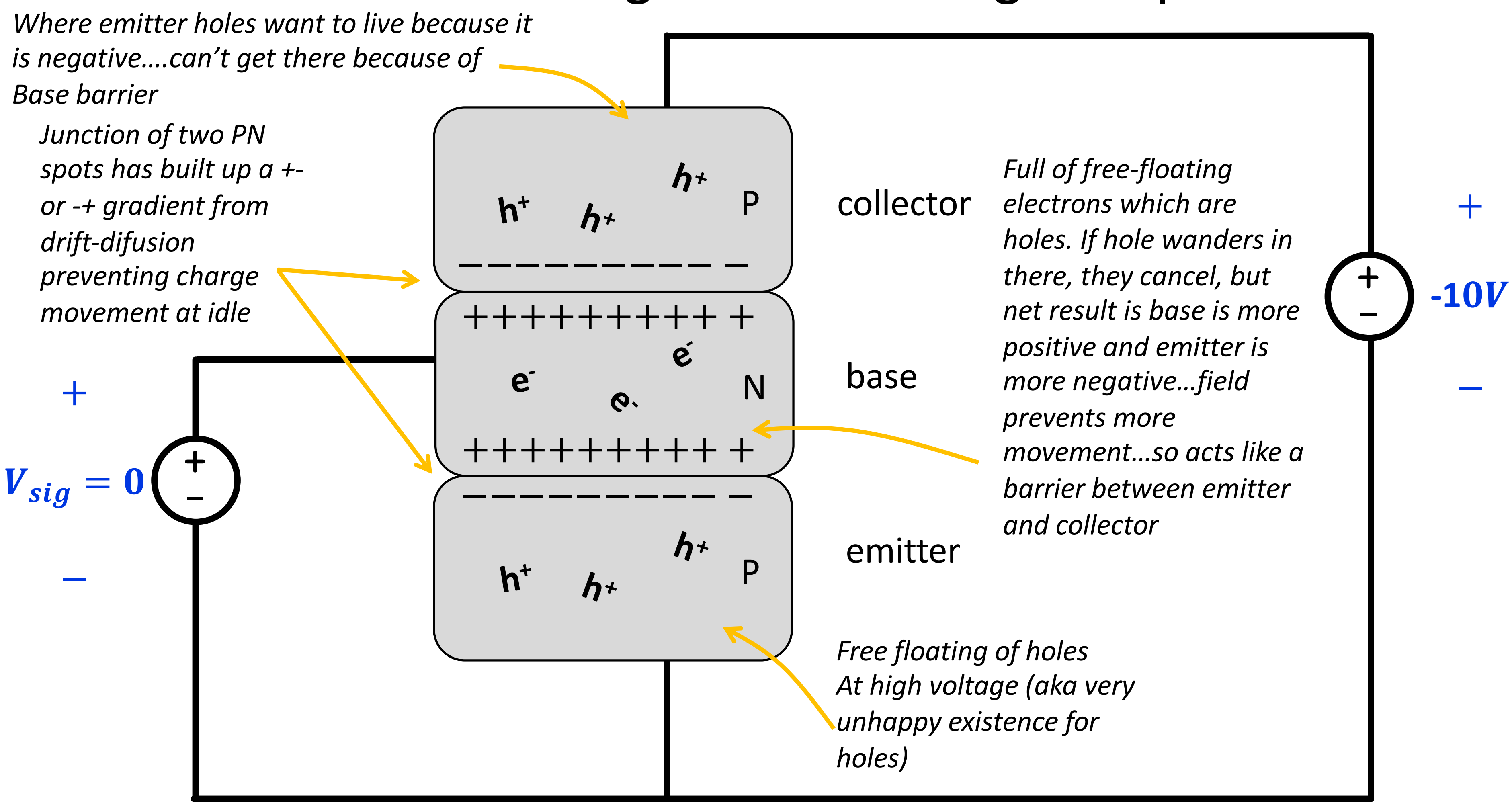
Let a little current flow into base (allow a few electrons to escape there…)

- No buildup in base-emitter



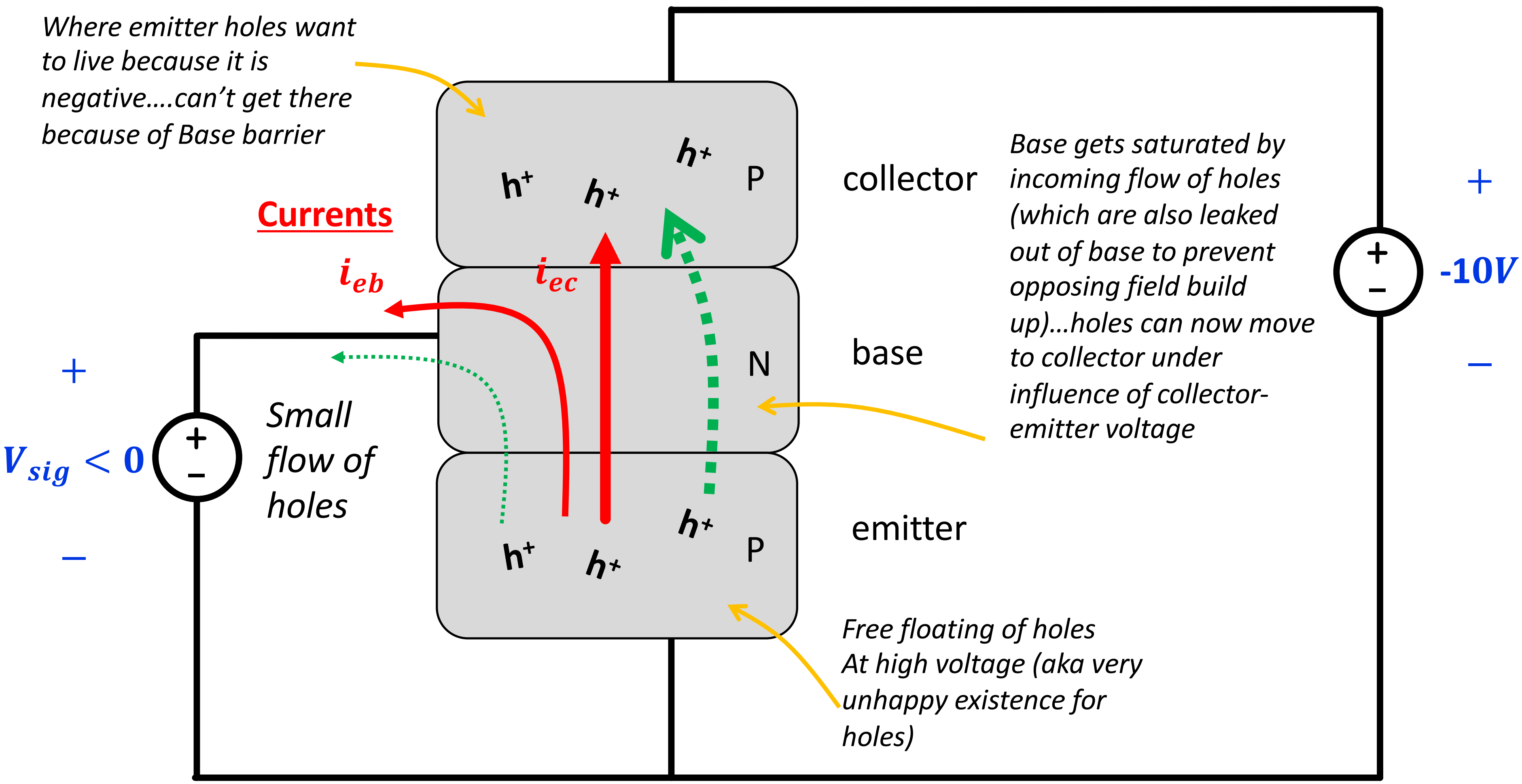
Same But Opposite with PNP

- Worked off the charge carriers being manipulated



Same But Opposite with PNP

- Worked off the charge carriers being manipulated

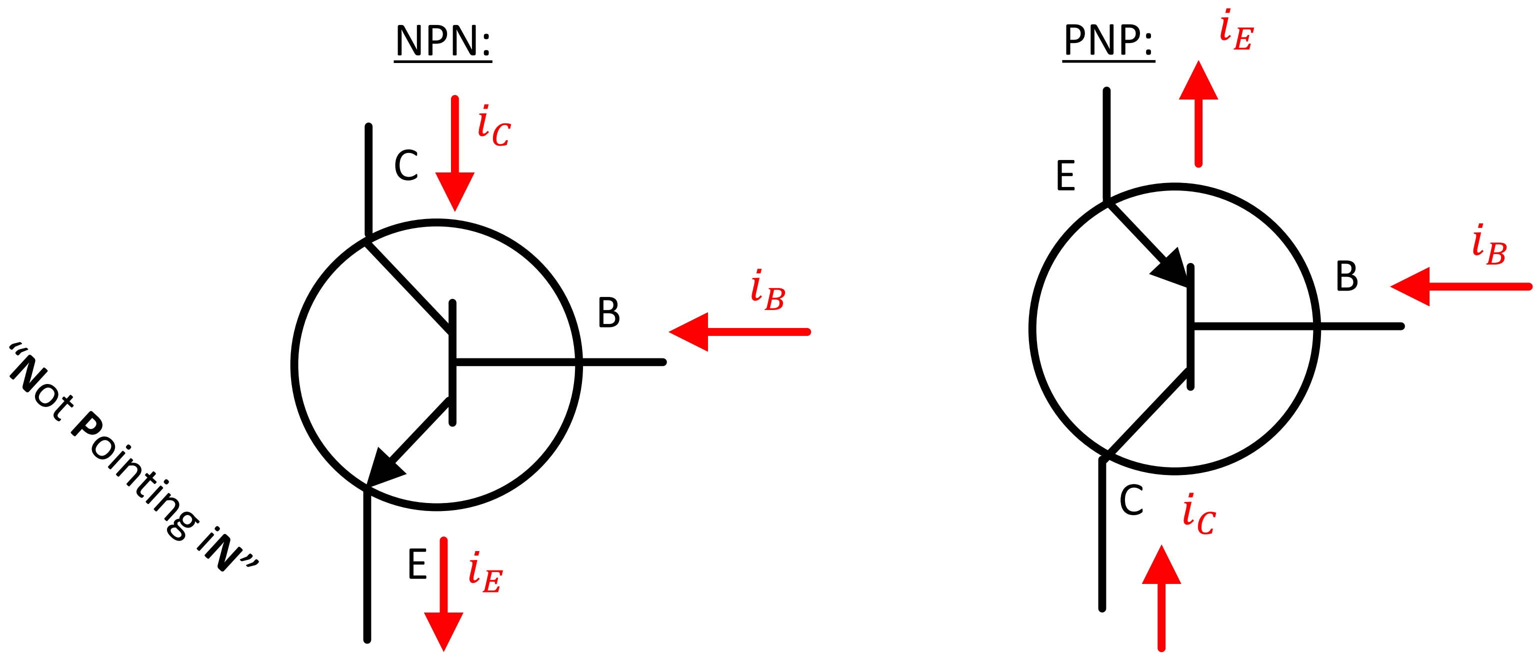


But really...

- My stuff is just cartoons...
- Go take 6.208, 6.209, 6.250

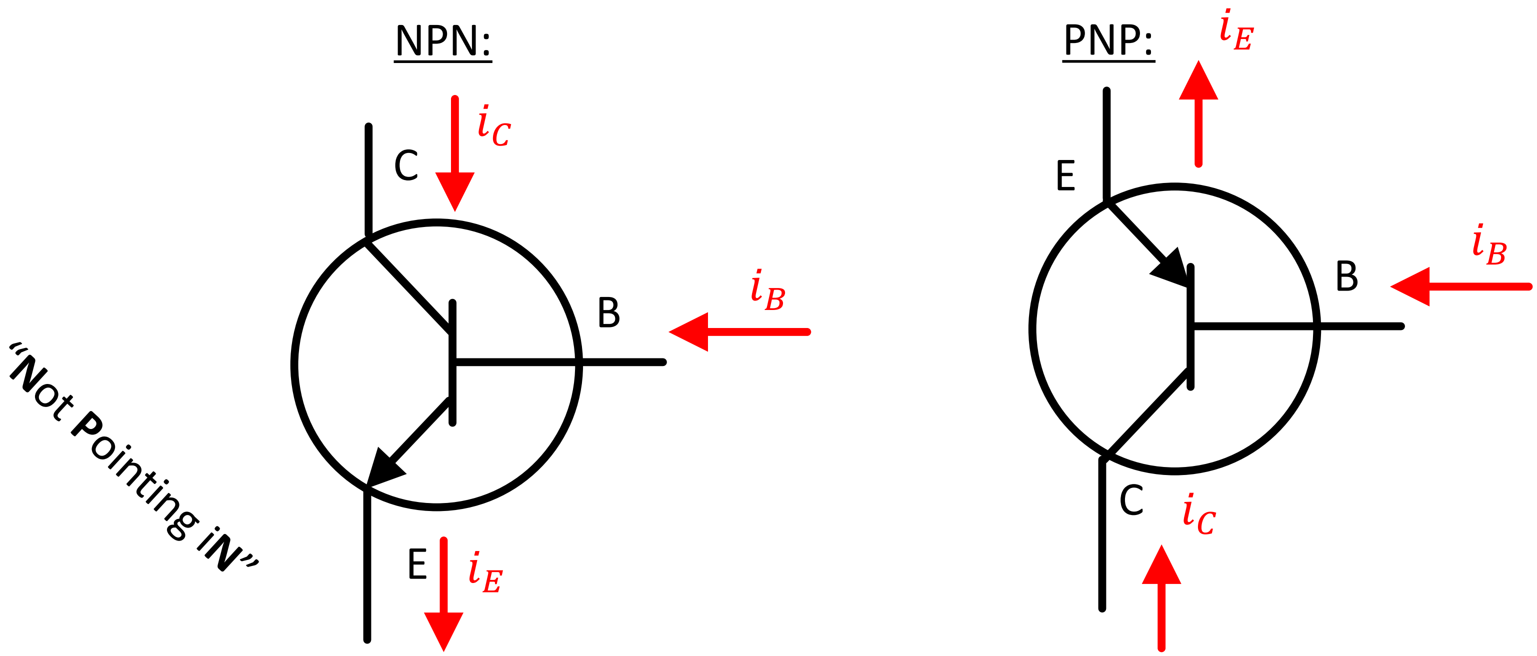
Second Big Departure: Two Types of Transistors

- With transistors by swapping the semiconductor "type" order you could get two different complementary devices:
  - NPN where you modulate the flow of electrons
  - PNP where you modulate the flow of holes



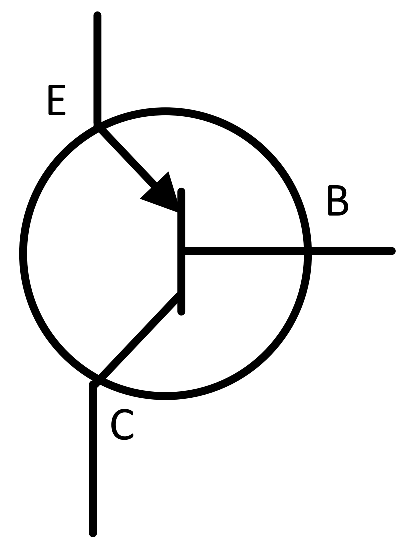
The Result of these two devices:

- NPN: Collector current (positive) flows when base current is positive!
- PNP: Collector current (negative) flows when base current is negative!



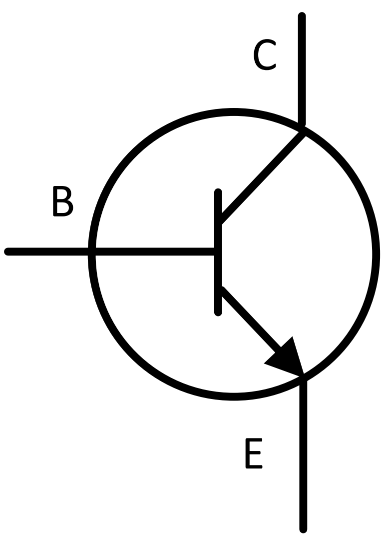
Early Transistors

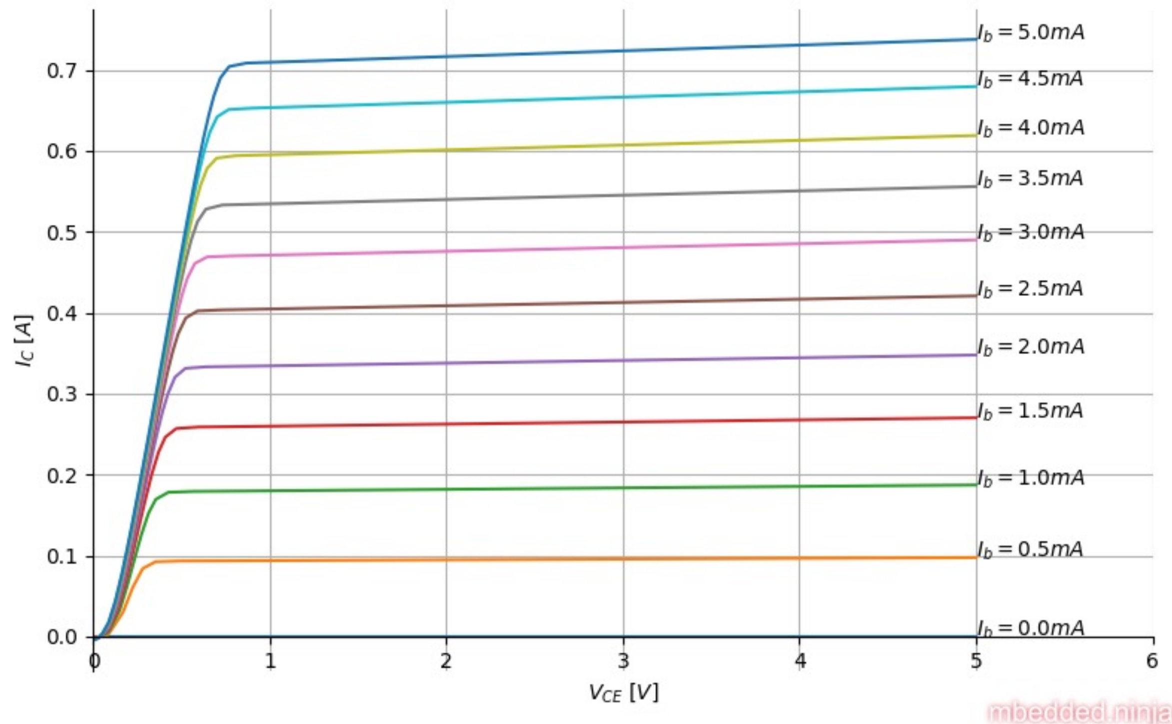
- Germanium was easier to purify early on so it was used a lot at first.
- The majority of early germanium transistors were PNP-based.
  - Based on a number of manufacturing limitations with the different dopants
- NPN transistors did exist but never became common-place until mid 1950s
- Silicon proved to be a far better:
  - Band-gap voltage of 0.7V rather than 0.2V for germanium, so could make better insulators (when needed)
  - Had better thermal properties



Transistors were three-terminal devices…just like triodes/tetrodes/pentodes

NPN:





https://blog.mbedded.ninja/electronics/components/transistors/bipolar-junction-transistors-bjts/output-transfer-characteristics-microcap-sim/plot.png

Pay careful Attention!

- NPN and PNP type devices work oppositely:
- In NPN, small current from *base-to-emitter* causes large current from *collector-to-emitter*
- In PNP, small current from *emitter-to-base* causes large current from *emitter-to-collector*.
- Pay real close attention to directions defined for devices in datasheets and schematics.
- People would often try to avoid drawing negative numbers where possible, so you'd have like i_{be} vs. i_{eb} for NPN or PNP defined, etc...

Semiconductor Device Physics

- The "Transistors" Service Training Course written by *Bob Widlar* in 1960 does a fantastic job of showing how transistors work without necessarily disappearing too much into physics
- I've included on course website

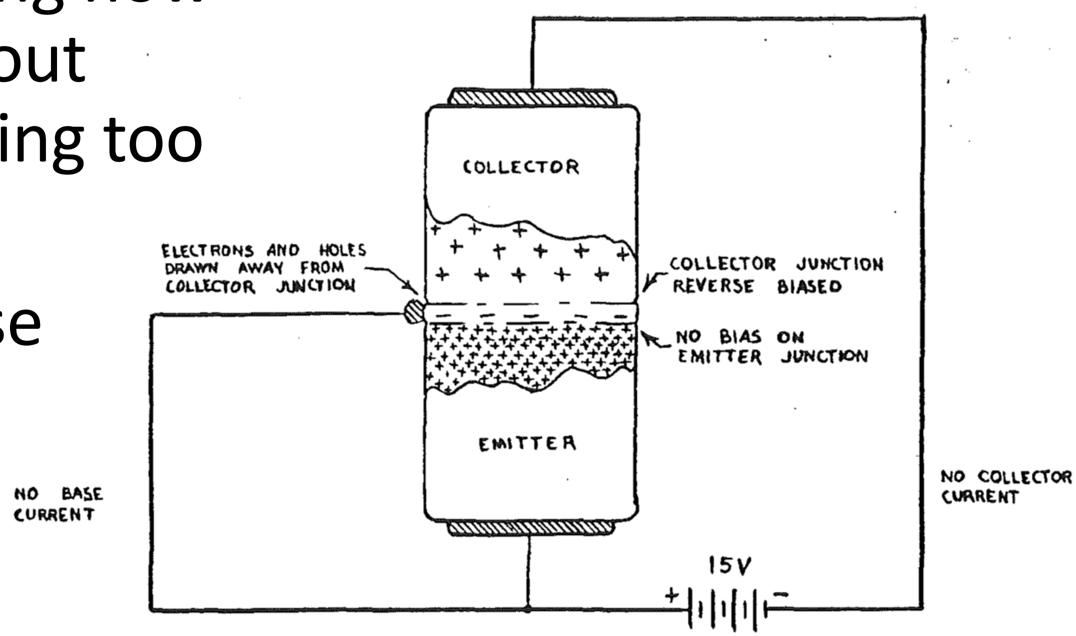
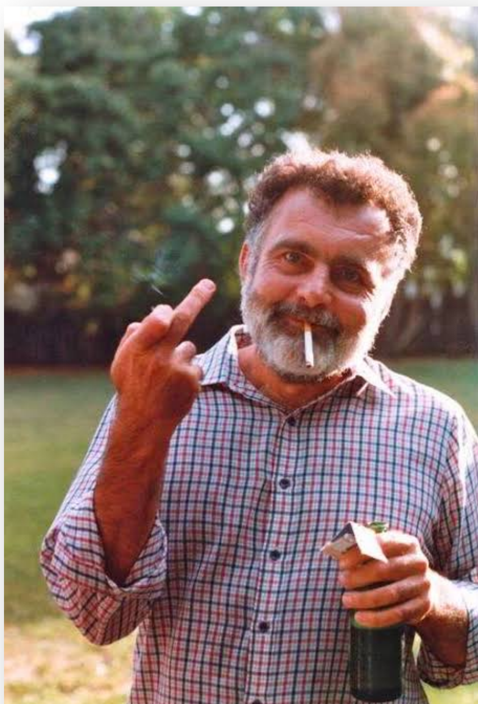


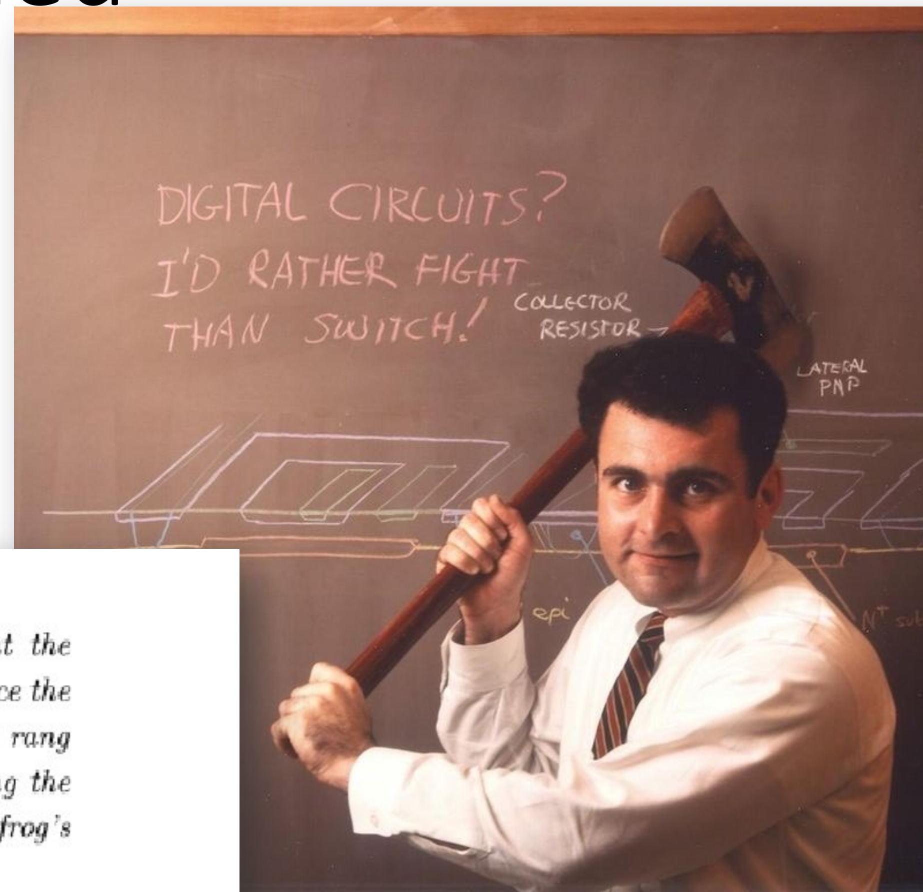
Figure 1.7. PNP Transistor in Nonconducting State.

Aside: Bob Widlar

- Early Analog Transistor Engineer
- Weird Guy
- Designed first real integrated op amp and many other famous circuits



Bob Widlar, continued

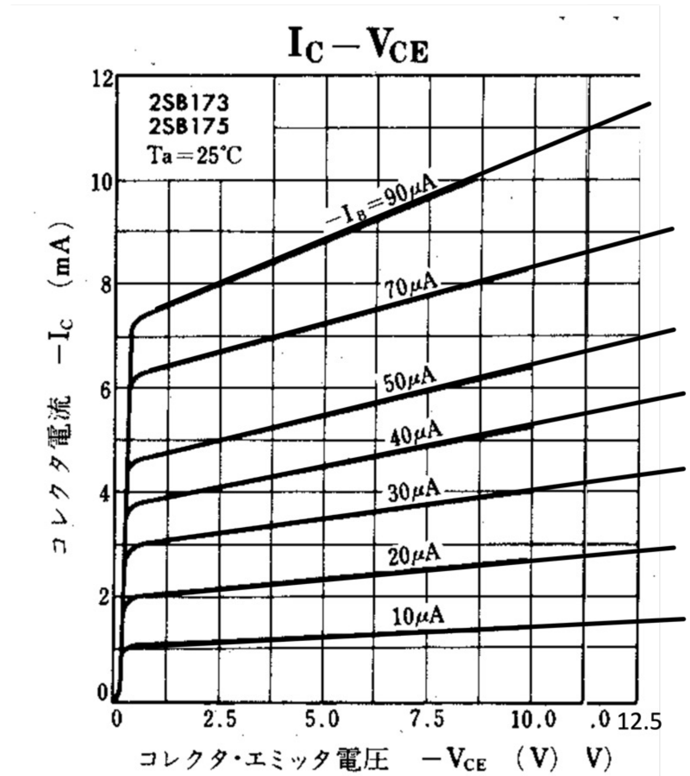


"A Fairchild researcher trained a frog to jump at the sound of a bell. The researcher measured the distance the frog would jump, then removed the frog's legs and rang the bell again. The frog did not move, thus proving the Fairchild R&D group hypothesis that removing a frog's legs deafens the animal."

Robert J. Widlar,
describing Fairchild's R&D group in 1967

Third Big Departure with Transistors

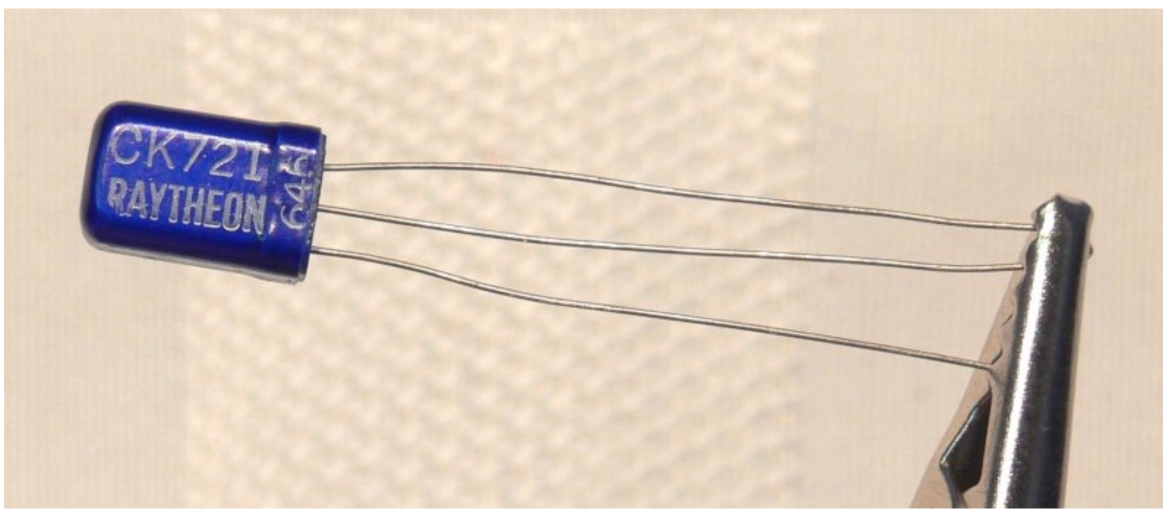
- Transistors could do what we needed (give us a juicy pentode-like I-V set of curves) all while running at very low voltages!
- Also didn't need to be heated
  - Tubes generated free carriers via thermionic emission which needed hungry hungry hippos/heaters
  - Transistors had free carriers because of material science and the doping of semiconductors



Look 12.5V!!!

Early Transistors

- Development Happened Fast!
- First transistor: ~Dec 23, 1947 (79 ish years ago)
- First good junction transistor available for non-government people was CK721 (Raytheon)…around 1953…cost about 7 dollars

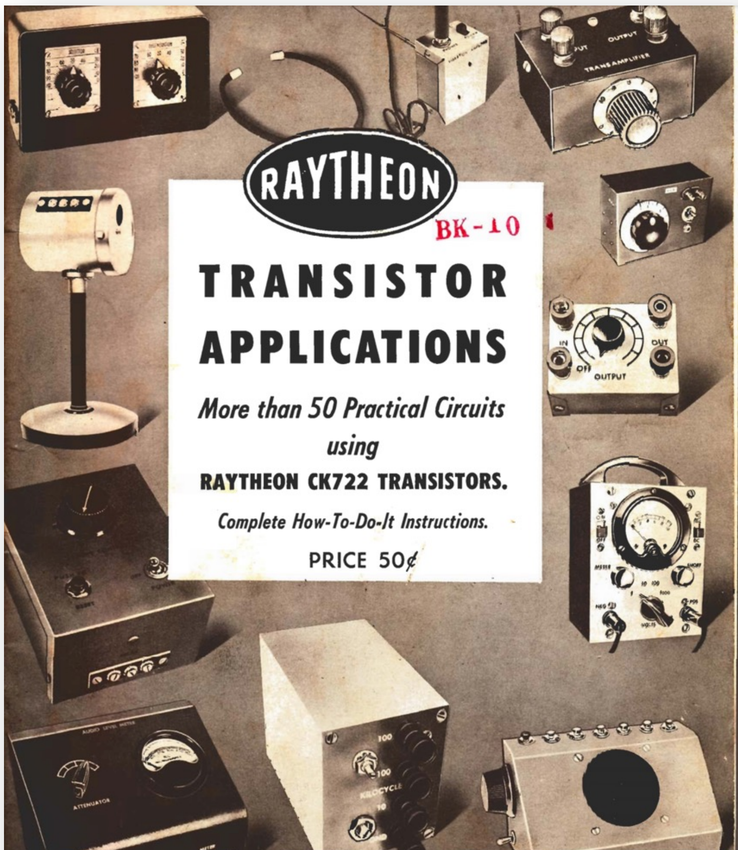


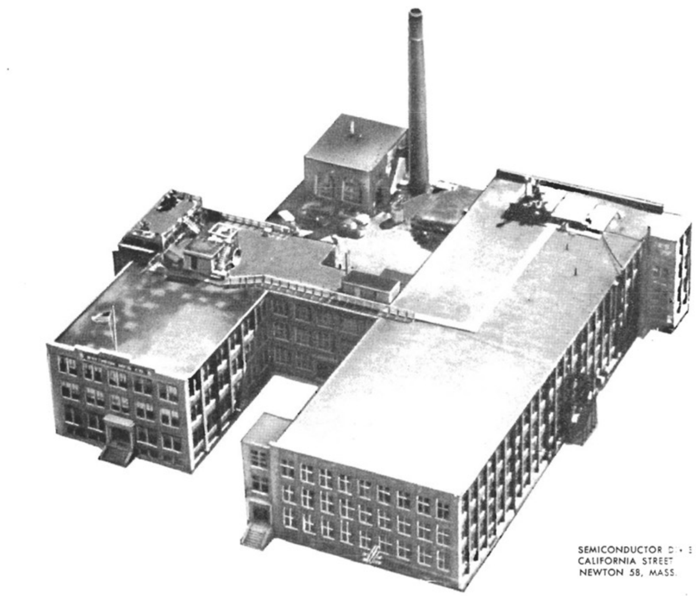
So as a circuit engineer in the early 1950s…

- Found yourself in a rapidly changing field where:
  - The amplifying devices were different (current vs. voltage based control)
  - The primary new type worked opposite the way you knew (tubes were N-type…most transistors were P-type at first)
  - Voltage ranges for regular operation were much smaller!
- Manufacturers Needed to Show Users How to Build with Transistors and provided technical manuals and lists of circuits to build along with discussions about how to work with them!

Early Transistor Manufacturers

- Tons of early transistor manufacturers.
- Raytheon was a big early one





THE HOME OF RAYTHEON TRANSISTORS

This multimillion dollar plant is the largest in the world devoted exclusively to the production of semiconductors. Three times the size of former facilities it meets the demand for Raytheon Transistors brought about by Raytheon leadership in transistor design and development.

Raytheon produced the first commercial transistors for hearing aids — the transistors that have revolutionized the hearing aid industry.

In the computer industry and in the newest and finest portable and automobile radios the new Raytheon RF Transistors are proving equally valuable and important.

Today, there are several million Raytheon Transistors in use —

More In Use Than All Other Makes Combined

Lots of Really Cool Simple Designs

AUDIO AMPLIFIERS

By **CHARLES W. MARTEL**
Raytheon Manufacturing Company

crystal mike will give at least 10 db less power than a dynamic microphone and, in addition all crystal microphones have high impedances which will not match the relatively low input impedance of the grounded emitter CK722 unless coupled through a step-down transformer. The circuit will be identical to that of Fig. 3C except that the transformer primary impedance should be as high as possible (several hundred thousand ohms) and the secondary impedance should be about 1000 ohms. An interstage transformer of the type used to couple the voice coil of a loudspeaker microphone to the input tube grid may be used "in reverse" to obtain a reasonably good impedance match.

With the input circuit determined, the next step is to add transistor stages to obtain the desired gain. The user of this amplifier will listen-in

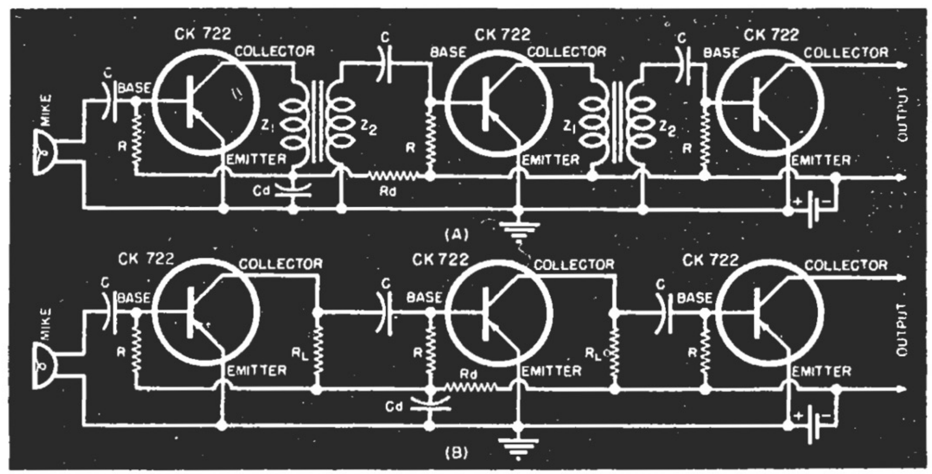
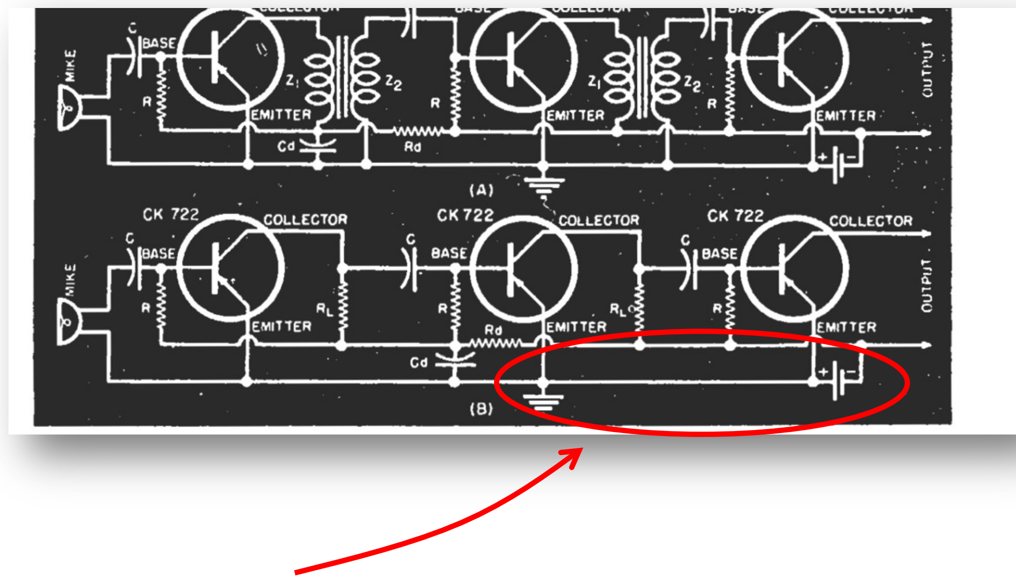


Fig. 2. (A) Transformer-coupled and (B) resistance-coupled amplifiers using transistors.

a voltage at the collector because of

Lots of Really Cool Simple Designs

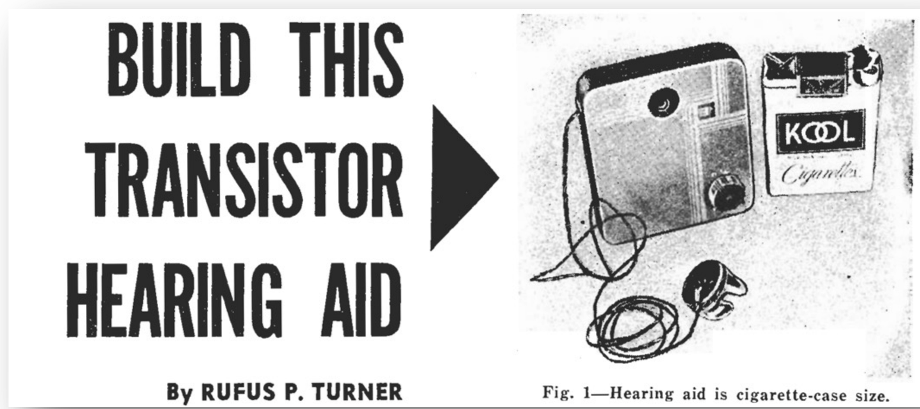
- They'd sometimes do weird things to make the tube-to-transistor transition be easier.
- Many PNP-transistor circuits have their ground being the high voltage of the circuit!
- This is to keep the same emitter/cathode-at-bottom pattern consistent



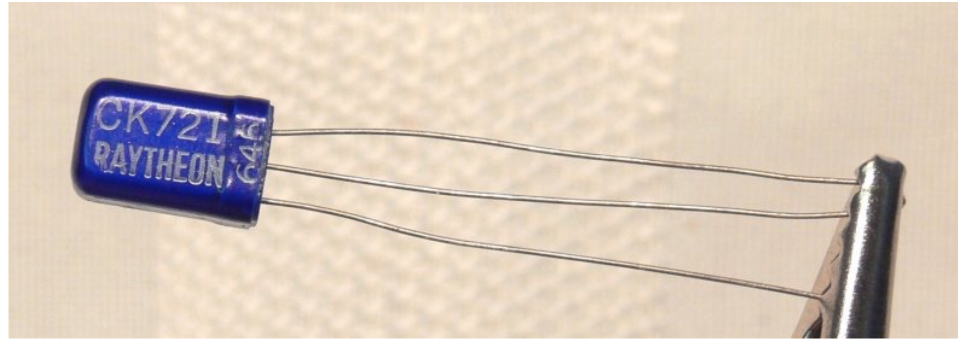
Early Killer-Apps for Transistors!

- Hearing Aids and Nuclear missiles were the first two big applications.
- Want a tiny battery powered hearing aid
- Want your detonator to be very robust on a ballistic missile

First electronic transistorized hearing aid
Used several CK718 transistors



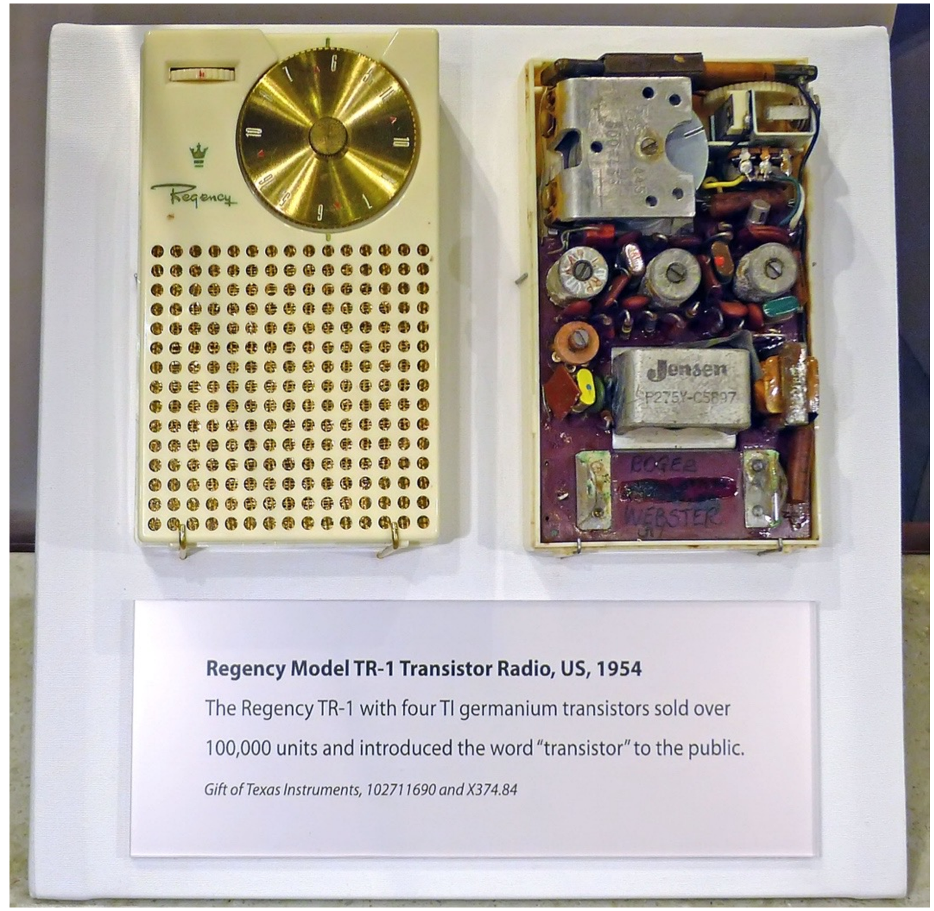
CK721/722



- Hearing aid transistor (CK718) rejects that didn't have as much gain were classified as either CK721 or CK722 depending on actual gain and then sold at different price points to general population
- These formed the basis of startups and lots of new circuits and ideas. A lot of the integrated circuit designers that showed up over the next few decades got their start with these parts.

Regency TR-1

- First Transistor Radio
- Made by Texas Instruments in 1954
- Really expensive at time compared to vacuum tube radios ($49.95)…about $443 in today's dollars
- Meant to be personal...walk around with earphones in...never before!



http://www.regencytr1.com/

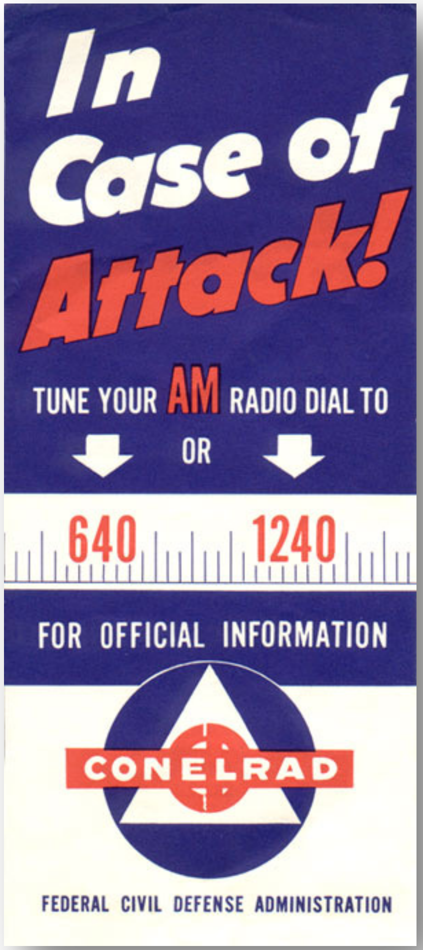
Interesting Aside…

- What are these red markings for?

- They correspond to:
  - 640 kHz
  - 1240 kHz

CONELRAD System

- Between late 1953 and 1963 all US radios were required to have markings for these two stations
- In time of Soviet attack, all US AM stations would go off the air and only certain ones would broadcast emergency info on two frequencies (640 kHz and 1240 kHz)...stations would broadcast for short periods then rotate to other stations.
- Designed to confused Soviet bombers so they couldn't geolocate using commercial frequencies



https://en.wikipedia.org/wiki/CONELRAD

Anyways…

- Back to Transistors....

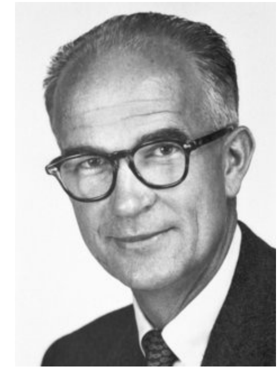
- And William Schockley

Transistor Trio in Life Photoshoot in late 50’s when they won their Nobel

- Transistor guys ended up winning Nobel Prize for their work...

https://hotcore.info/babki/william-shockley-john-bardeen-and-walter-brattain.htm

Shockley TRANSISTOR



- In Mid 50's Shockley decided to found his own company called Shockley Semiconductor in Mountainview, CA mainly for family reasons (sick mother nearby).
- Was dumpy area then. Land was cheap and mostly orchards
- Hired a bunch of smart people to work on transistors but also got really obsessed with what would eventually become the thyristor

Shockley

- NOT a good boss…yelled a lot, fired people, made people take lie detector tests…changed his mind all the time…really messy
- Bunch of engineers got fed up and quit, founded their own company with support from Fairchild Corporation!

- These eight became known as the "Fairchild Eight" or the "Traitorous Eight" by Shockley

- Very early Conglomerate Company. Had:
- Aircraft Division (got their start)
- Camera Division
- Scientific Instrumentation Division
- Weapons Division: ArmaLite…invented AR-15 and variants then sold that off
- Semiconductor Division: Fairchild Semiconductor
- And many others…did a lot of seed funding

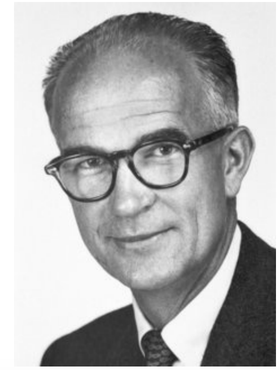
Fairchild Semiconductors

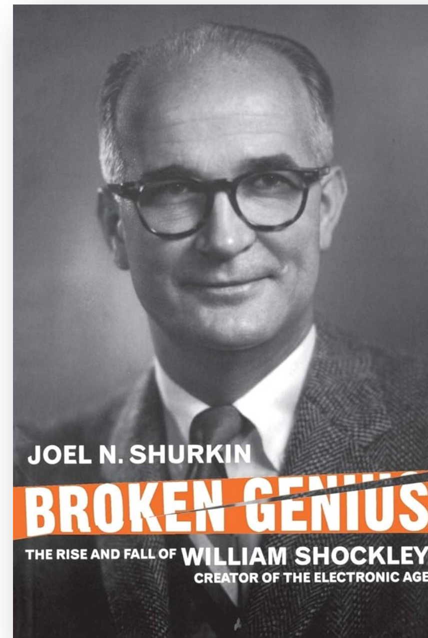
- Gordon Moore and Bob Noyce among the founders of Fairchild
- After Fairchild was success, they left to found Integrated Electronics…which was shortened to Intel
- Noyce also co-invented integrated circuit at same time as Jack Kilby who was at Texas Instruments
- TI was the other big early semiconductor company…their big angle was moving to Silicon early

Original contract they signed together

Shockley…

- Shockley Semiconductor failed
- But all the people he pissed off stayed around in the Valley area and basically spawned pretty much everything. Early Apple and Microsoft people came from Intel, then people from those companies were involved with Google, Facebook, etc…
- Shockley became a professor at Stanford
- He was also kinda a racist and into eugenics and alienated a lot of people and died mostly estranged from his family
- Joel Shurkin's *Broken Genius* is a good read on him if you want.

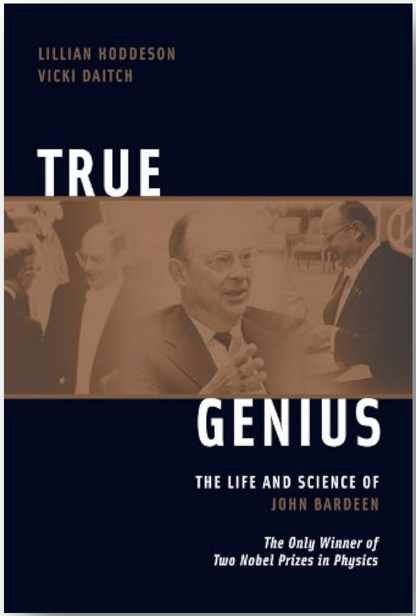




Bardeen vs. Shockley

- Hoddeson and Daitch Wrote a bio of Bardeen *True Genius* also…kinda funny to contrast that title to Shockley's *Broken Genius*

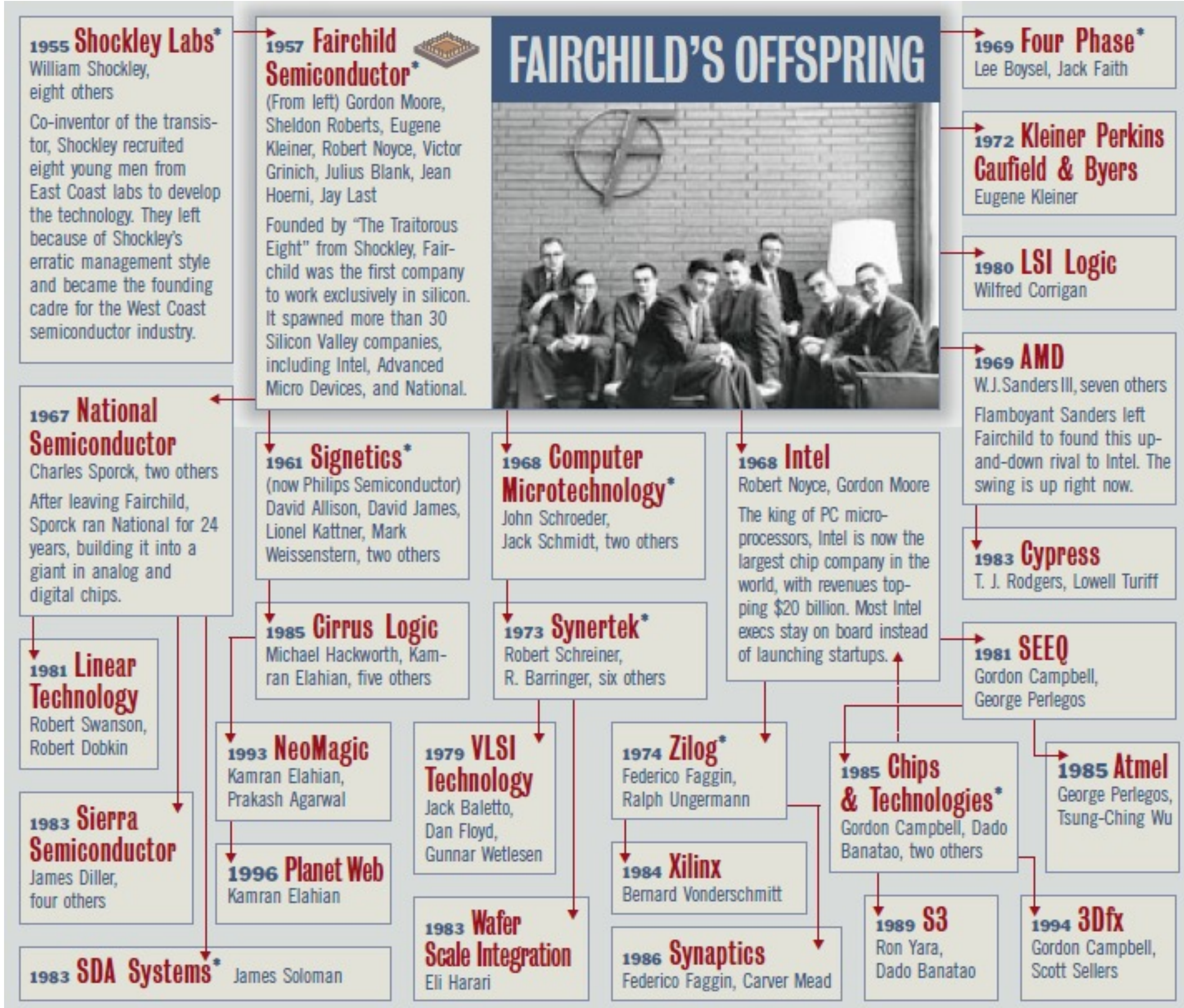
- No bio on Brattain that I know of, but by all accounts, he was a nice dude....had his Nobel Prize...lived a good life.



Family Tree

The rest is history. Direct line from Shockley/Fairchild to almost <u>every</u> modern company

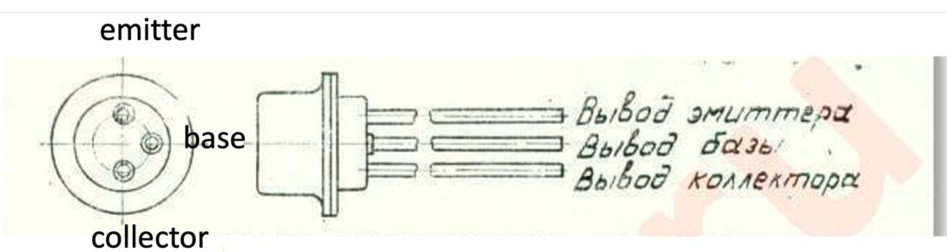
If not through direct engineering, then through investing, advisorial roles, etc…

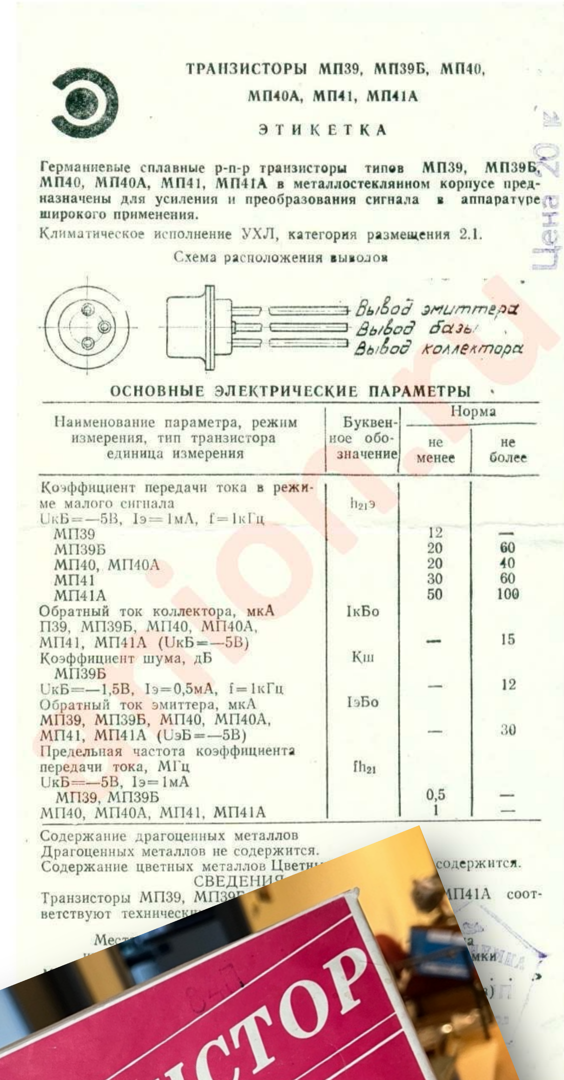


https://daviddhovey.files.wordpress.com/2010/09/blog101.png

Lab 07

- Build a halfway-decent Germanium Audio Amplifier
- For transistors we'll use two different types:
  - МП25Б: preamplifier
  - МП20: mid amplifier
  - П214Б: Power Transistor
- Both are PNP Germanium-type transistors from the Soviet Union





ТРАНЗИСТОРЫ МП39, МП39Б, МП40, МП40А, МП41, МП41А

ЭТИКЕТКА

Германиевые сплавные p-n-p транзисторы типов МП39, МП39Б, МП40, МП40А, МП41, МП41А в металлостеклянном корпусе предназначены для усиления и преобразования сигнала в аппаратуре широкого применения.

Климатическое исполнение УХЛ, категория размещения 2.1.

Схема расположения выводов

Вывод эмиттера
Вывод базы
Вывод коллектора

ОСНОВНЫЕ ЭЛЕКТРИЧЕСКИЕ ПАРАМЕТРЫ

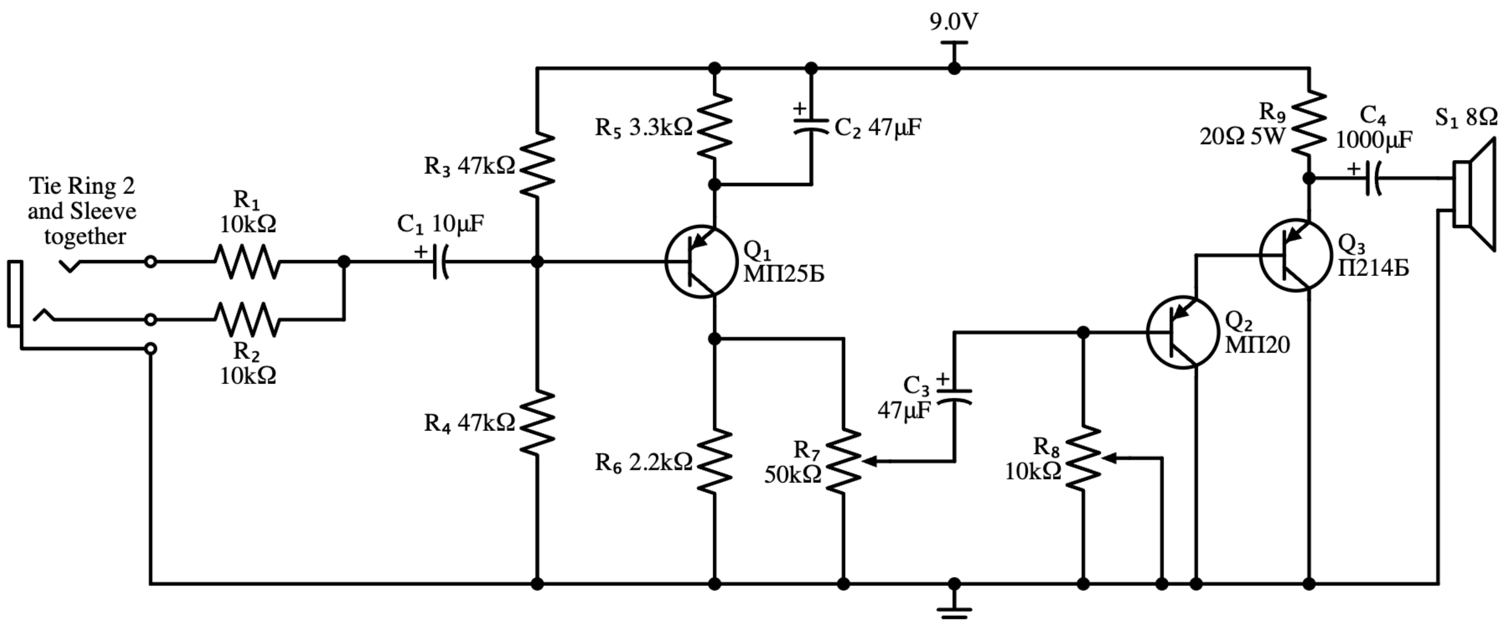
Наименование параметра, режим измерения, тип транзистора единица измерения	Буквенное обозначение	Норма	
		не менее	не более
Коэффициент передачи тока в режиме малого сигнала UкБ=—5В, Iэ=1мА, f=1кГц	h₂₁э		
МП39		12	—
МП39Б		20	60
МП40, МП40А		20	40
МП41		30	60
МП41А		50	100
Обратный ток коллектора, мкА П39, МП39Б, МП40, МП40А, МП41, МП41А (UкБ=—5В)	IкБо	—	15
Коэффициент шума, дБ МП39Б UкБ=—1,5В, Iэ=0,5мА, f=1кГц	Кш	—	12
Обратный ток эмиттера, мкА МП39, МП39Б, МП40, МП40А, МП41, МП41А (UэБ=—5В)	IэБо	—	30
Предельная частота коэффициента передачи тока, МГц UкБ=—5В, Iэ=1мА	fh₂₁		
МП39, МП39Б		0,5	—
МП40, МП40А, МП41, МП41А		1	—

Содержание драгоценных металлов
Драгоценных металлов не содержится.
Содержание цветных металлов Цветн... содержится.
СВЕДЕНИЯ
Транзисторы МП39, МП39... МП41А соответствуют техническ...

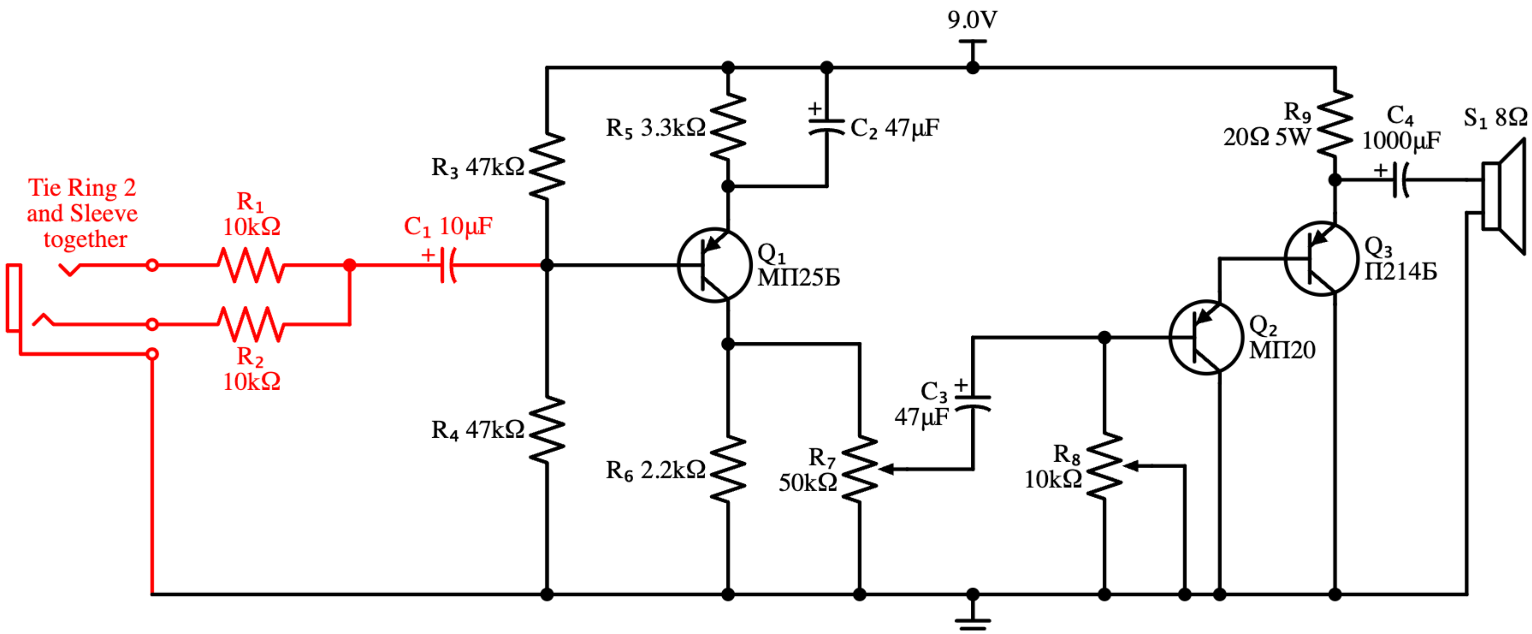
Цена 20 к

Lab 07

- Three transistor amplifier built only using PNP...kind of a weird amplifier

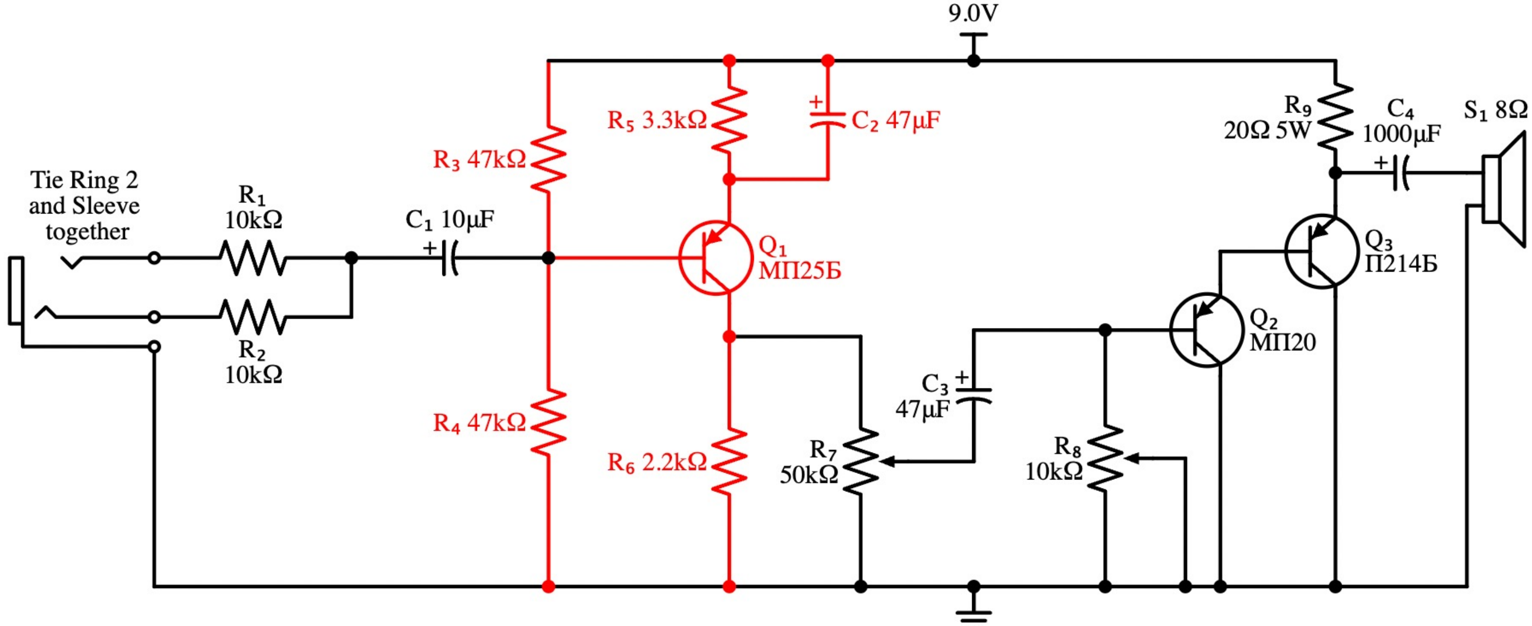


Lab 07: Audio In



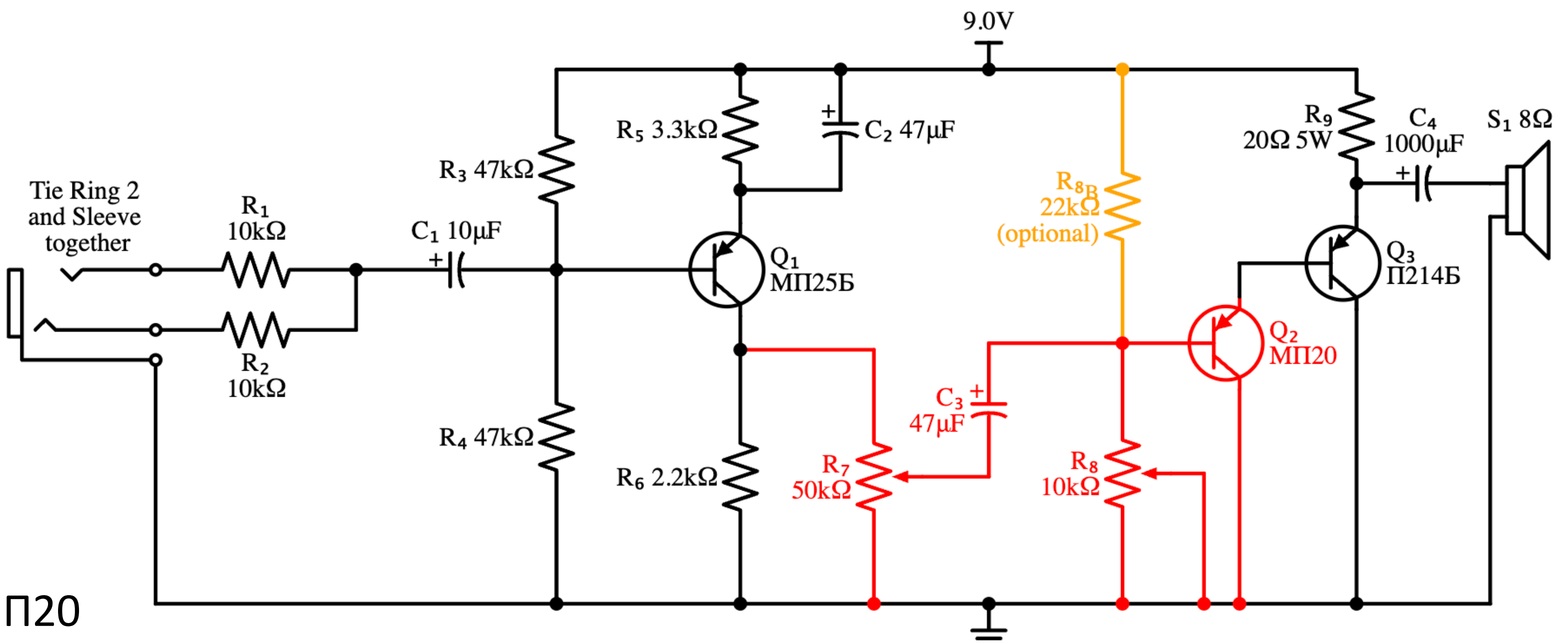
Lab 07: Preamplifier

- A little voltage gain



Q_1= M

Lab 07: Volume and First Buffer

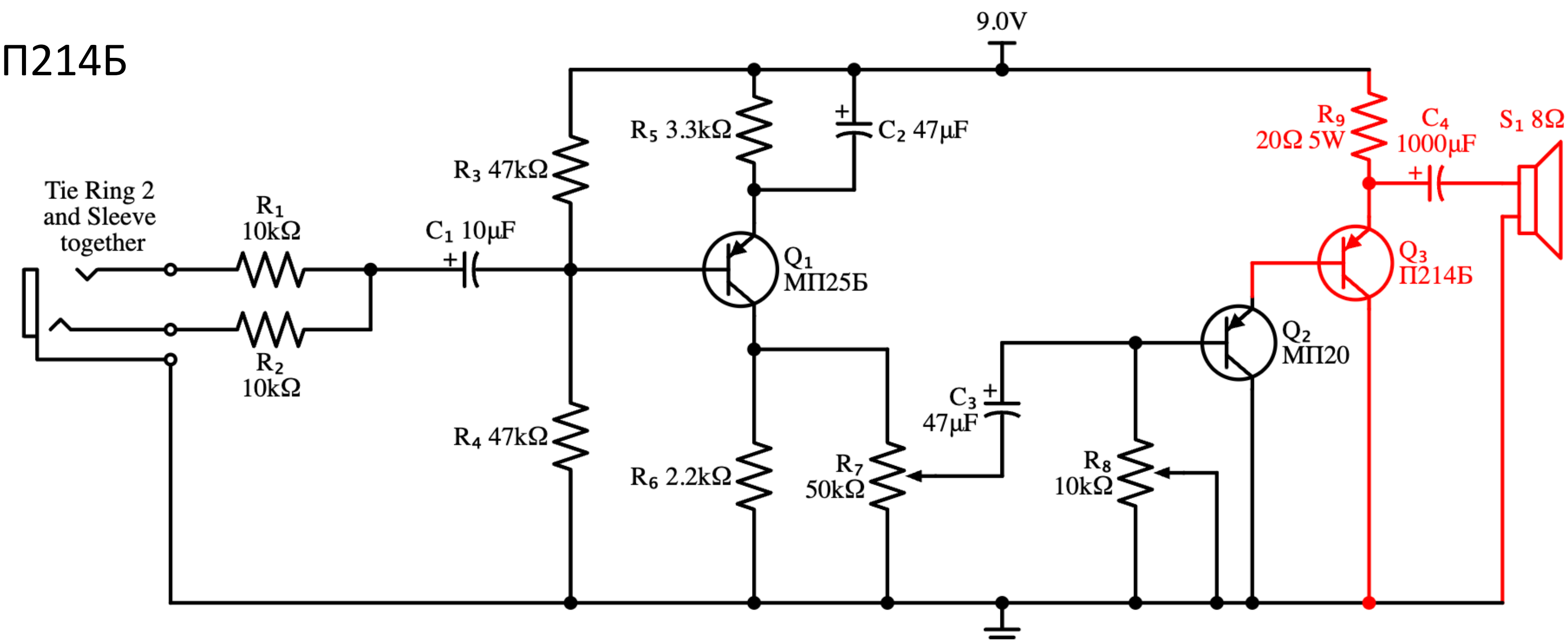


Q_2= МП20

Lab 07: Output Speaker Driver

- Use a second emitter follower stage for additional high-current buffering
- Resistor R9 is a high-wattage power resistor used for biasing
- Class A

Q_3= =П214Б



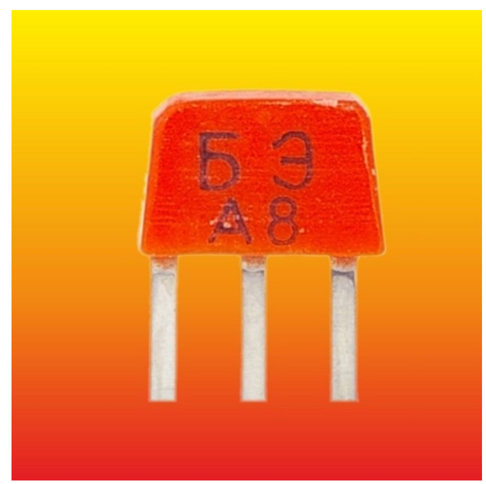
I'm sorry, I thought this was America? Why not American Transistors?

- Is complicated…basically very hard to get American transistors from the era
- Early transistors were not super reliable. Broke sometimes as often as vacuum tubes
- Also very variable (make a bunch, pick your best, chuck the rest).
- Also tech updated crazy fast in the West.
  - By 1957 (ten years after transistor invention), TI was making silicon NPN transistors not that different from "modern" designs
  - Transistors weren't made in large volumes since most things that needed to be reliable kept using tubes until very early 1960's
- Also US did not archive stuff…many old circuits and stocks were discarded before they were seen as "history"

But Why *Soviet* Transistors?

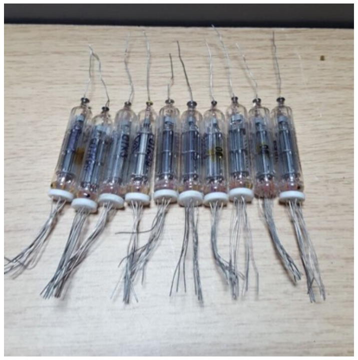
- Is complicated…Soviet Union lagged the West in terms of electronics technology by about ~10 years.
- When Western firms were starting to tame Silicon, Soviet scientists were just starting to get transistors in germanium to work at all (mid 50's)
- Silicon proved very difficult and expensive to get working…Soviets didn't have decent silicon transistors until early 1970's

KT315…very late 1960's…~about ten years after equivalent US NPN silicon transistors



Why Soviet Transistors?

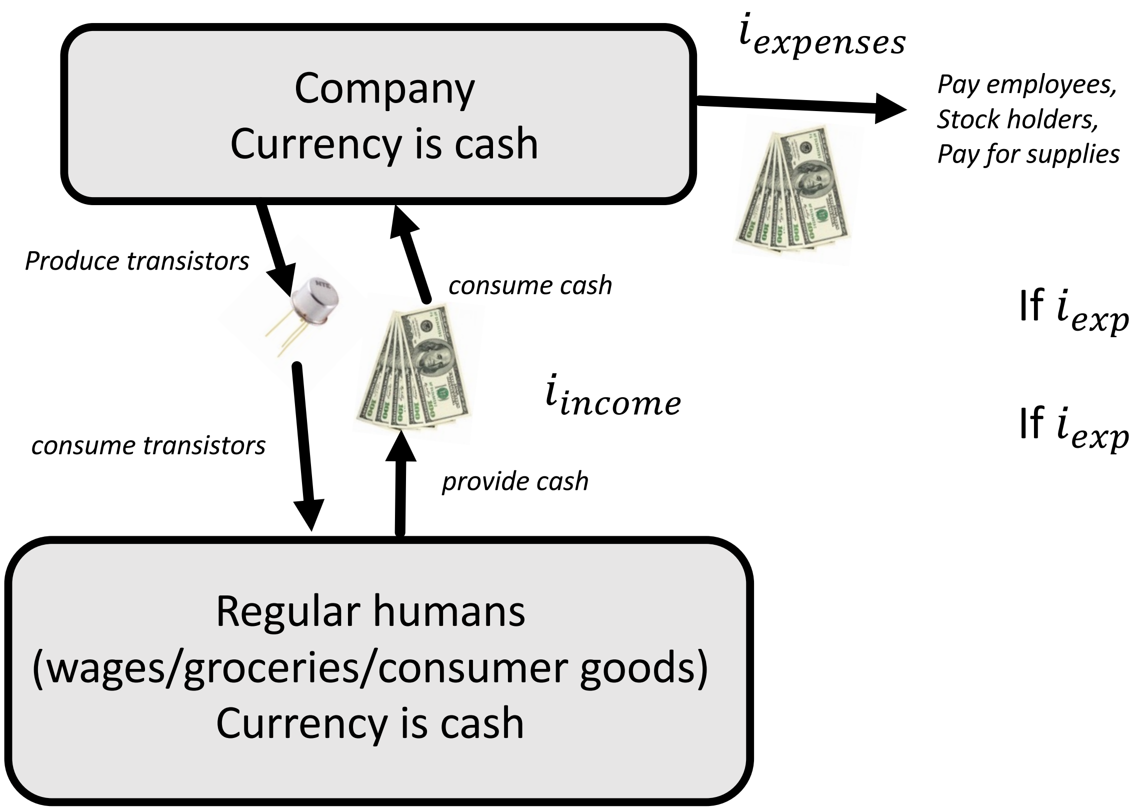
- The Soviet Union did a lot of stuff: huge military, space technology program, lots of science, so they needed good amplifying devices.
- Space race, development of nuclear arsenal, massive military export/expansion all happened in their Germanium transistor window so a lot of legacy equipment kept using them even into the 90s
- Kept perfecting Germanium and vacuum tubes long after Western companies had started to move on.



Soviet sub-mini tubes from 1950s

Modern "Western" Economic System

- While money may exist in several "forms", the different forms are largely fluid with one another.

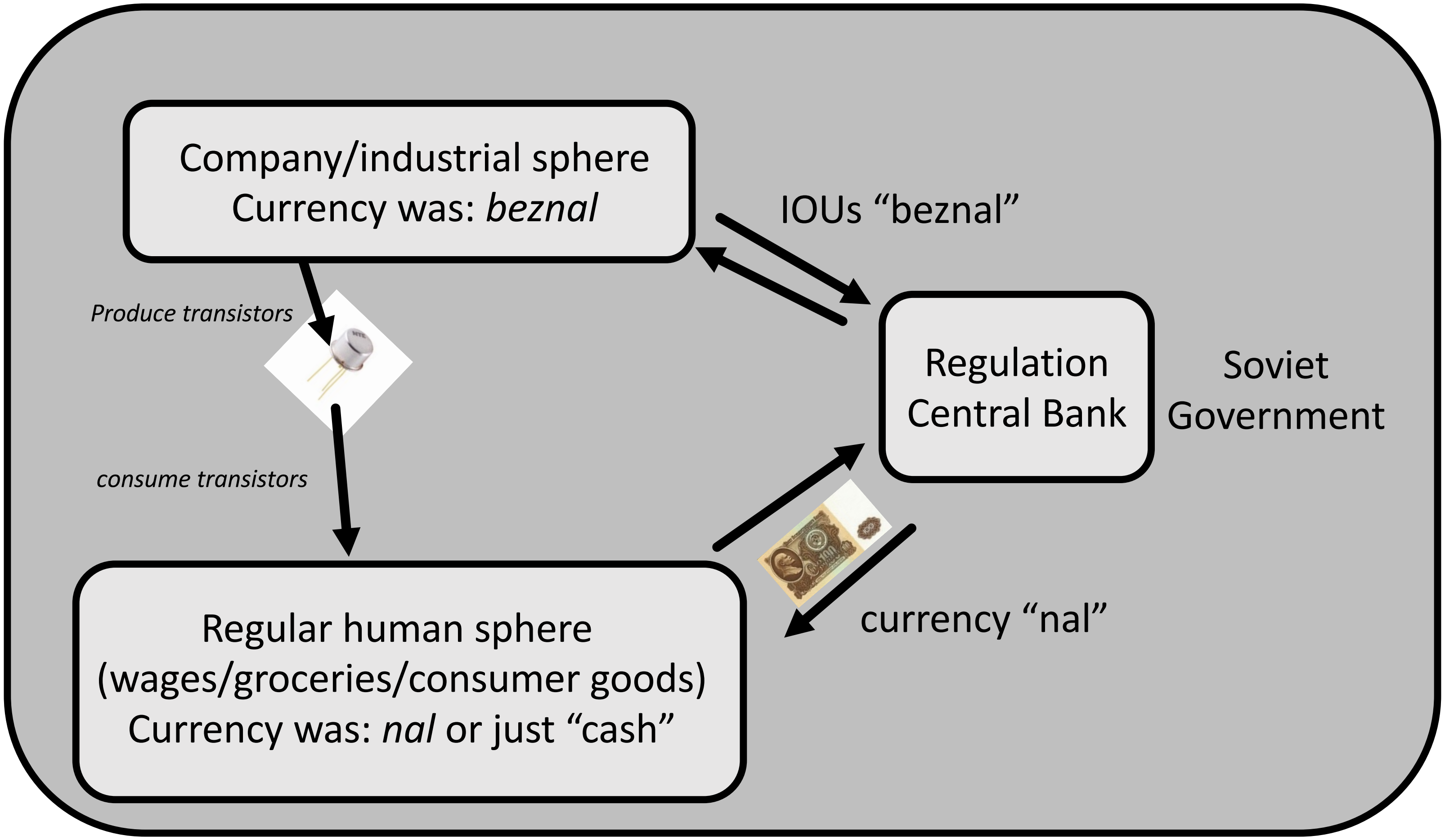


If $i_{expenses} \leq i_{income}$ then all is well

If $i_{expenses} > i_{income}$ then go bye bye

Soviet Economic System

- Soviet economy was two disconnected spheres with essentially two disconnected forms of currency



Money

- In modern Western system the dollars used at the company level and the consumer level are, at least in theory, interchangeable, if not identical

- In the Soviet System, up until near the very end *nal* and *beznal* had no mechanism to exchange one another so no exchange rate...that was actually a big issue when they started to open up the economy in the 1980s and it got abused a lot.

The Result

- Feedback loop regarding many technologies such as tubes but also early transistor variants was essentially disconnected.
- Factories would keep producing "out-of-date" equipment because they were told to do so from central committee and because they kept getting paid to do so (in *beznal*) even though devices weren't getting used.
- In addition to consumer uses, the Soviet Union had a habit of stockpiling huge amounts of equipment in expectation of war/conflict.
  - Lack of need or use was not necessarily an immediate issue like one would see in Western system

The Result

- Soviets were still making and stockpiling huge amounts of vacuum tubes and 1950s-style transistors up until the early 1990s
- When the USSR collapsed into its disparate component countries, you had these huge stockpiles of vintage equipment exposed to west
- Sort of like a time-capsule
- Factories and warehouses that would have been torn down/sold-off in the West decades before were still there and people have been selling these things off ever since.

Example

- A used Raytheon CK721 costs about 60 USD on Ebay.
- I can get a 100 MP41 transistors (a somewhat similar set of specs) for about 10 USD from Ukraine over Ebay depending on model
- Same with lots of other equipment
- So yeah you have to read Cyrllic a bit, but the datasheets are out there if you need germanium transistors

Soviet Semiconductors

- In Lab 07 transistors used:

Pluton Plant
Moscow, Russia

Gamma Plant (Electronics Plant #77)
in Zaporizhzhia, Ukraine
(shut down in 1995)

JSC OKB Planeta
Veliky Novogrod, Russia

Silicon El Group
Bryansk, Russia
Bombed by Ukrainian drones last spring

Right Up Until the End

П214Б

РП14

МП20

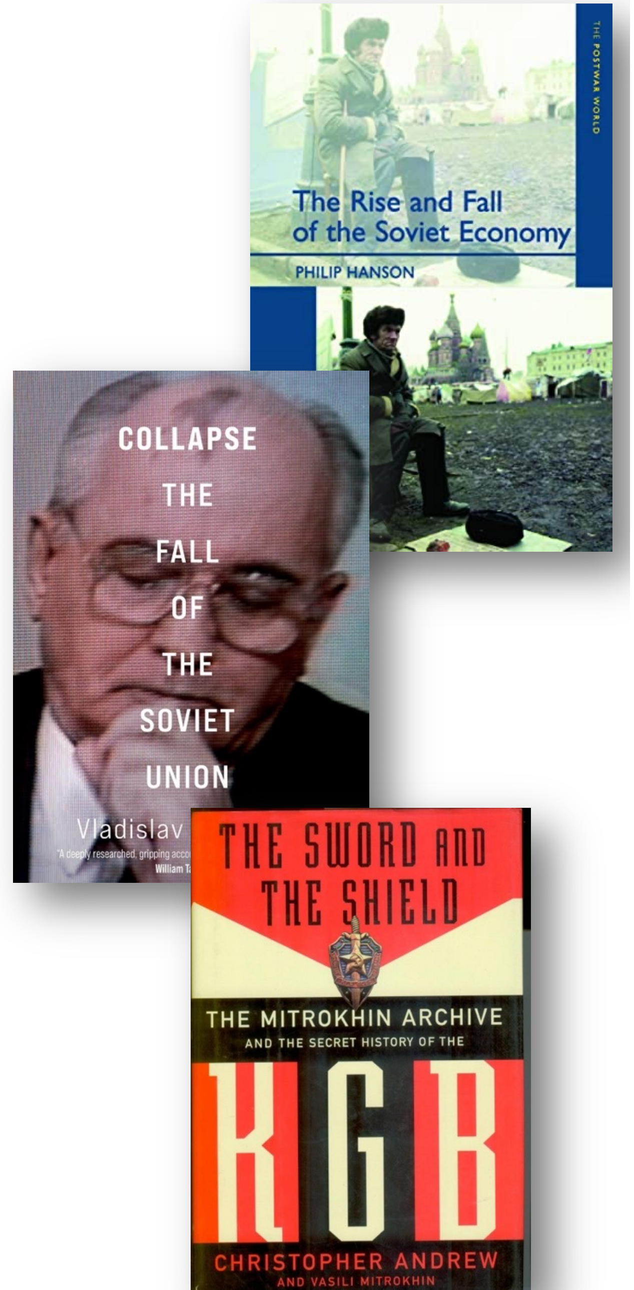
(date code October 1991 😬)

(date code October 1987)

- Soviet Union dissolved in December 1991

Further Reading

- In case you're interested in this, these books don't cover much in the way of electronics, but do discuss the Soviet economic system a lot
- *The Rise and Fall of the The Soviet Economy: An Economic History of the USSR from 1945* by Philip Hanson
- *Collapse: The Fall of the Soviet Union* by Vladislav Zubok
- *The Sword and the Shield* by Christopher Andrew, discusses a lot of commercial espionage



So What About Tubes?

- Did they Just disappear?....no
- Vacuum tubes continued to be better at high frequencies for several decades
- Plus also just technical momentum
- A few tube variants tried to delay the inevitable, however

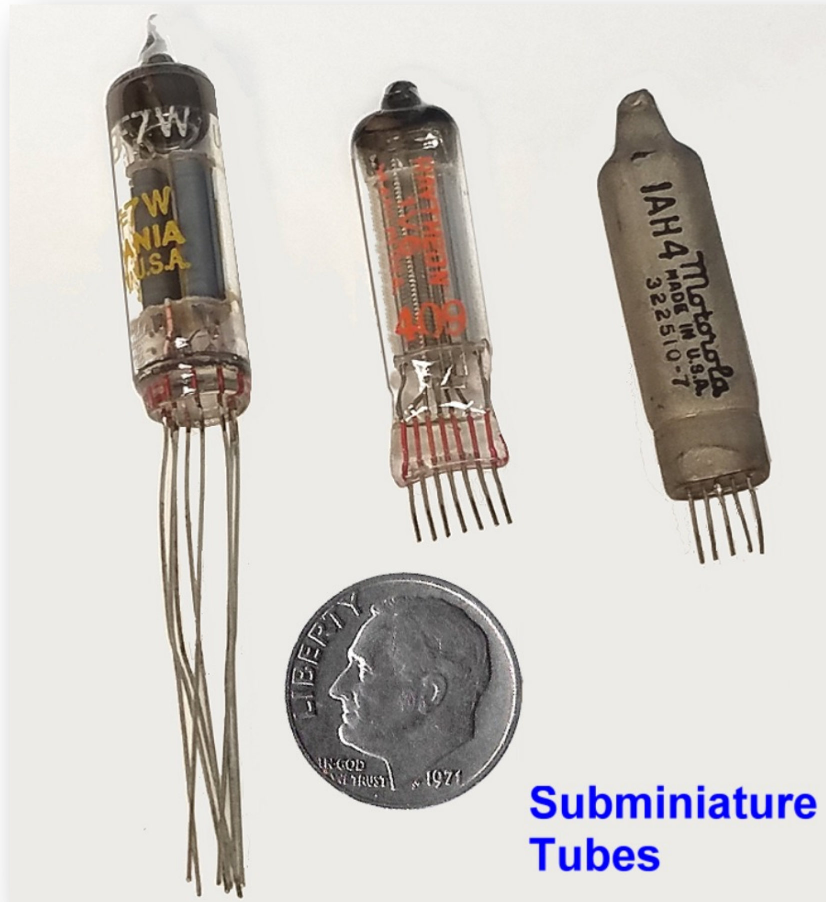
	Point Contact Type	Junction Type	Tubes
Gain	20 - 30 db	30 - 50 db	20 - 50 db
Efficiency (Class A) (Class C)	30% 90%	45 - 49 % 95%	1 to 25 % 70%
Life	70,000 hrs.	90,000 hrs.	5,000 hrs. ?
Vibration	100 g	100 g	
Shock	20,000 g	20,000 g	
Uniformity	±3 db	±2 db	±3 db
Minimum Powers	1 mw.	1 microwatt	1/10 watt
Temperature	70° C	70° C	500° C
Frequency	30 - 70 mc	3 - 5 mc	60,000 mc
Gain X Bandwidth	1000 mc	120 mc	1000 mc
Noise Figure	45 db	15 db	10 - 30 db
Maximum Power	100 mw	1 watt	1 megawatt

Summarizing - up to 30 mc, transistors can do a better job than tubes within the limits of power and temperature.

1952 analysis of pros/cons of tubes vs. transistors

Sub-miniature tubes

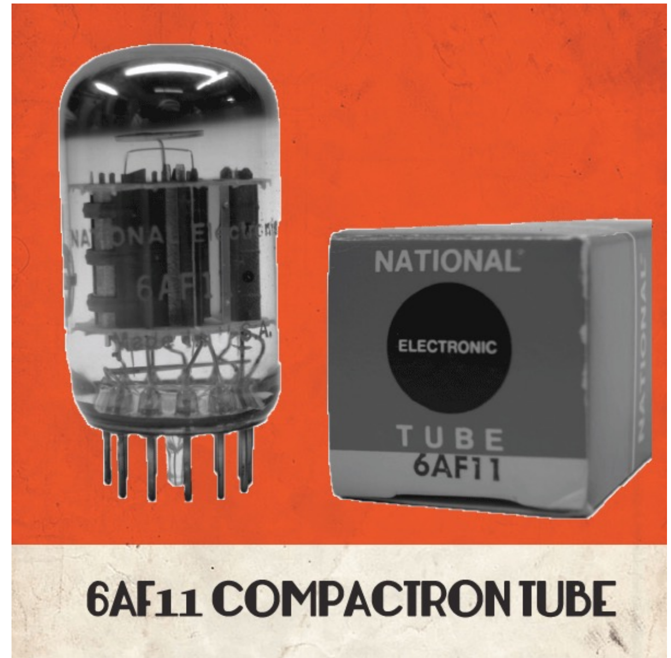
- Very small tubes ran at "lower" voltages maybe 50V rather than 300V



https://www.radiolaguy.com/Tubes/Sunminiature%20Vacuum%20tubes.htm

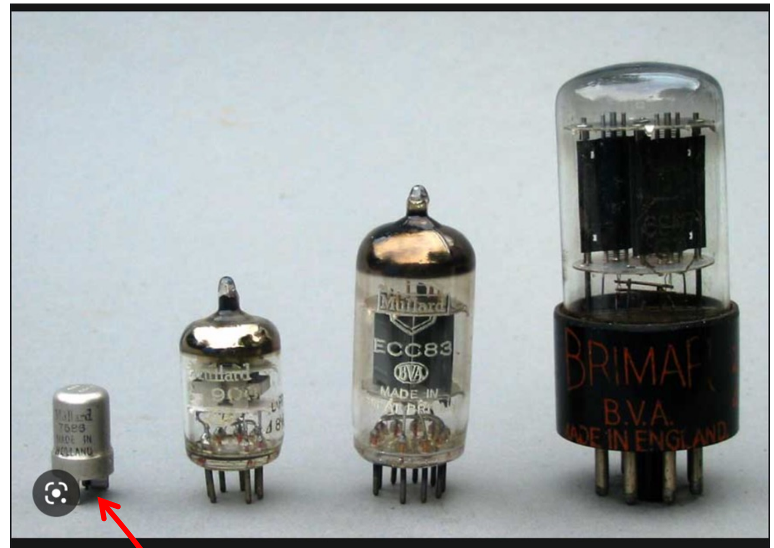
Compactrons

- 12-pin tubes that would often incorporate three or four triodes or pentodes into one internally-wired package.
- The idea was to provide better self-contained integration than transistors could for a little while.
- Very popular in TV sets in the late 1960s to mid 1970s



Nuvistors

- Developed by RCA in 1959
- From outside they look like an early transistor
- On inside they were a tiny vacuum tube.
- Good for high frequency stuff and stayed competitive with transistors up through early 1970s



nuvistor

1975 Ad:

- But even by the 1970s, TVs, which were one of the last holdouts* had started to fully transition

"100% solid state" is a selling point!

*because TV signals were at very high frequencies

Vacuum Tubes Sort of Disappeared

- That was the end
- It took until the mid-seventies for transistors to be cheap enough and work at higher frequencies, so vacuum tubes stuck around in TVs for a while
- By the mid-seventies, you just didn't see them anymore with few very niche applications
- Almost Everything was solid state by the eighties.
- Few exceptions:
  - Microwave Ovens (Cavity Magnetron is technically a vacuum tube)
  - Some high-frequency/power transmitting systems still use very special flavors of vacuum tube, but every year that goes by, more and more of these are getting replaced by solid state designs as that tech continues to advance
  - Vacuum Fluorescent Displays hung around until 2000's until LEDs caught up in brightness/efficiency

Transistors Replaced Everything

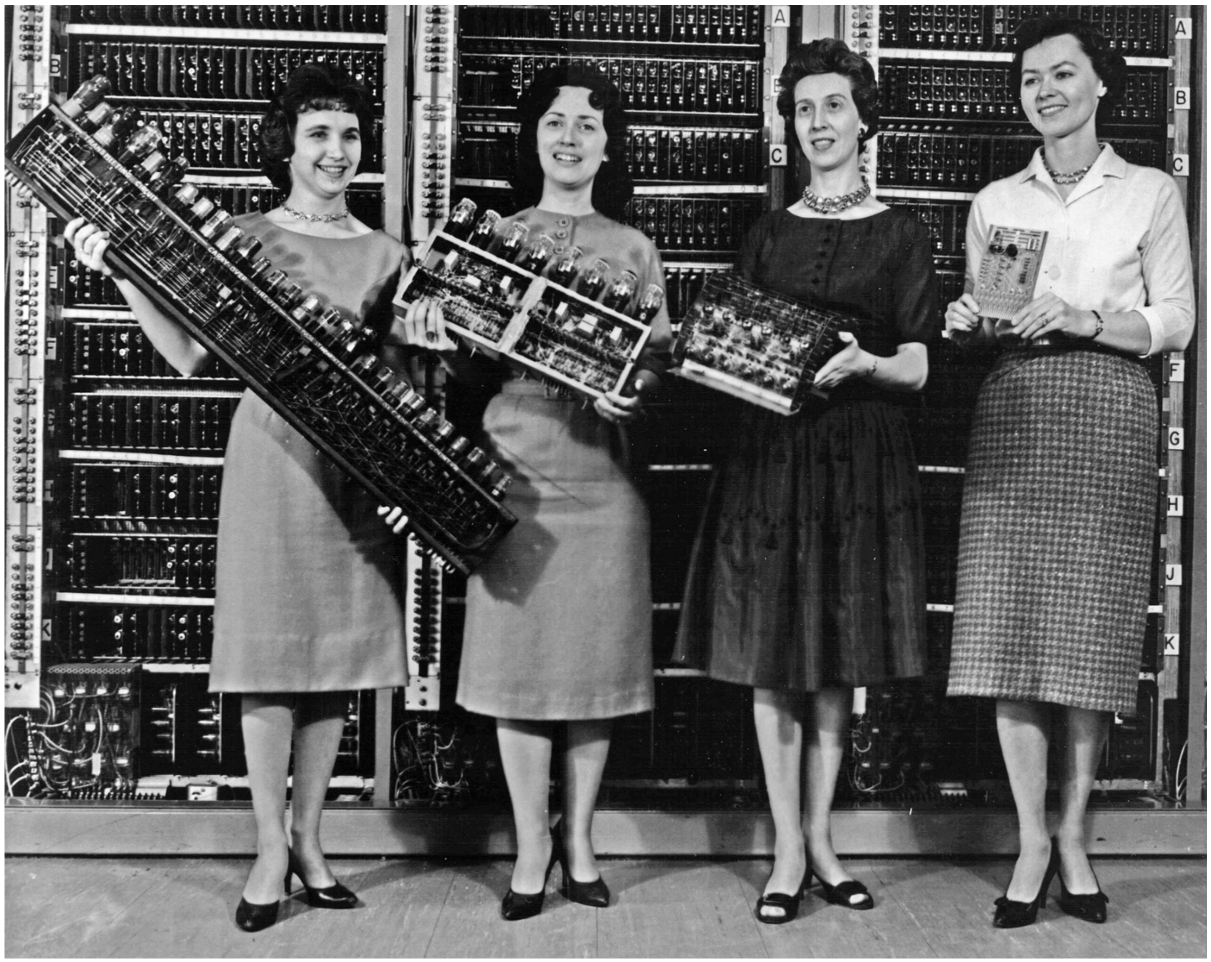
- Anywhere you'd have used tubes transistors came in and replaced.
- Transistors also allowed high-density assembly which necessitated the development of printed circuit boards
- They were also a technology that could shrunken and assembled together into pre-made packages (integrated circuits)
- The real "scaling" of electronics began with transistors right around 1960

Early Computers

- Many systems that needed lots of active elements (computers) kept using tubes into the early 1960s.
- Transistors were expensive so unless you were the government which basically didn’t care about cost, or you were making high-end consumer electronics, you still saw tubes.
- But even by early 1960s transistors got robust enough and cheap enough that computers started to transition as well

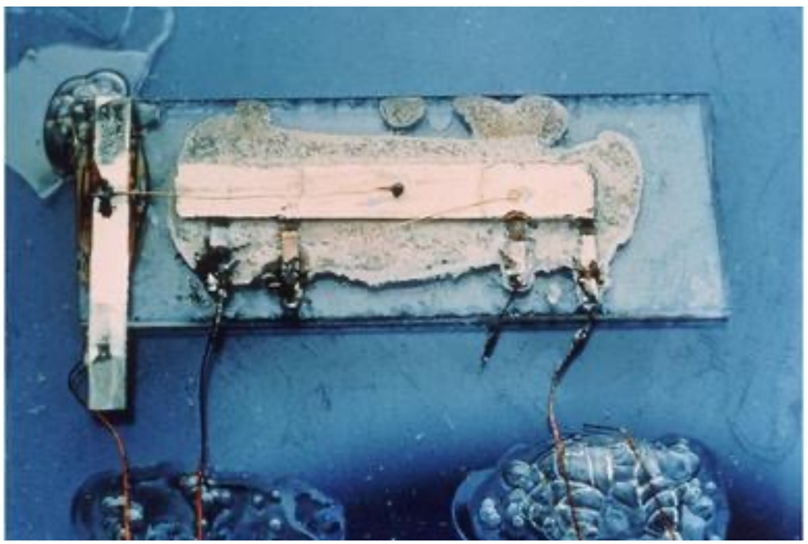
Transistors Replaced Everything

- 1961 photo showing off the ***"massive"*** scaling of equivalent circuit boards from ENIAC (1945, left) to BRLESC (1962, right)



Integrated Circuits

- Jack Kilby (@ TI) and Bob Noyce (@ Fairchild) both kinda developed the integrated circuit right around 1958/59



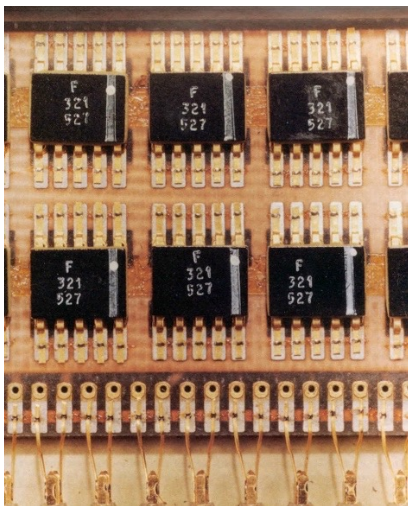
First Integrated Circuit by Jack Kilby

Kilby

Noyce

Early Integrated Circuits

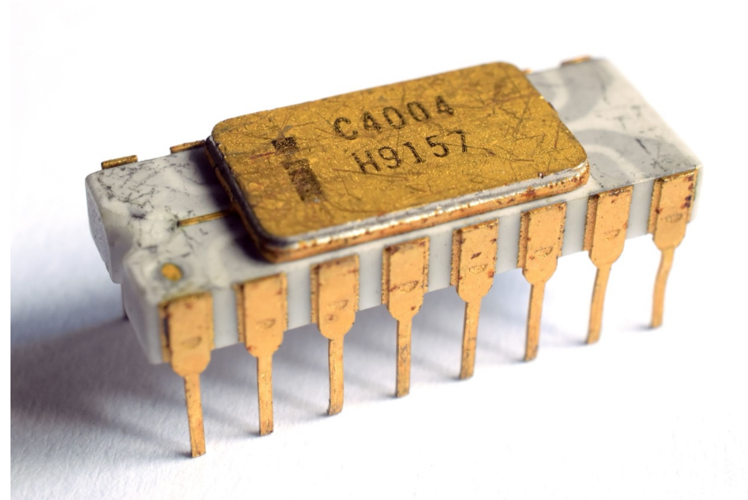
- Early Integrated Circuits would be in "flatpacks" which were replaced by "Dual Inline Packages (DIPs)" by the late 1960s



Apollo Guidance Computer built completely from 3-input NOR gates in flatpacks

https://en.wikipedia.org/wiki/Flatpack_(electronics)

Intel 4004

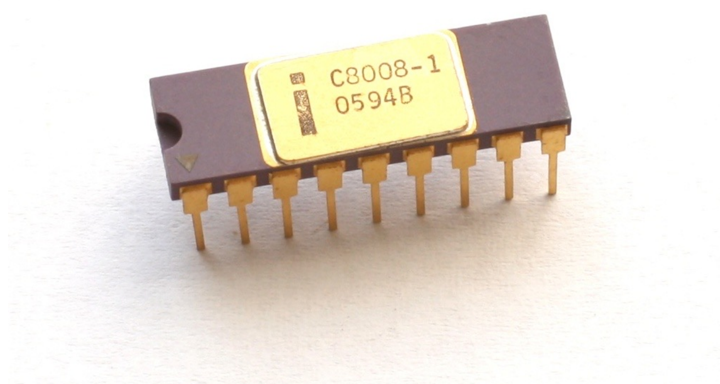


- 1971
- 2,300 transistors
- First real Large Scale Integration Chip (LSI)

- Cool emulator here with ISA: http://e4004.szyc.org/iset.html

https://en.wikipedia.org/wiki/Intel_4004

Intel 8008

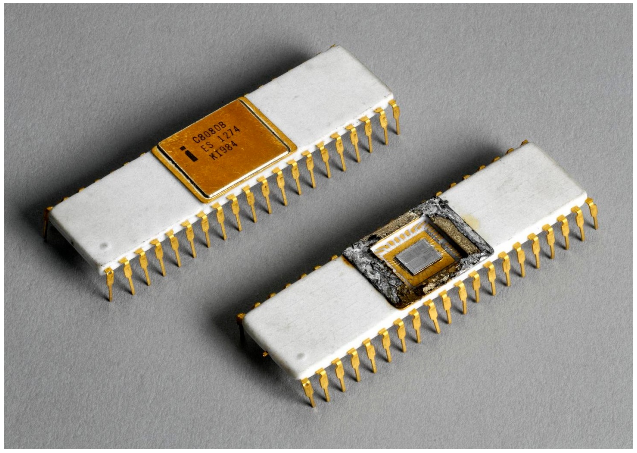


- 1972
- 3,500 transistors
- 8 bit

https://en.wikipedia.org/wiki/Intel_8008

Intel 8080

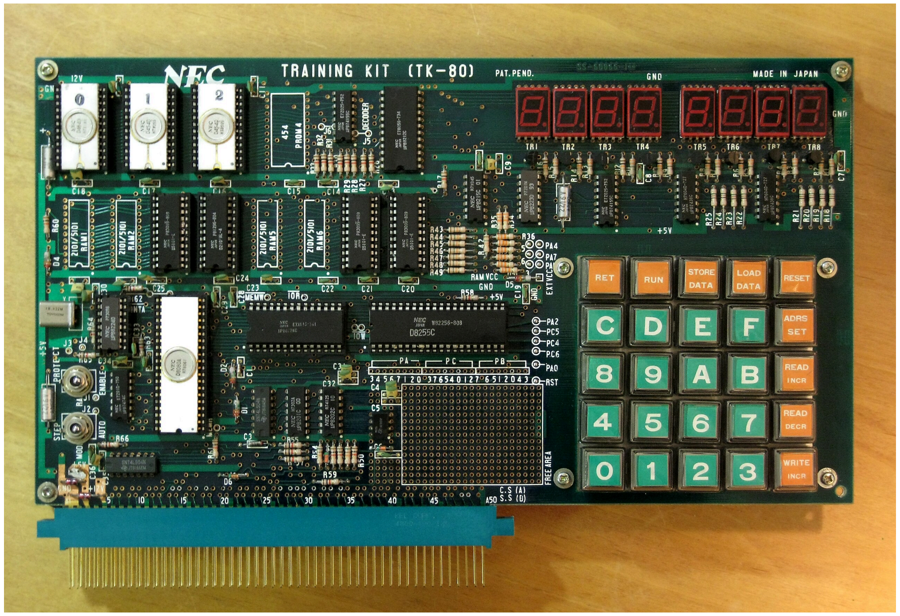
- 1974
- 6,000 transistors



https://en.wikipedia.org/wiki/Intel_8080

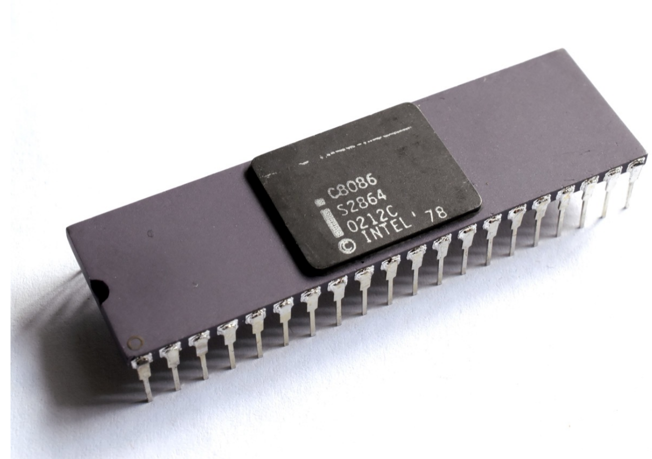
TK-80

- Cool single-board computer built around 8080



- Very popular in Japan for tariff reasons. MIT had a whole stash of them for some reason they were throwing out in 2014. I kept three of them.

Intel 8086



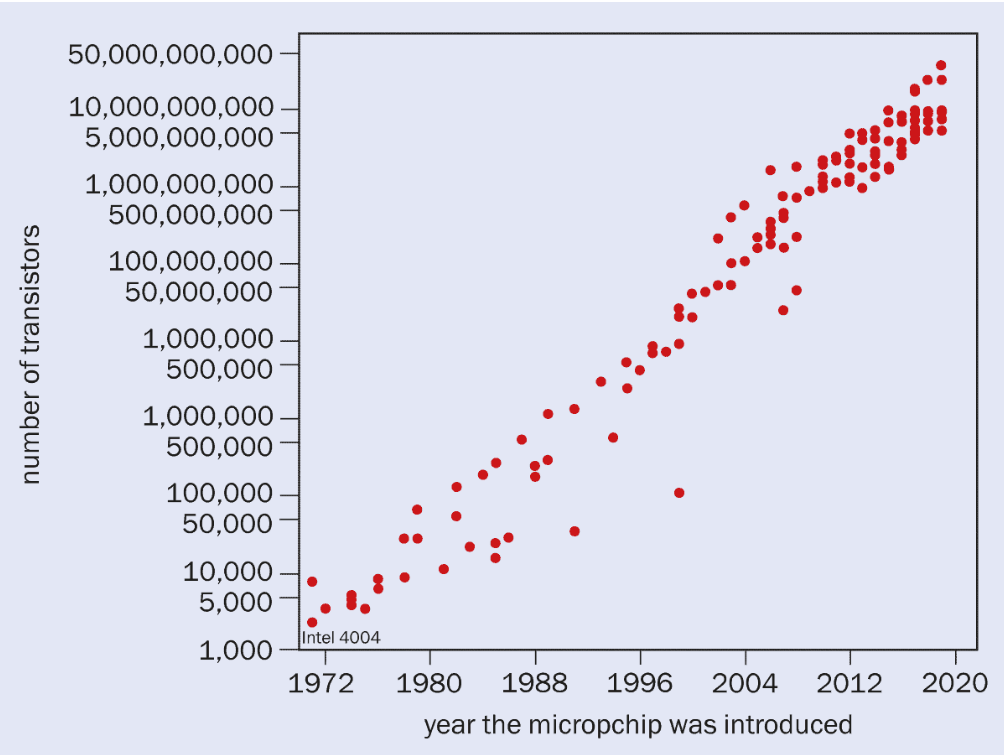
- 1979
- 29,000 transistors

- Birth of x86 architecture

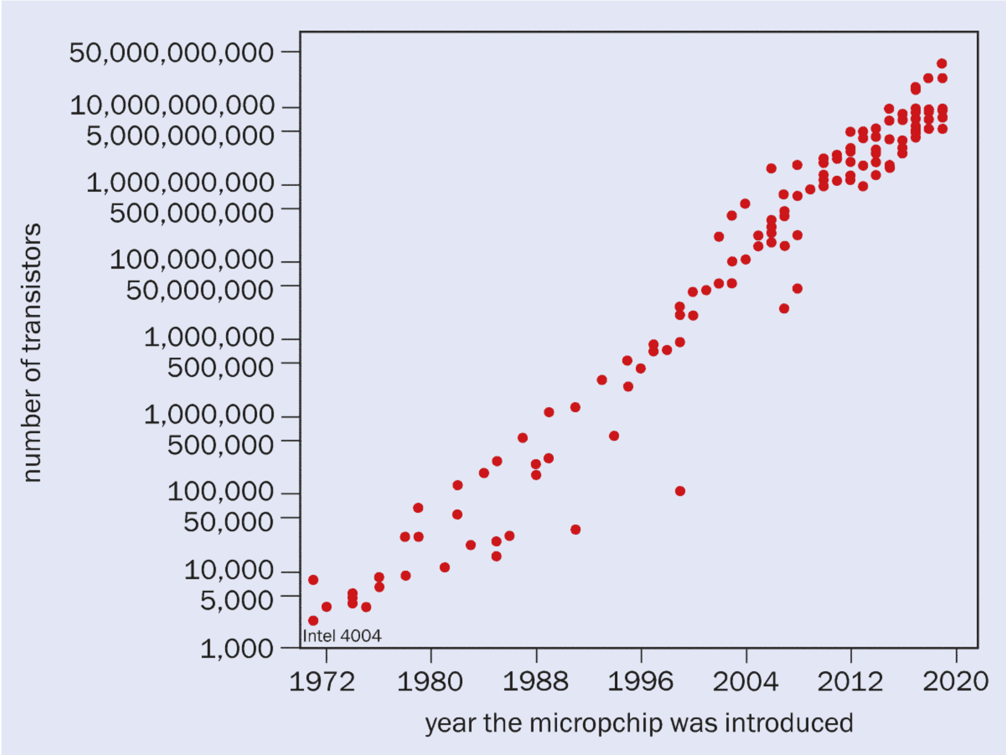
https://en.wikipedia.org/wiki/Intel_8086

And things just kept going…

- 1971: Intel (spinout of Fairchild, which was spinout of Shockley) releases 4004, first commercially available single-chip computer
- Gordon Moore made his prediction-kinda thing



And things just kinda kept going and going…

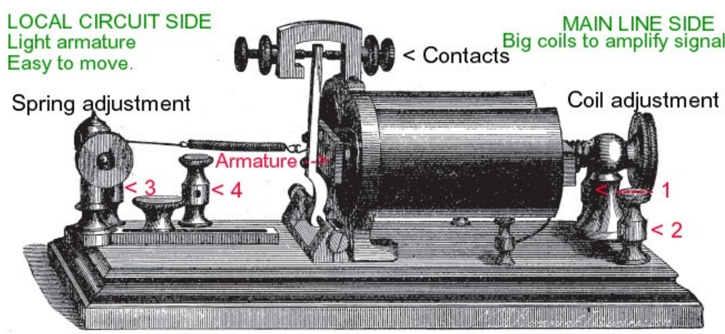


- 2023 Apple M3 processor has 25 billion transistors on it

And things just kinda kept going and going…

- The only real constant in all of this is change (and your basic circuit laws)

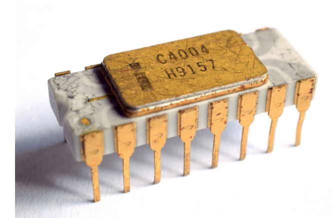
Aldini Reanimating an Ox Head



1840

1925

1953



1971

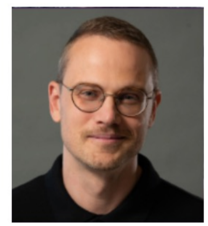
2026

Where to Go From Here

- Anyways…we'll end it here (WITH EXCEPTION OF FRIDAY GUEST TALK)
- Lots of tubes out there.
- Lots of transistors
- Lots of stuff…every year stuff goes obsolete.
- Build stuff with them
- Appreciate them…you'll appreciate modern stuff all the more.

Courses

- 6.204, 6.208 are both courses in analog design...do those and then revisit tubes
- STS (Science Technology Society) classes here at MIT. David Mindell is really cool does a lot of history of tech stuff:
  - *Digital Apollo*: on Apollo Guidance Computer
  - *Between Human and Machine:* Controls prior to computers
- New faculty for 2026



Ben Lindquist joined the History section and EECS as an assistant professor in a shared appointment with the Schwarzman College of Computing. Through a historical lens, his work observes the ways that computing has circulated with ideas of religion, emotion, and divergent thinking. His book, “The Feeling Machine” (University of Chicago Press, forthcoming), follows the history of synthetic speech to examine how emotion became a subject of computer science. He was a postdoc in the Science in Human Culture Program at Northwestern University and earned his PhD in history from Princeton University.