CMOS Logic

Dov Kruger

Department of Electrical and Computer Engineering
Rutgers University

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By the end of this unit you will be able to

- Define basic terminology for semiconductors
- Identify different types of transistors
- Describe how CMOS gates work
- build a logic gates using transistors (but we won't)
- Use a MOSFET to turn on a power circuit
- Drive MOSFETs from your digital circuits
- Read a spec sheet for a MOSFET

Logic Implementation History

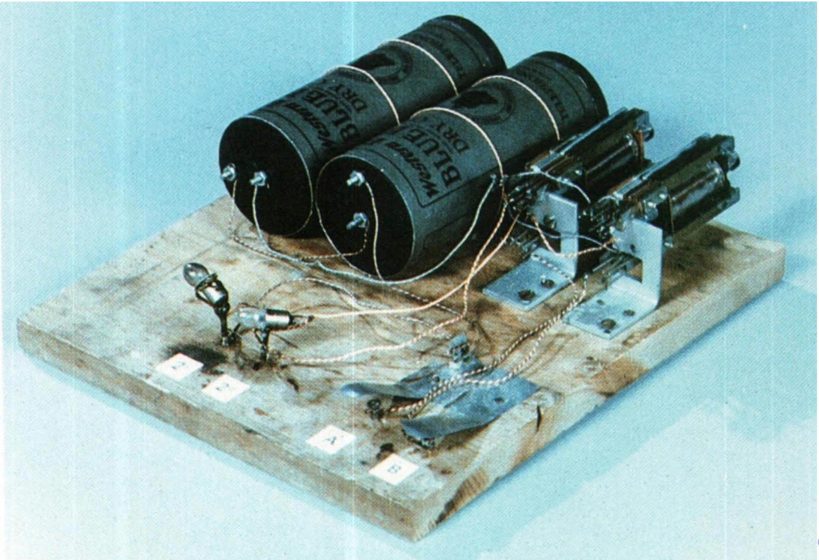
Part	Technology	Speed	Power	Date / Description
	Relay	10 ms	~ 5W	1930s-1940s
	Tubes	μs	~ 6W	1940s
	BJT	ns	~ 0.06W	1950s
7400	TTL	10-20 ns	1-10 mW	1960s
Intel 4004	PMOS	~ 100 ns	$\sim 217\mu$W	1971
74HC	CMOS	10-20 ns	μW	1980s
Motorola 68k	NMOS	~ 100 ns	$\sim 22\mu W$	1979, 8 MHz
Intel 80386	NMOS	~ 20 ns	$\sim 5.5\mu W$	1985, 12 MHz
Apple M1/M4	CMOS	~ 10 ps	few fJ	2020s, 5 nm
AMD Ryzen	CMOS	$\sim 5 - 20$ ps	few fJ	2023, 5 nm

Overview

- Technology improved from tubes to discrete transistors to integrated circuits
- Power per gates improved from watts to micro watts to femto watts
- Older circuits used power all the time
- Modern circuits use power only when state is changing
- Power per gate continues to decrease
- Speed of gates continues to increase slowly
- Problem is we keep using more transistors so power usage increases

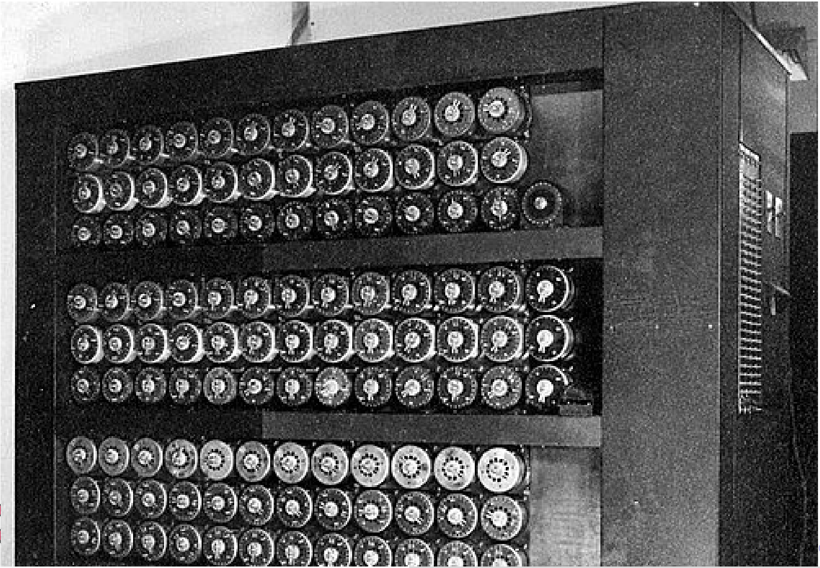
1920s: Relays

A relay is an electromechancial switch
Early automation of the phone system



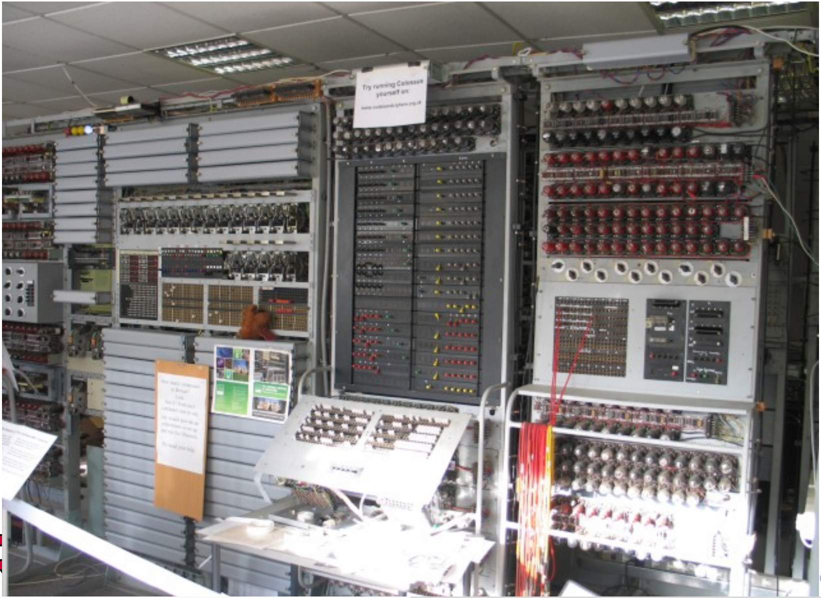
Last gasp of Relays: Turings Bombe

In World War II, used to break the German Enigma code
Fictionalized in the movie "The Imitation Game"

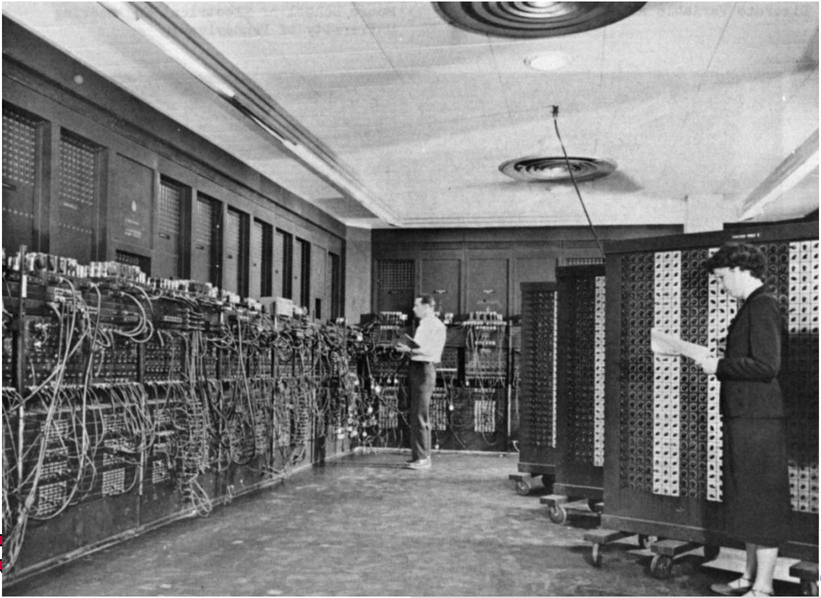


1940s: Tubes

Much faster than Turing's Bombe: Collossus in WW II



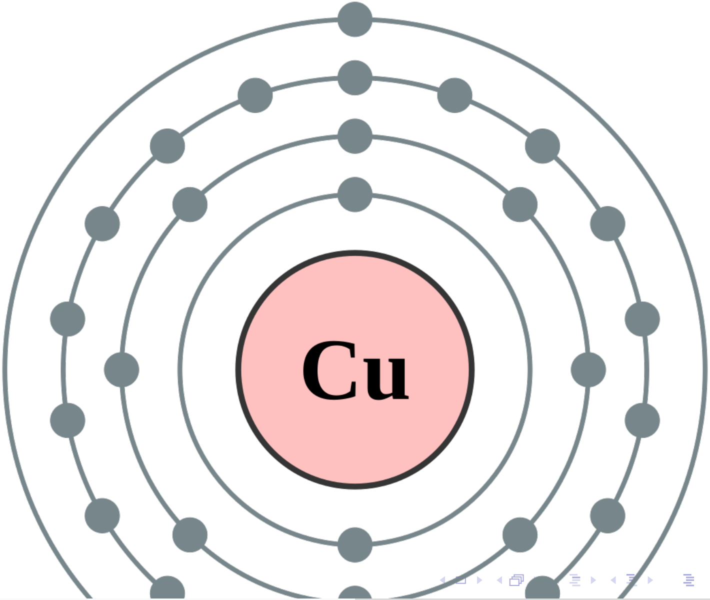
Early Tube Computers: ENIAC 1946



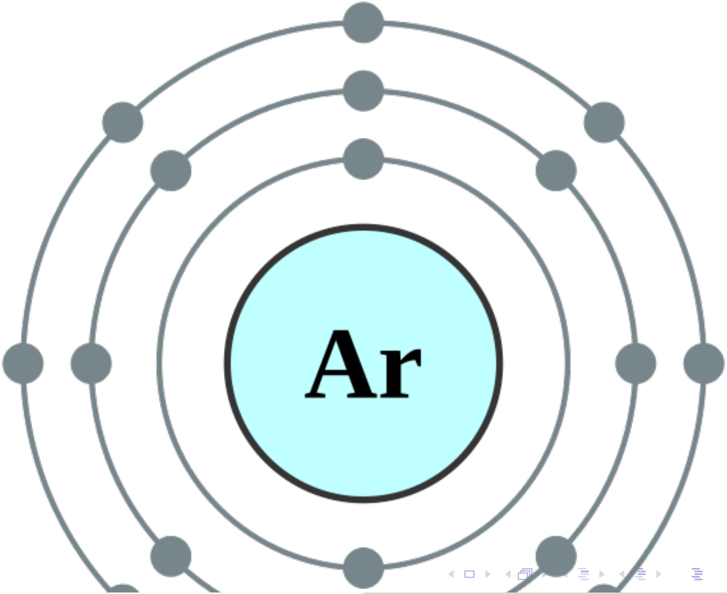
Semiconductors

- Semiconductors: materials with electrical conductivity between conductors and insulators
- Silicon is the original, simple semiconductor
- Gallium Arsenide is more efficient for some applications
- Pure Semiconductors are poor conductors
- Doping: adding impurities to radically change conductivity
- N-type: doped with elements having extra electrons (e.g., phosphorus)
- P-type: doped with elements having fewer electrons (e.g., boron)

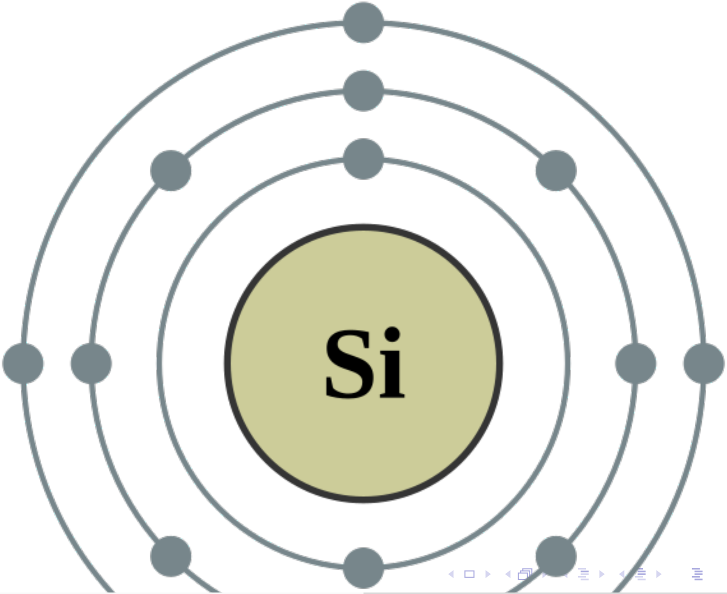
Conductor



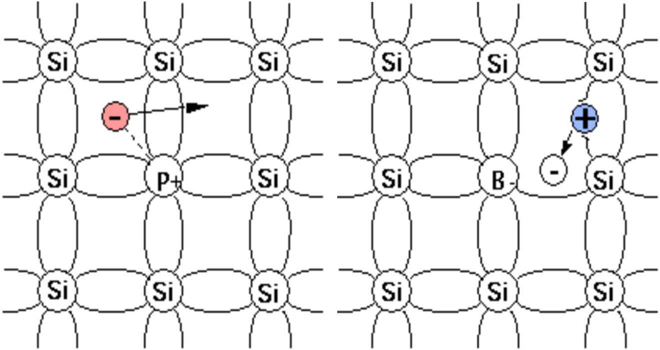
Insulator



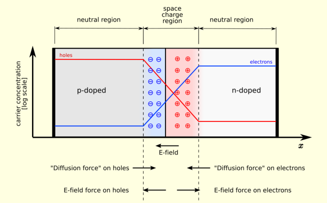
Semiconductor: Silicon

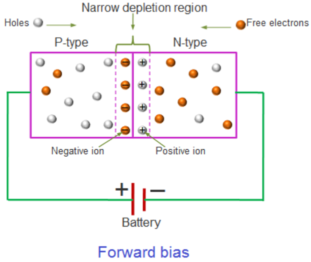


Silicon Lattice Structure



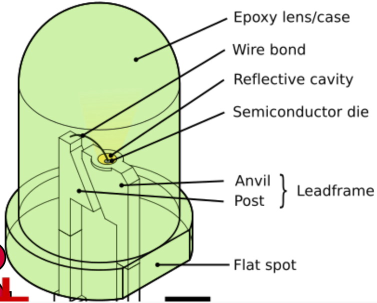
- Diode: electronic component allowing current flow in one direction
- PN Junction: boundary between P-type and N-type semiconductors
- Forward bias: allows current flow (P connected to positive, N to negative)
- Reverse bias: blocks current flow (P connected to negative, N to positive)





Light Emitting Diodes (LEDs)

- LEDs are semiconductor devices that emit light when current flows through them
- Highly efficient: convert up to 70% of energy into light (compared to 10% for incandescent bulbs)
- Produce monochromatic light due to their atomic structure
- The material used determines the energy level of the photons emitted, hence the color
- Not made of silicon, but other semiconductor materials



LED Materials and Colors

- Different semiconductor materials are used to produce different colors:
  - Red: Aluminum Gallium Arsenide (AlGaAs)
  - Green: Indium Gallium Nitride (InGaN)
  - Blue: Silicon Carbide (SiC) or Zinc Selenide (ZnSe)
  - White: Blue LED with yellow phosphor coating
- The choice of material is crucial for achieving the desired wavelength (color) of light
- Interesting history of blue LEDs: `https://www.youtube.com/watch?v=AF8d72mA41M`

LED Voltage Requirements by Color

Color	Typical Forward Voltage
Infrared	1.2V - 1.5V
Red	1.8V - 2.1V
Orange	2.0V - 2.2V
Yellow	2.1V - 2.4V
Green	2.9V - 3.4V
Blue	3.0V - 3.4V
White	3.0V - 3.4V
Ultraviolet	3.1V - 4.4V

- Note: Actual voltage varies with material and implementation

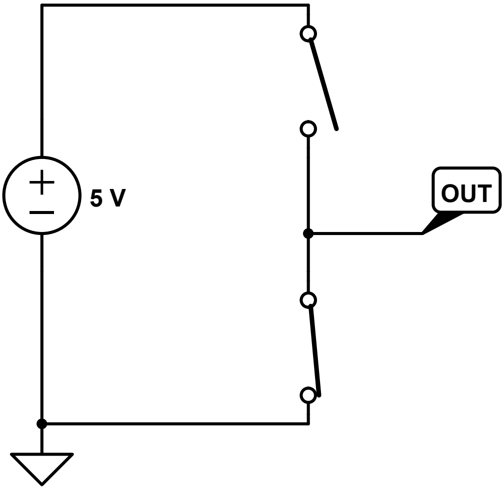
Interesting: LEDs work in Reverse

- LEDs take in electricity and efficiently turn it to light
- In reverse, they turn light into electricity
- This is how solar cells work
- Photovoltaic effect: Einstein 1905, Nobel 1922
- Solar cells are more efficient though
- Design is not symmetric
- Similar principle: Motors and generators

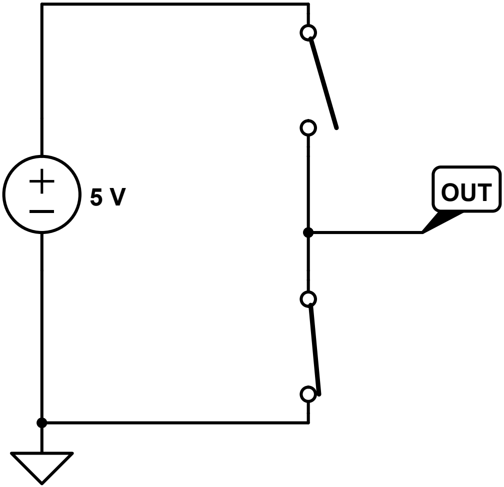
Interesting: Pulsed LEDs are (ok) LASERS

- An LED produces monochromatic light
- A laser produces coherent monochromatic light
- All light in phase, maintains a tight beam
- Needed
  - Resonant cavity
  - Half-silvered mirror
  - Short pulses of higher power
- Not the best laser, but pretty good

Switch Equivalents of Transistors

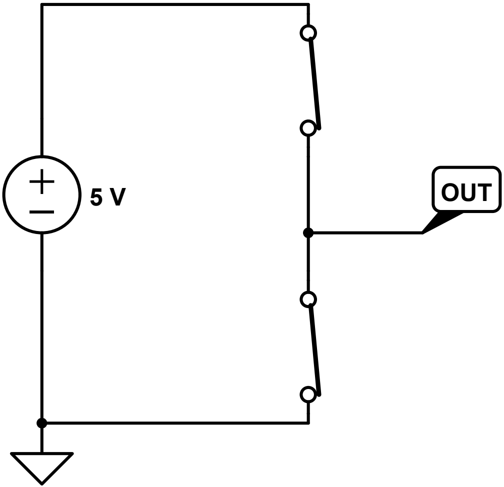


Switch Equivalents of Transistors 2



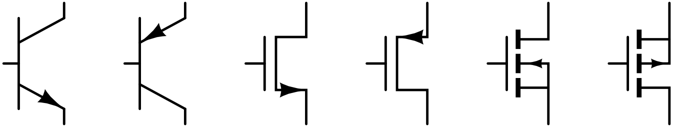
Switch Equivalents of Transistors 3

This had better not happen!



Two Kinds of Transistors

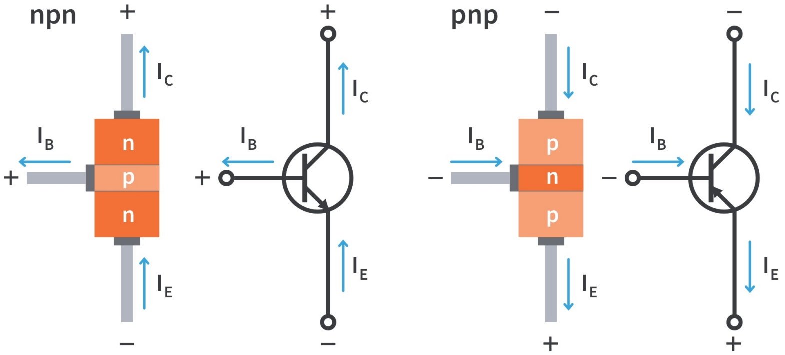
- Bipolar Junction Transistors (BJT)
  - Base, Emitter, Collector
- Field Effect Transistors (FET)
  - Gate, Source, Drain



BJT: Bipolar Junction Transistor

- First kind of Transistor
- Three terminals: Base, Emitter, Collector
- A small current at the base controls a larger current from the emitter to the collector
- Two types: NPN and PNP
- NPN is more efficient than PNP
- Dominated for most applications by FETs, used in low-cost applications

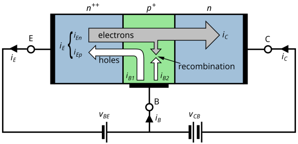
BJT: Bipolar Junction Transistor



See: BJT Basics

Bipolar Junction Transistor (BJT)

- Invented in 1947: Shockley, Brattain, and Bardeen
- Three terminals: Base, Emitter, Collector
- Small current at base controls larger current
- From Emitter to Collector
- Types: NPN and PNP (NPN is more efficient)



- BJT was the first kind of transistor Invented
- Generally uses more current (less efficient) than MOSFET
- Cheaper, so still used in low-cost applications
- Electrons are more mobile than holes
- N-type materials are therefore superior to P
- NPN transistors are more efficient than PNP
- NPN symbol: 

- PNP symbol: 

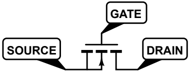
- FETs are controlled by voltage
- Three terminals: Gate, Source, Drain
- Much lower power consumption than BJTs
- Very high gate resistance ($> 1M\Omega$)
- N-Channel: Turns on with $V_g > S + V_{GS}$
- P-Channel: Turns on with $V_g < S - V_{GS}$

Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

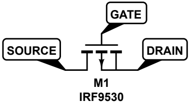
- Invented by Mohamed Atalla and Dawon Kahng in 1959
- Three terminals: Gate, Source, Drain
- Controlled by voltage to the Gate
- A dielectric on the gate prevents current
- Extremely high gate resistance
- FETs are the technology used for computers.

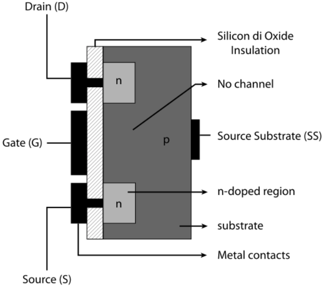
Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

- N-channel: Turn on when $Gate = Source + V_{GS}$
- P-channel: Turn on when $Gate = Source - V_{GS}$
- N-channel symbol:



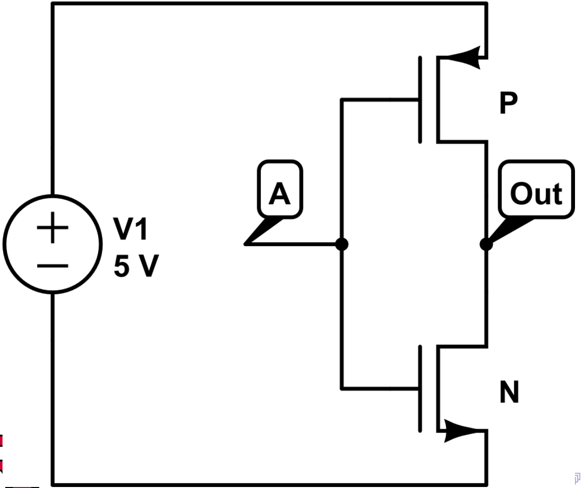
- P-channel symbol:

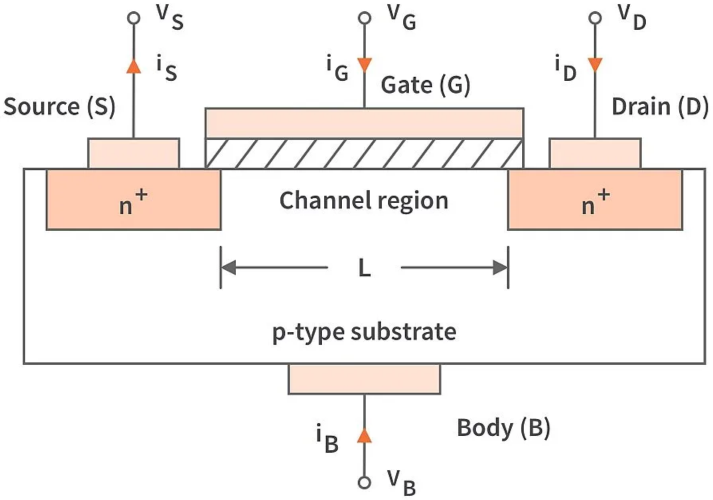




Complementary Metal-Oxide-Semiconductor (CMOS)

- Combines N-channel and P-channel MOSFETs
- Used in digital logic circuits
- Low power consumption: Very high resistance on Gate




V_S
i_S
Source (S)
i_G
V_G
Gate (G)
V_D
i_D
Drain (D)
n+
Channel region
n+
L
p-type substrate
i_B
Body (B)
V_B

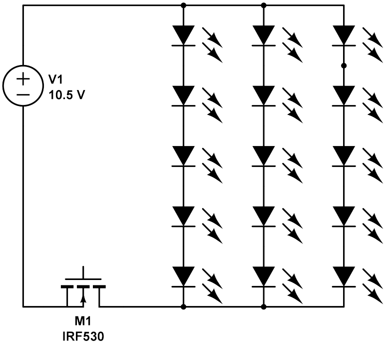
Specific MOSFET Examples

- 2N7000 (Small signal MOSFET)
  - N-channel
  - Max Voltage $V_{DS} = 60V$
  - Max Current $I_D = 200mA$
  - V_{GS} for max current: 10V
  - Max V_{GS}: 20V
  - On-Resistance $RDS_{on} = 5\Omega$
- IRF630 (Power MOSFET)
  - N-channel
  - Max Voltage $V_{DS} = 200V$
  - Max Current $I_D = 9A$
  - V_{GS} for max current: 10V
  - Max $V_{GS} = 20V$
  - On-Resistance $RDS_{on} = 0.4\Omega$

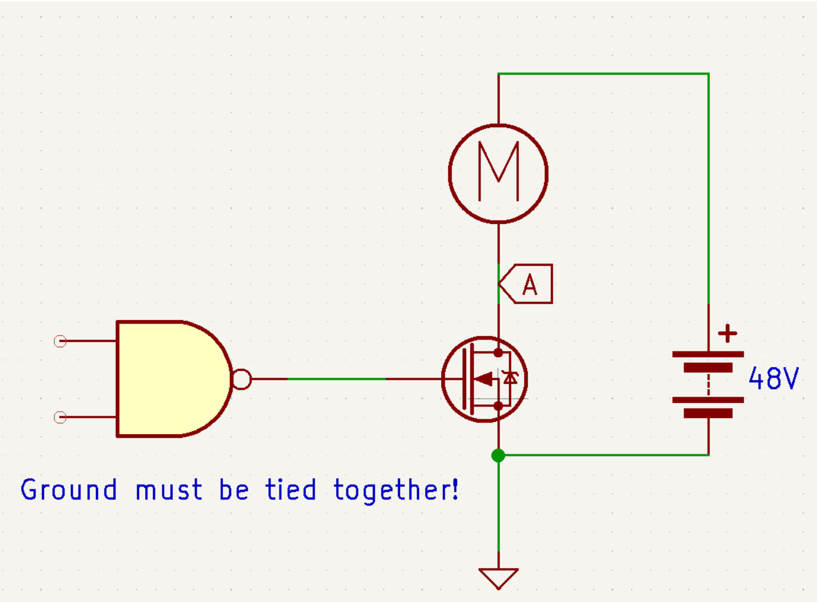
Controlling a Bank of LEDs with an N-channel MOSFET

- Use an N-channel MOSFET to control multiple LEDs
- Connect the source to ground
- Connect the drain to the cathode of the LEDs
- Connect the anode of the LEDs to the power supply through current-limiting resistors
- Apply a voltage to the gate to turn on the MOSFET and light up the LEDs

Controlling a Bank of LEDs with an N-channel MOSFET



Use a Power MOSFET to control a motor



MOSFET: Reading a Spec Sheet

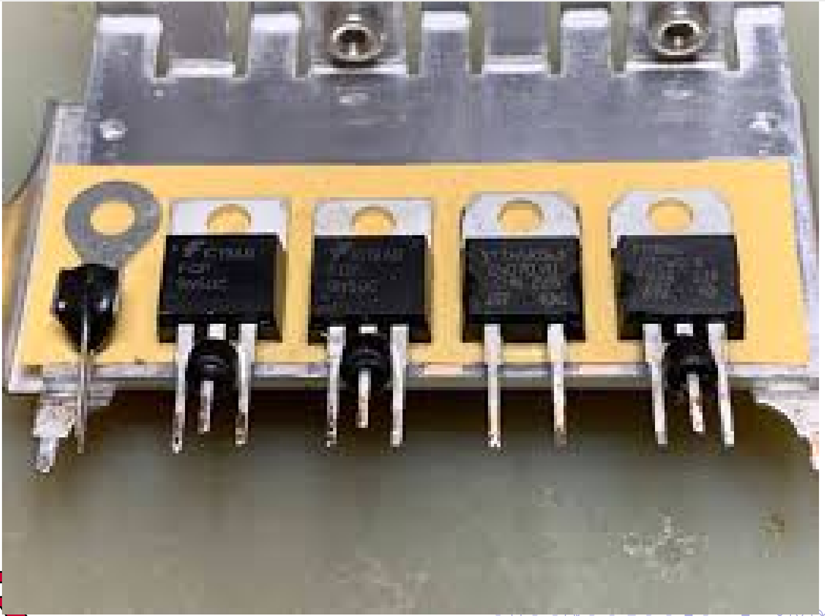
IRF540N Datasheet

- Maximum Drain-Source Voltage (V_{DS})
- Maximum Gate-Source Voltage (V_{GS})
- Maximum Drain Current (Id)
- Threshold Voltage ($V_{GS}(th)$)
- On-Resistance (RDS_{on})

MOSFET: Reading a Spec Sheet

Search part number + "spec" or "datasheet" How much voltage can the MOSFET switch on? (V_{DS})
What is the maximum voltage that can be applied to the gate?
What is the voltage to the gate needed to turn the MOSFET completely on?
What is the maximum current that can be drawn from the drain? (Id)
Note: This will require a heat sink to keep the MOSFET from overheating.
What is the resistance of the MOSFET when it is on? (RDS_{on})

MOSFET: Heat Sinks



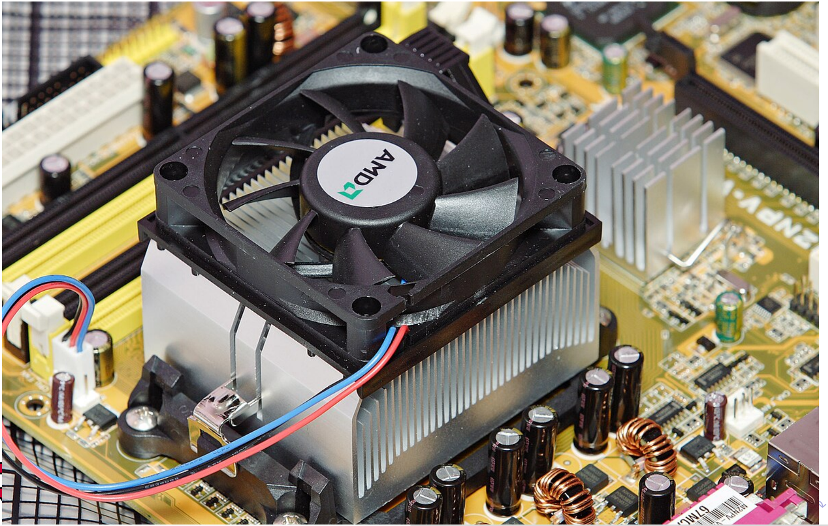
CPU Heat

- Heat is proportional to I^2R
- Consider each generation shrinking transistors by a factor of 2
- R decreases by a factor of 2?
- But there are now 4 times as many transistors
- I increases by a factor of 2? (seems wrong)
- So $P = I^2R$ increases by a factor of 4?
- this is not my area. But I have read that power consumption/dissipation increases by $\sqrt{2}$
- In any case, this is why voltage keeps decreasing. It has to.

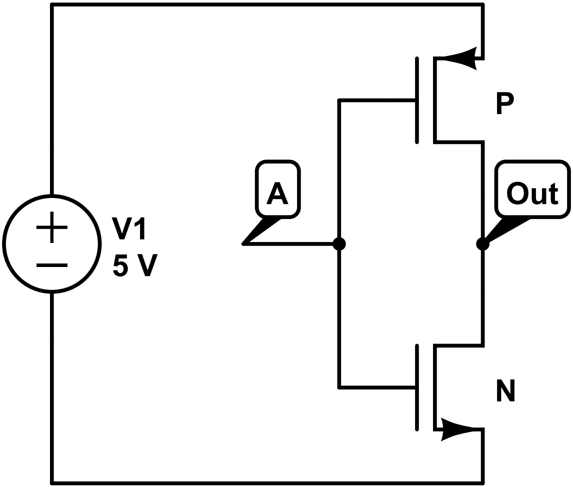
CPU Heat Sinks

The transistors in computers are very small, but there are a lot of them packed tightly

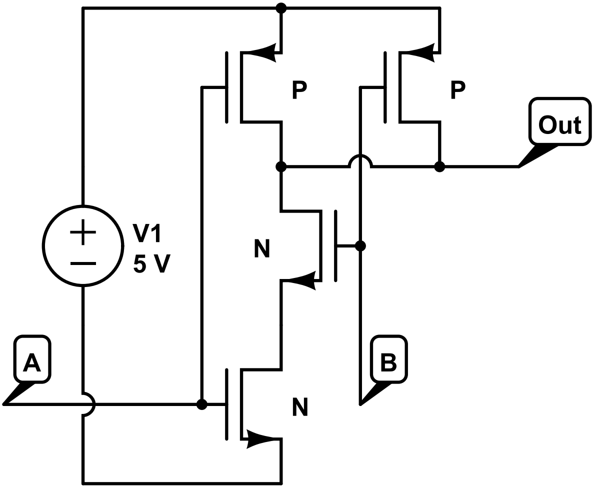
This generates a lot of heat

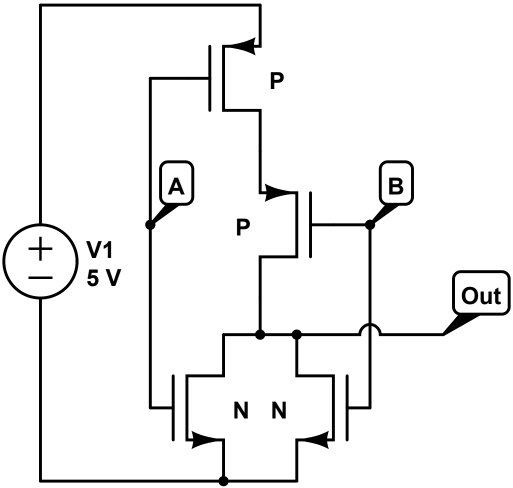


CMOS NOT Implementation

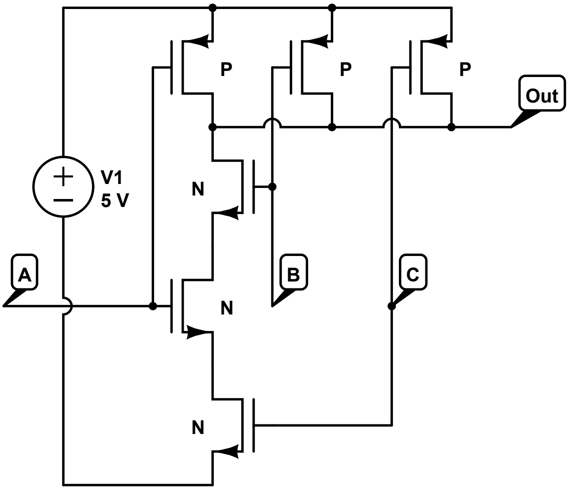


CMOS NAND Implementation

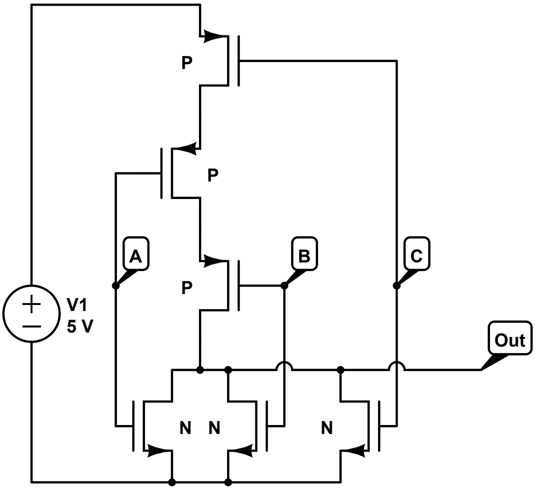



P
A
P
B
V1
5 V
Out
N
N

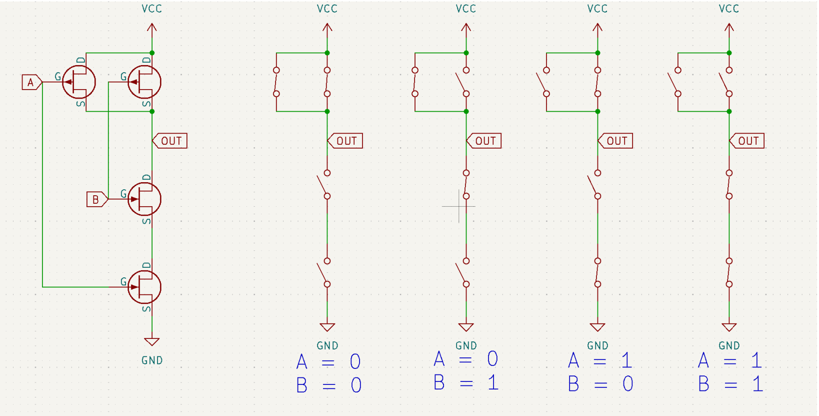
CMOS 3-Input NAND Implementation



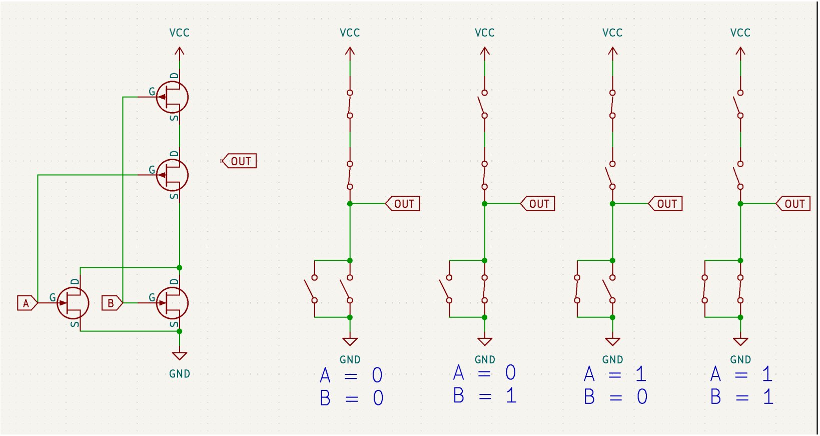
CMOS 3-Input NOR Implementation



Switch Equivalent States: NAND



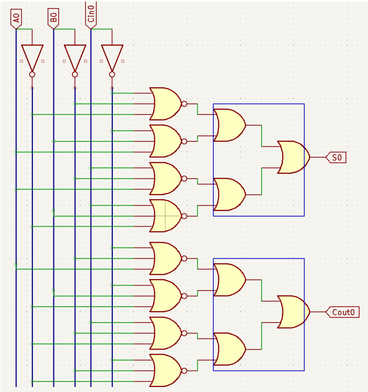
Switch Equivalent States: NOR



Gate Delays

- Switching a transistor on and off takes a finite time
- 74LS gate delays are 10ns
- 4000 CMOS delays are 1ns
- Modern Computers clock cycles of 3GHz
- In that time, hundreds of gate delays must happen
- Details are proprietary. Hard to find out how fast
- Assume 300 gate delays per clock cycle: $333ps/300 = 1.11ps$
- Chatgpt claims 5-20ps. It's probably right but I can't verify

Gate delay is the longest path through the circuit.
What is the delay, given the NOT takes 500ps and NAND/NOR/OR take 1ns?



A tri-state Buffer

A tri-state buffer can disconnect an input from an output
Used to create larger multiplexers by disconnecting all but one input