Electronics Overview

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Resistor

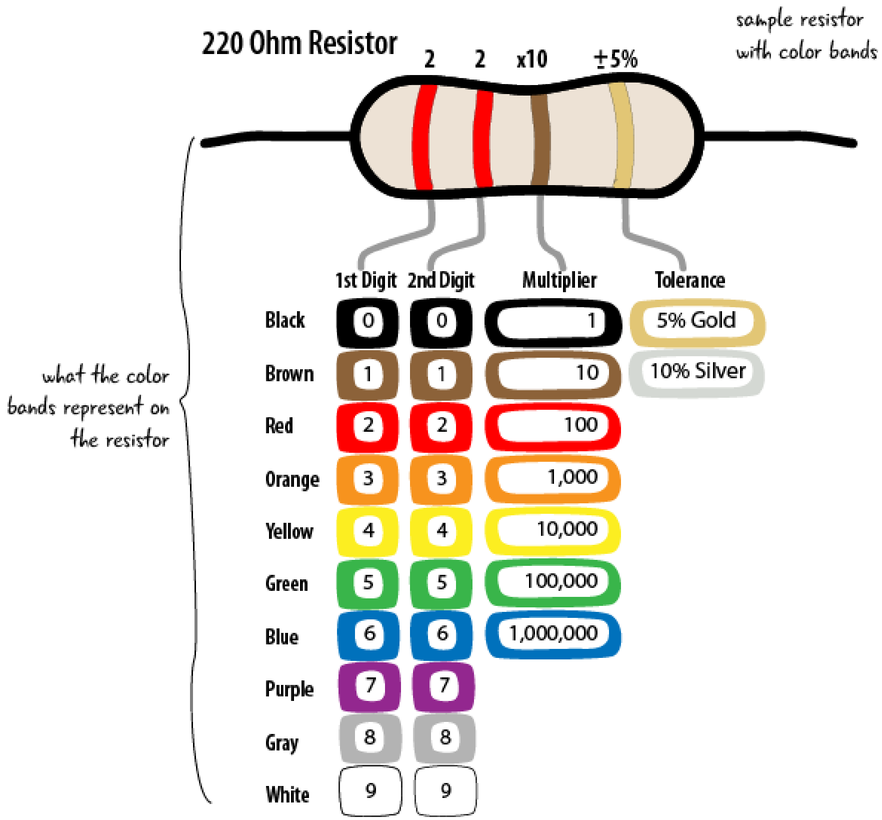
- Resistors play a crucial role in controlling the flow of electricity and shaping the behaviour of circuits.
- Role of Resistors in Circuits include:

- Current Limiting and Signal Adjustment: Resistors can be used to reduce the current flow in a circuit. This is particularly important in protecting sensitive components from excessive current.

- Voltage Division: Resistors can be used to divide voltages in a circuit. This is often used when a certain voltage level is needed for a component1.

- Timing and Filtering: In combination with capacitors, resistors can create RC circuits that are used for filtering purposes.

Resistor


220 Ohm Resistor
2
2
x10
±5%
sample resistor with color bands
what the color bands represent on the resistor
1st Digit
2nd Digit
Multiplier
Tolerance
Black 0 0 1 5% Gold
Brown 1 1 10 10% Silver
Red 2 2 100
Orange 3 3 1,000
Yellow 4 4 10,000
Green 5 5 100,000
Blue 6 6 1,000,000
Purple 7 7
Gray 8 8
White 9 9

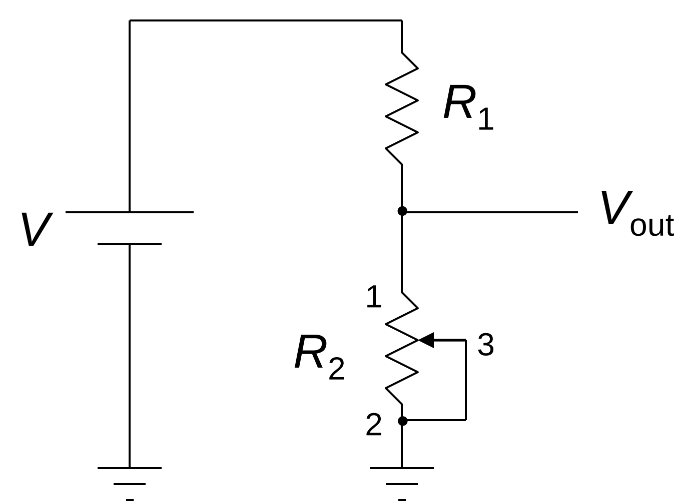
The Basic Relations

- V is voltage (volts: V); I is current (amps: A); R is resistance (ohms: Ω); C is capacitance (farads: F); L is inductance (henrys: H)
- Ohm's Law: $V = IR$; $V = \frac{1}{C}\int I dt$; $V = L(dI/dt)$
- Power: $P = IV = V^2/R = I^2R$
- Resistors and inductors in series add
- Capacitors in parallel add
- Resistors and inductors in parallel, and capacitors in series add according to:

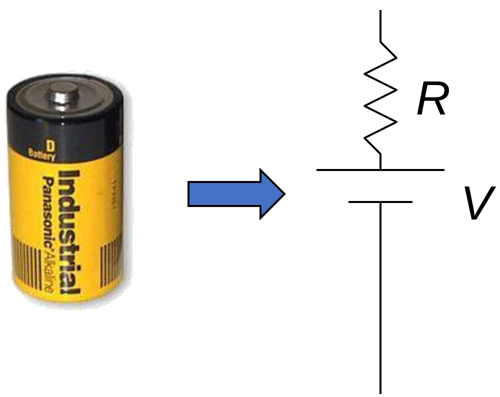
$$\frac{1}{X_{tot}} = \frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \ldots$$

Example: Voltage divider

- Voltage dividers are a classic way to set a voltage
- Works on the principle that all charge flowing through the first resistor goes through the second
  - so $\Delta V \propto R$-value
  - provided any load at output is negligible: otherwise some current goes there too
- So $V_{out} = V(R_2/(R_1 + R_2))$
- R_2 here is a variable resistor, or *potentiometer*, or “pot”
  - typically three terminals: R_{12} is fixed, tap slides along to vary R_{13} and R_{23}, though $R_{13} + R_{23} = R_{12}$ always



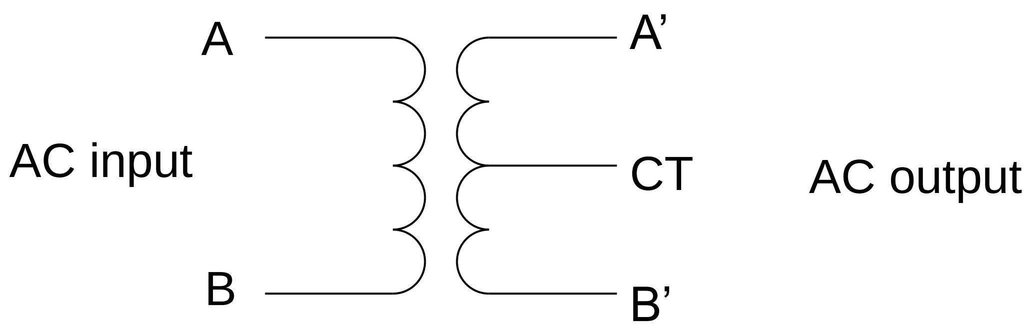
Real Batteries: Output Impedance



- A power supply (battery) is characterized by a voltage (V) and an output impedance (R)
  - sometimes called *source impedance*
- Hooking up to load: R_{load}, we form a voltage divider, so that the voltage applied by the battery terminal is actually $V_{out} = V(R_{load}/(R+R_{load}))$
- Example: If 10.0 V power supply droops by 1% (0.1 V) when loaded to 1 Amp (10 Ω load):
  - internal resistance is 0.1 Ω
  - called *output impedance* or *source impedance*
  - may vary with load, though (not a real resistor)

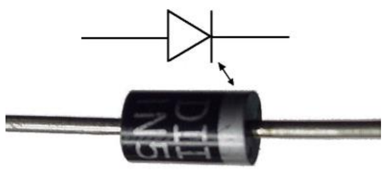
Power Supplies and Regulation

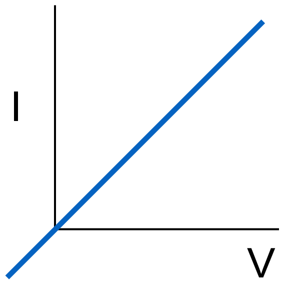
- A power supply typically starts with a transformer
  - to knock down a high peak-to-peak (e.g., 120 V AC) to something reasonable/manageable
- We can use a center-tap transformer



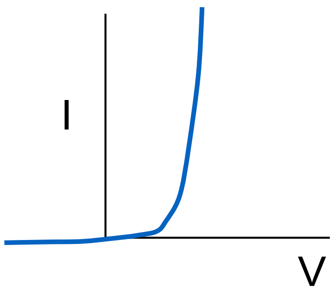
Diodes

- Diodes are essentially one-way current gates
- Symbolized by:
- Current vs. voltage graphs:

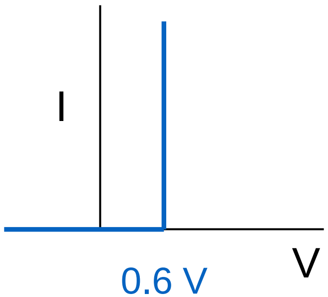




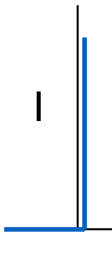
plain resistor



diode

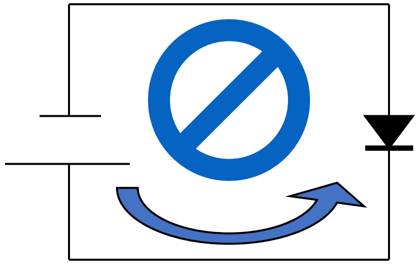


idealized diode

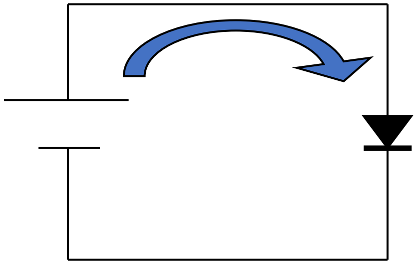


acts just like a wire (will support arbitrary current) provided that voltage is positive

WAY idealized diode



no current flows

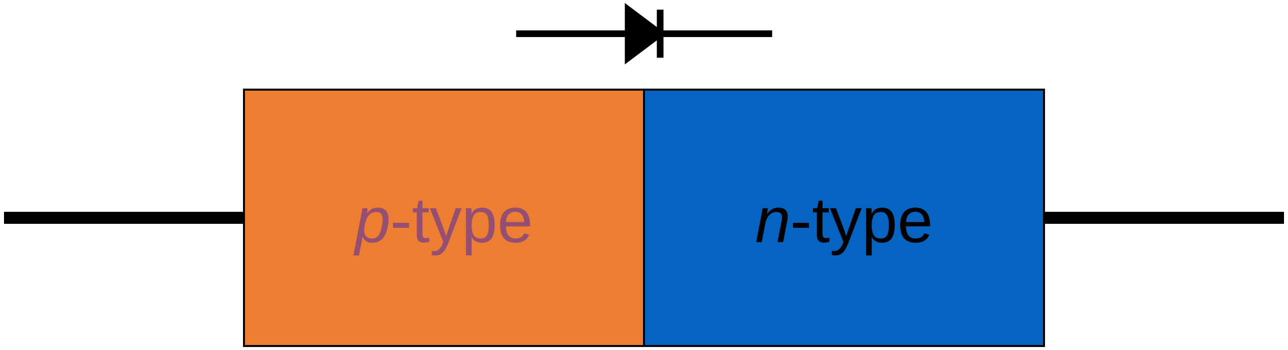


current flows

the direction the arrow points in the diode symbol is the direction that current *will* flow

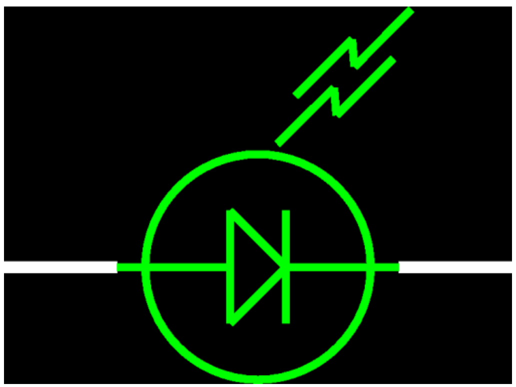
Diode Makeup

- Diodes are made of semiconductors (usually silicon)
- Essentially a stack of *p*-doped and *n*-doped silicon to form a *p-n junction*
  - doping means deliberate impurities that contribute extra electrons (*n*-doped) or "holes" for electrons (*p*-doped)
- Transistors are *n-p-n* or *p-n-p* arrangements of semiconductors



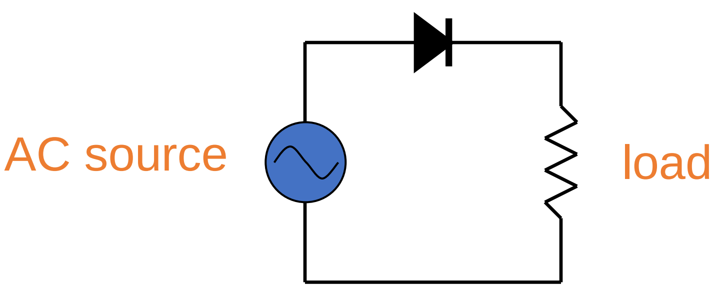
LEDs: Light-Emitting Diodes

- Main difference is material used in ordinary diodes/transistors
  - typically 2-volt drop instead of 0.6 V drop
- When electron flows through LED, loses energy by emitting a photon of light rather than vibrating lattice (heat)
- LED efficiency is 30% (compare to incandescent bulb at 10%)
- Must supply current-limiting resistor in series:
  - figure on 2 V drop across LED; aim for 1–10 mA of current

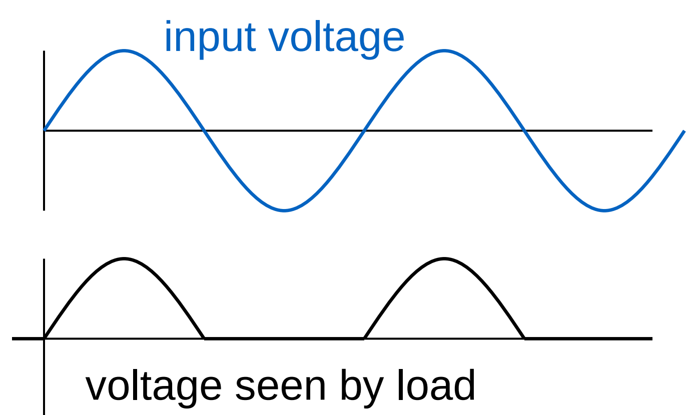


Getting DC back out of AC

- AC provides a means for us to distribute electrical power, but most devices actually *want* DC
  - bulbs, toasters, heaters, fans don’t care: plug straight in
  - sophisticated devices care because they have diodes and transistors that require a certain polarity
    - rather than oscillating polarity derived from AC
    - this is why battery orientation matters in most electronics
- Use diodes to “rectify” AC signal
- Simplest (half-wave) rectifier uses one diode:

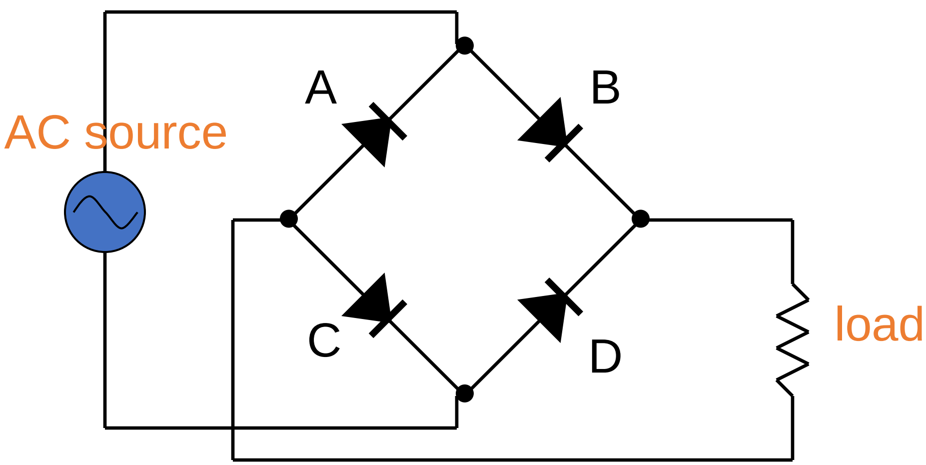


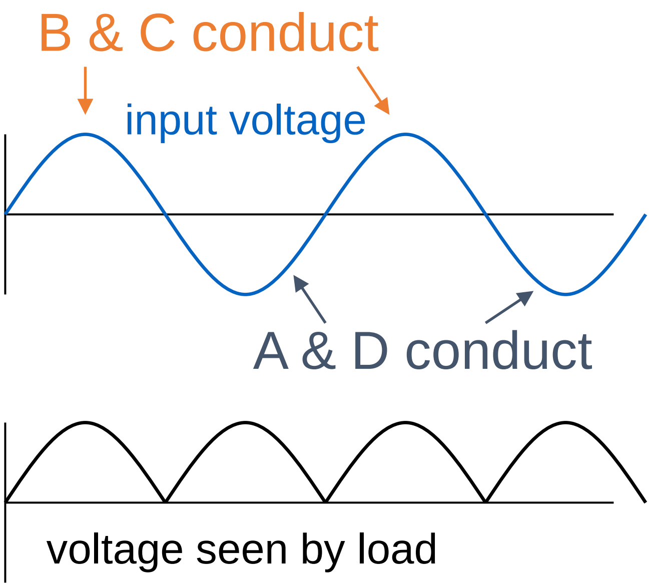
diode only conducts
when input voltage is positive



Doing Better: Full-wave Diode Bridge

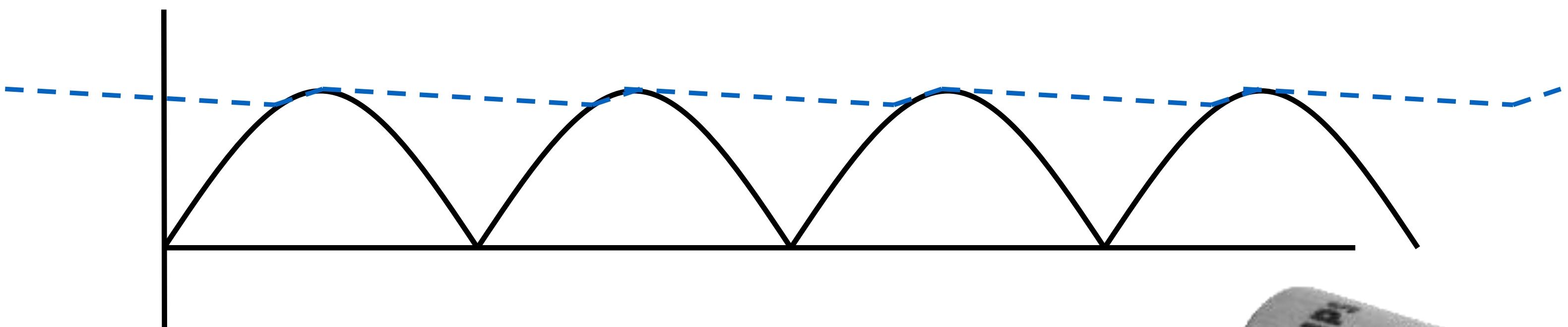
- The diode in the rectifying circuit simply prevented the negative swing of voltage from conducting
  - but this wastes half the available cycle
  - also very irregular (bumpy): far from a “good” DC source
- By using four diodes, you can recover the negative swing:

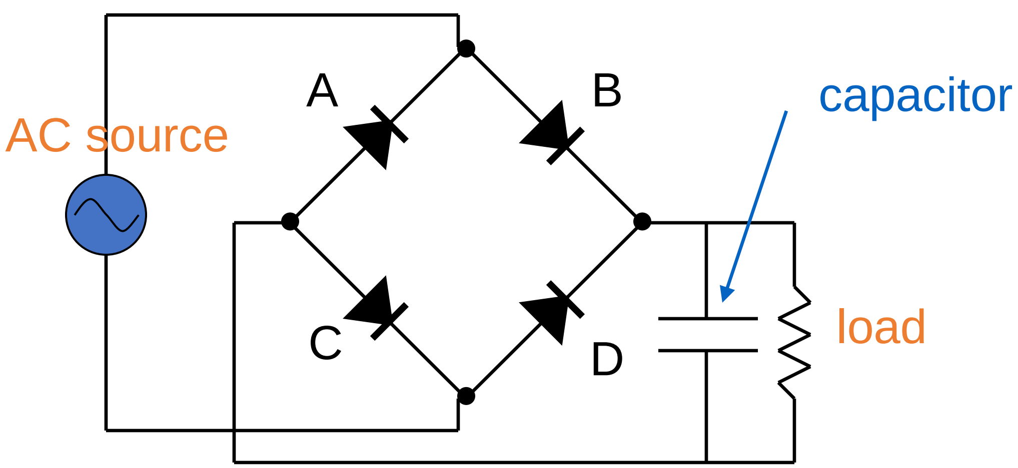


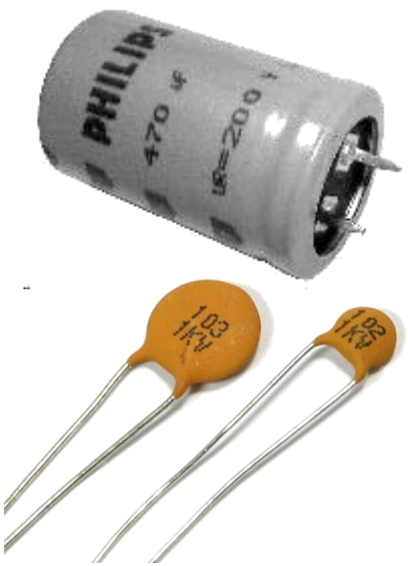


Smoothing

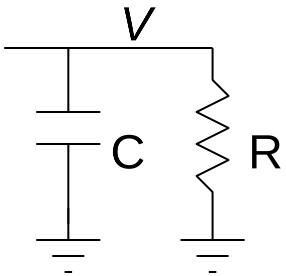
- We can smooth this out with a capacitor
  - capacitors have capacity for storing charge
  - acts like a reservoir to supply current during low spots
  - voltage regulator smoothes out remaining ripple



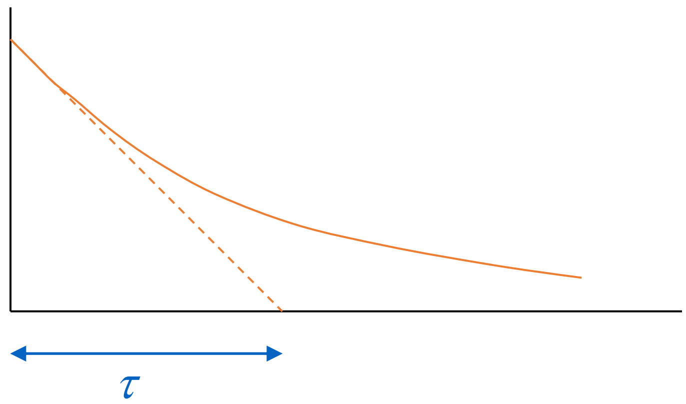




How to smooth?

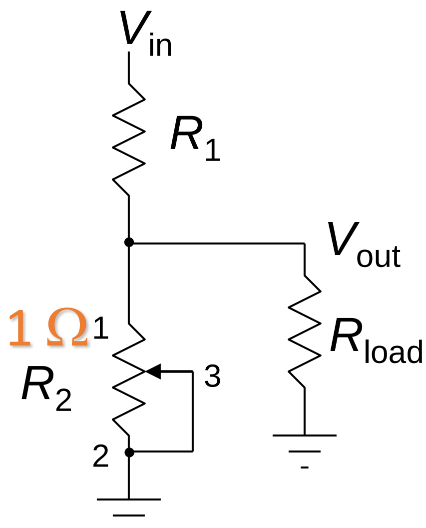


- An RC circuit has a time constant $\tau = RC$
  - because $dV/dt = I/C$, and $I = V/R \rightarrow dV/dt = V/RC$
- Any exponential function starts out with slope = Amplitude/τ



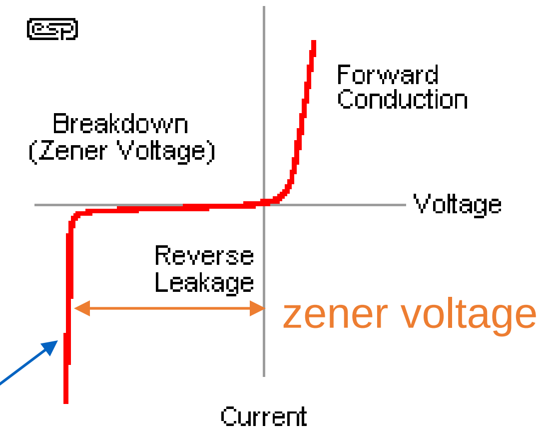
Regulating the Voltage

- The unregulated voltage may not be at the value you want
  - depends on transformer, etc.
  - suppose you want 15.0 V
- You *could* use a voltage divider to set the voltage
  - the divider will draw a lot of current
  - perhaps straining the source
  - power expended in divider >> power in load
- Not a "real" solution
- Important note: a "big load" means a small resistor value: 1 Ω demands more current than 1 MΩ

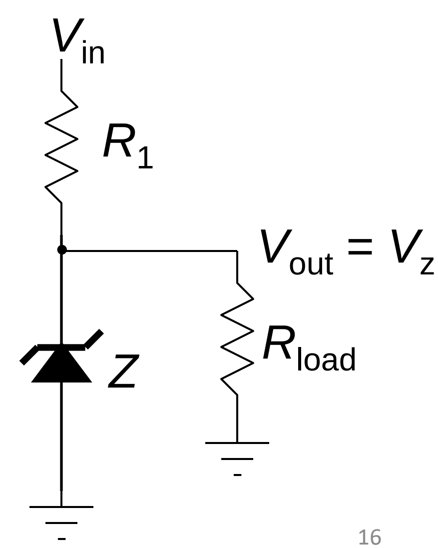


The Zener Regulator

- Zener diodes break down at some reverse voltage
    - can buy at specific breakdown voltages
    - as long as *some* current goes through zener, it'll work
    - good for rough regulation
- Conditions for working:
    - let's maintain some minimal current, I_z through zener (say a few mA)
    - then $(V_{in} - V_{out})/R_1 = I_z + V_{out}/R_{load}$ sets the requirement on R_1
    - because presumably all else is known
    - if load current increases too much, zener shuts off (node drops below breakdown) and you just have a voltage divider with the load

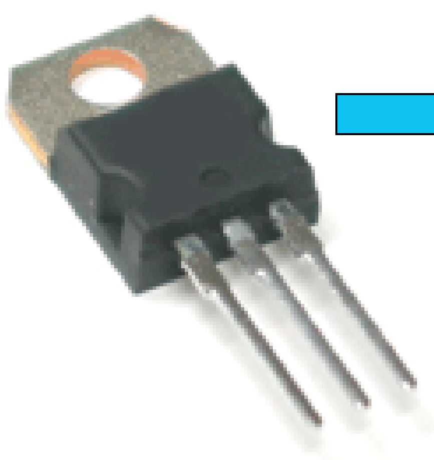


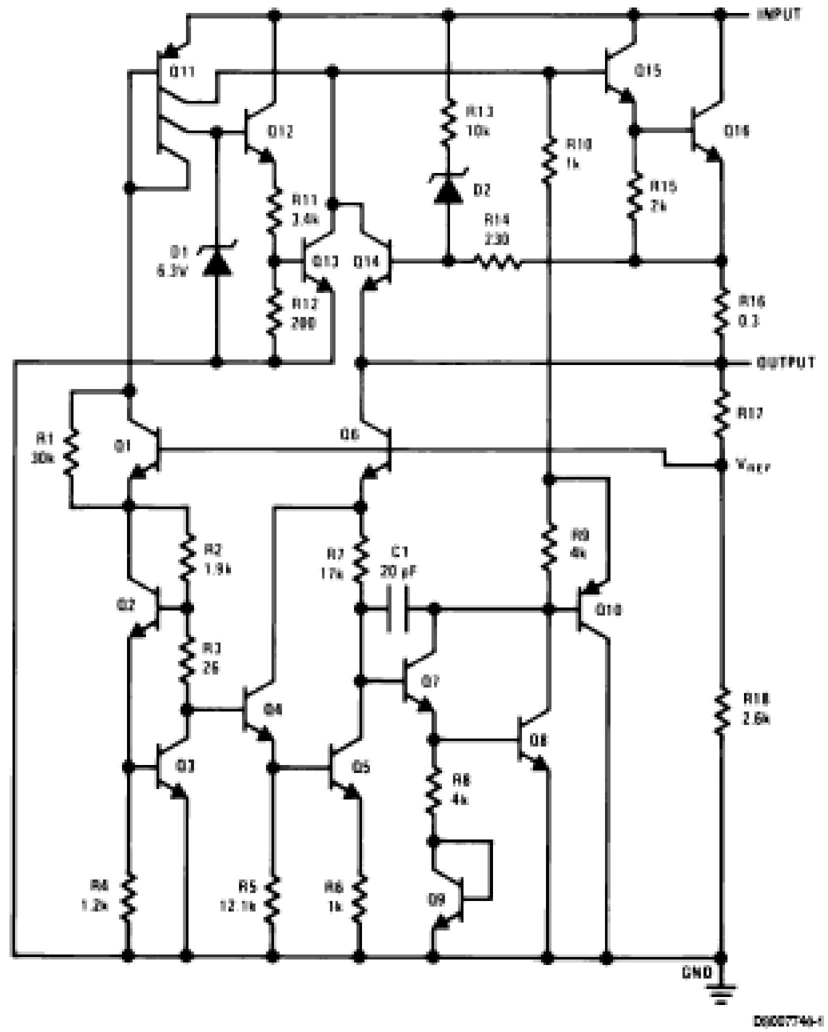
high slope is what makes the zener a decent voltage regulator



Voltage Regulator IC

- Can trim down ripply voltage to precise, rock-steady value
- Now things get complicated!
  - We are now in the realm of integrated circuits (ICs)
- ICs are whole circuits in small packages
- ICs contain resistors, capacitors, diodes, transistors, etc.

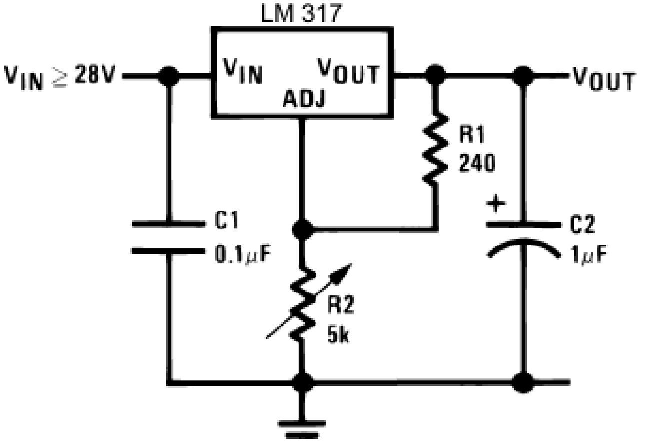




Voltage Regulators

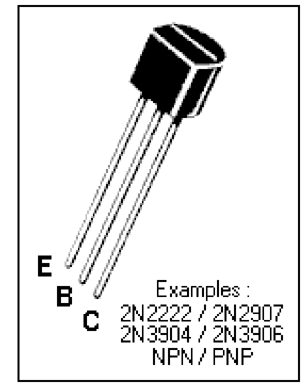
- The most common voltage regulators are the LM78XX (+ voltages) and LM79XX (– voltages)
  - XX represents the voltage
    - 7815 is +15; 7915 is –15; 7805 is +5, etc
  - typically needs input > 3 volts above output (reg.) voltage

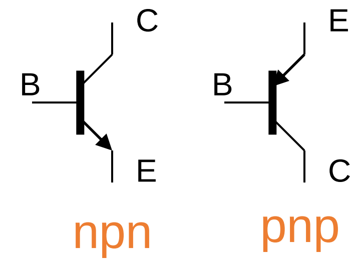
- A versatile regulator is the LM317 (+) or LM337 (–)
  - 1.2–37 V output
  - $V_{out} = 1.25(1+R_2/R_1) + I_{adj}R_2$
  - Up to 1.5 A
  - picture at right can go to 25 V
  - datasheetcatalog.com for details



Transistors

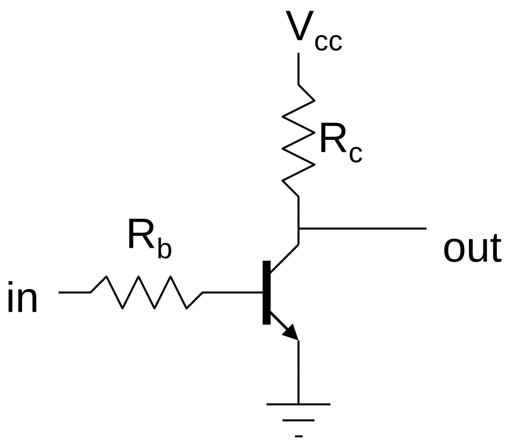
- Transistors are versatile, highly non-linear devices
- Two frequent modes of operation:
  - amplifiers/buffers
  - switches
- Two main flavors:
  - npn (more common) or pnp, describing doping structure
- Also many varieties:
  - bipolar junction transistors (BJTs) such as npn, pnp
  - field effect transistors (FETs): n-channel and p-channel
  - metal-oxide-semiconductor FETs (MOSFETs)

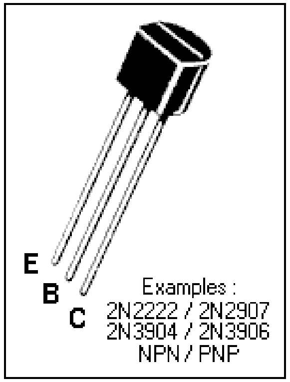


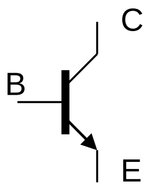


BJT Amplifier Mode

- Central idea is that when in the right regime, the BJT collector-emitter current is proportional to the base current:
  - namely, $I_{ce} = \beta I_b$, where β (sometimes h_{fe}) is typically ~100
  - In this regime, the base-emitter voltage is ~0.6 V



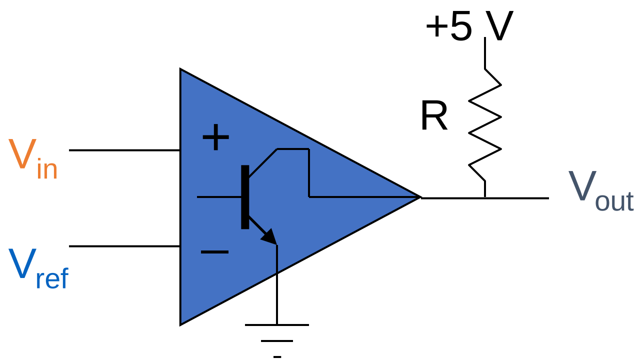


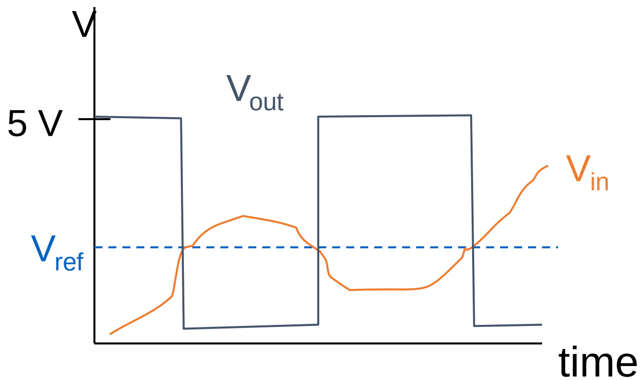


Switching: Driving to Saturation

- What would happen if the base current is so big that the collector current got so big that the voltage drop across R_c wants to exceed V_{cc}?

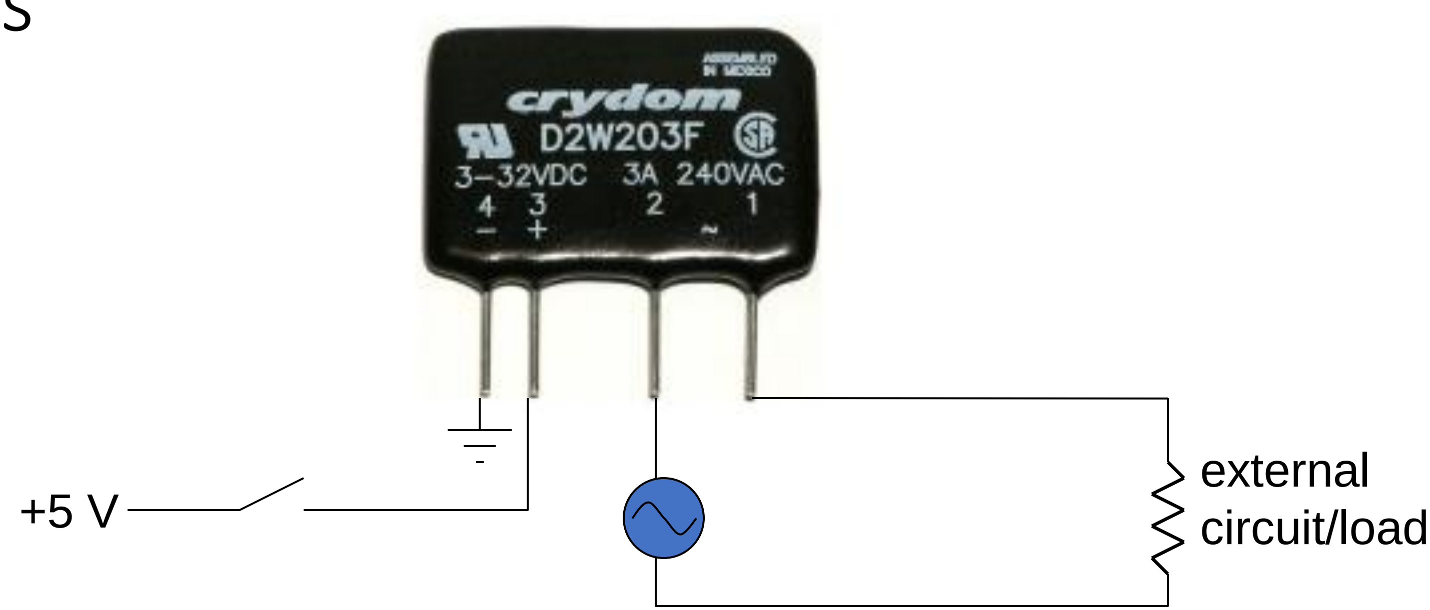
Op-Amp comparator





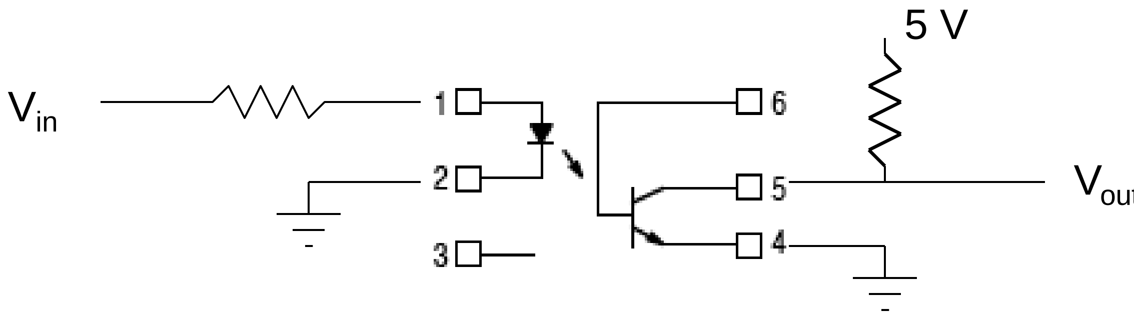
- When V_{in} < V_{ref}, V_{out} is pulled high (through the pull-up resistor—usually 1 kΩ or more)
  - this arrangement is called “open collector” output: the output is basically the collector of an npn transistor: in saturation it will be pulled toward the emitter (ground), but if the transistor is not driven (no base current), the collector will float up to the pull-up voltage
- The output is a “digital” version of the signal
  - with settable low and high values (here ground and 5V)
- Comparators also good at turning a slow edge into a fast one
  - for better timing precision

Relays



- Relays provide a way to switch on/off an AC line with a logic signal
- Simple: 5 volts in → AC switch flipped on
- Often will phase to AC line so it turns on at zero-crossing, so-as not to jar electronics

Opto-isolators



PIN 1. LED ANODE
2. LED CATHODE
3. N.C.
4. EMITTER
5. COLLECTOR
6. BASE

- Opto-isolators provide a means of connecting signals without copper (so can isolate grounds, noise, etc.)
  - LED shines light on a phototransistor, bringing it into saturation
  - in the above circuit, the output is pulled up to 5 V when the input is *inactive*, and drops near ground when the input sees a voltage

Field-Effect Transistors

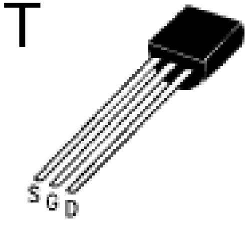
- The “standard” npn and pnp transistors use base-current to control the transistor current
- FETs use a field (voltage) to control current
- Result is no current flows into the control “gate”
- FETs are used almost exclusively as switches
  - pop a few volts on the control gate, and the effective resistance is nearly zero

FET Types

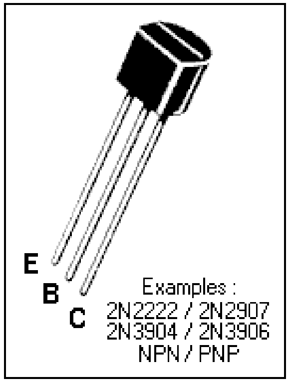
- Two types: JFET, MOSFET
- MOSFETs more common
- JFETs conduct “by default”
  - when $V_{gate} = V_{source}$
- MOSFETs are “open” by default
  - must turn on deliberately
- MOSFETs, as applied to logic designs, act as voltage-controlled switches

FET Generalities

FET



BJT



note pinout correspondence

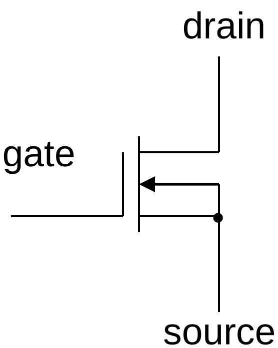
- Every FET has at least three connections:
  - source (S)
    - akin to emitter (E) on BJT
  - drain (D)
    - akin to collector (C) on BJT
  - gate (G)
    - akin to base (B) on BJT

Logic Families

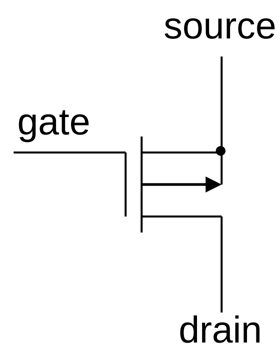
- TTL: transistor-transistor logic: BJT based
- CMOS: complimentary MOSFET
- CMOS is closer to the “ideal” that logic low is zero volts and logic high is 5 volts
  - and has a bigger dead zone
  - The differing input/output thresholds lead to noise immunity

MOSFET Switches

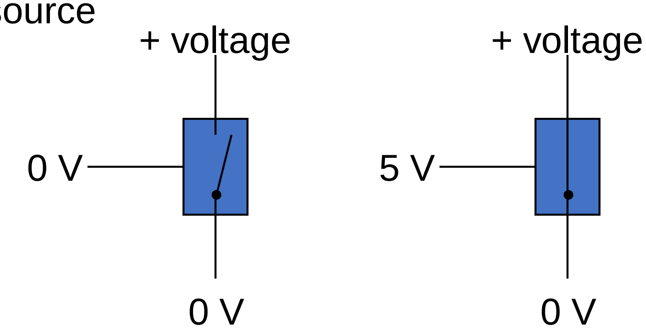
- MOSFETs (means metal-oxide semiconductor field effect transistor), as applied to logic designs, act as voltage-controlled switches
  - n-channel MOSFET is closed (conducts) when positive voltage (+5 V) is applied, open when zero voltage
  - p-channel MOSFET is open when positive voltage (+5 V) is applied, closed (conducts) when zero voltage

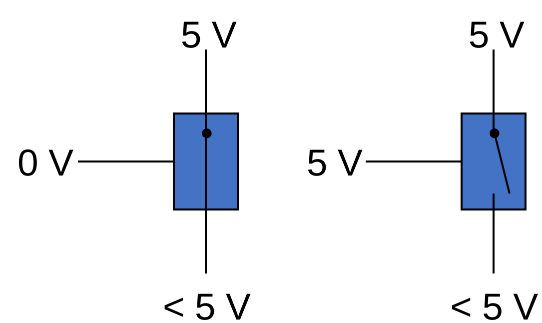


n-channel MOSFET



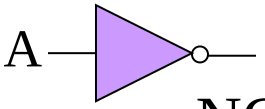
p-channel MOSFET





Data manipulation

- All data manipulation is based on *logic*
- Logic follows well defined rules, producing predictable digital output from certain input
- Examples:



NOT

A	C
0	1
1	0

AND

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

OR

A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

XOR

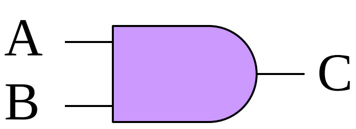
A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

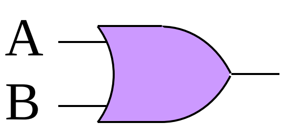
NAND

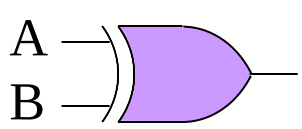
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

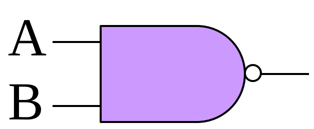
NOR

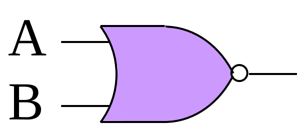
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0



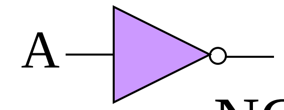






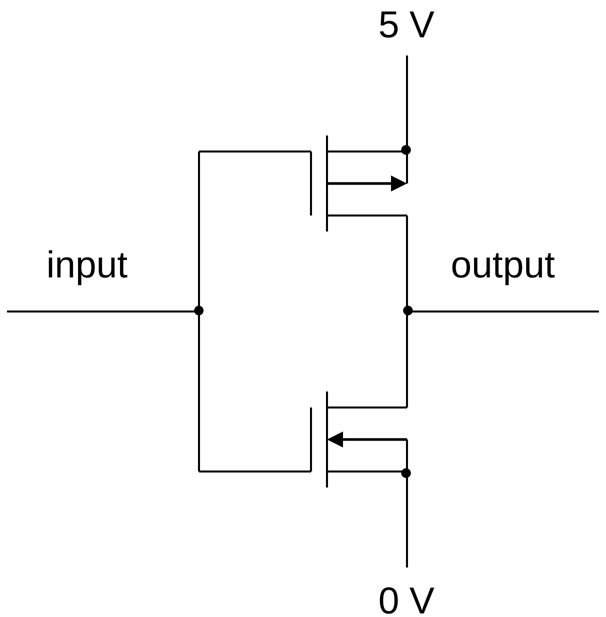


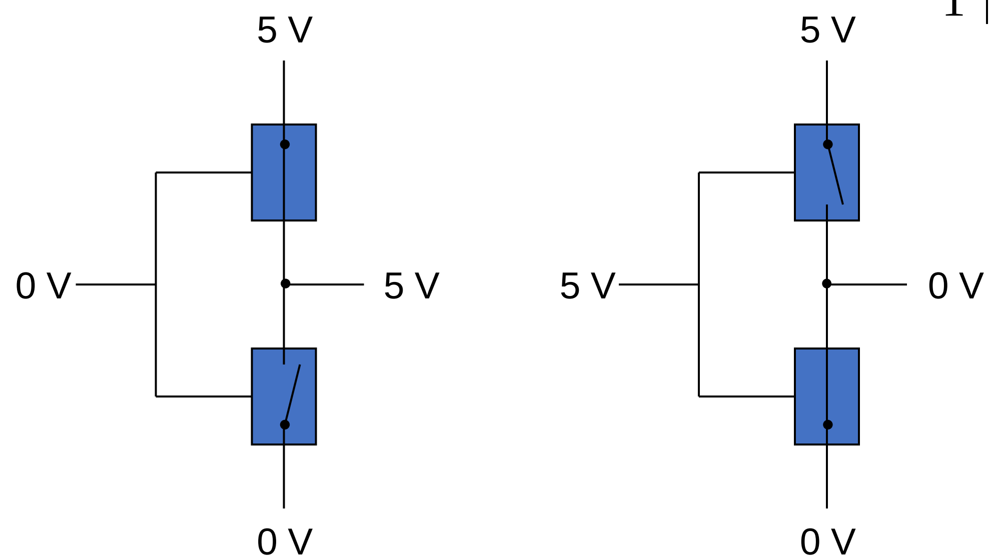
An inverter (NOT) from MOSFETS:



NOT

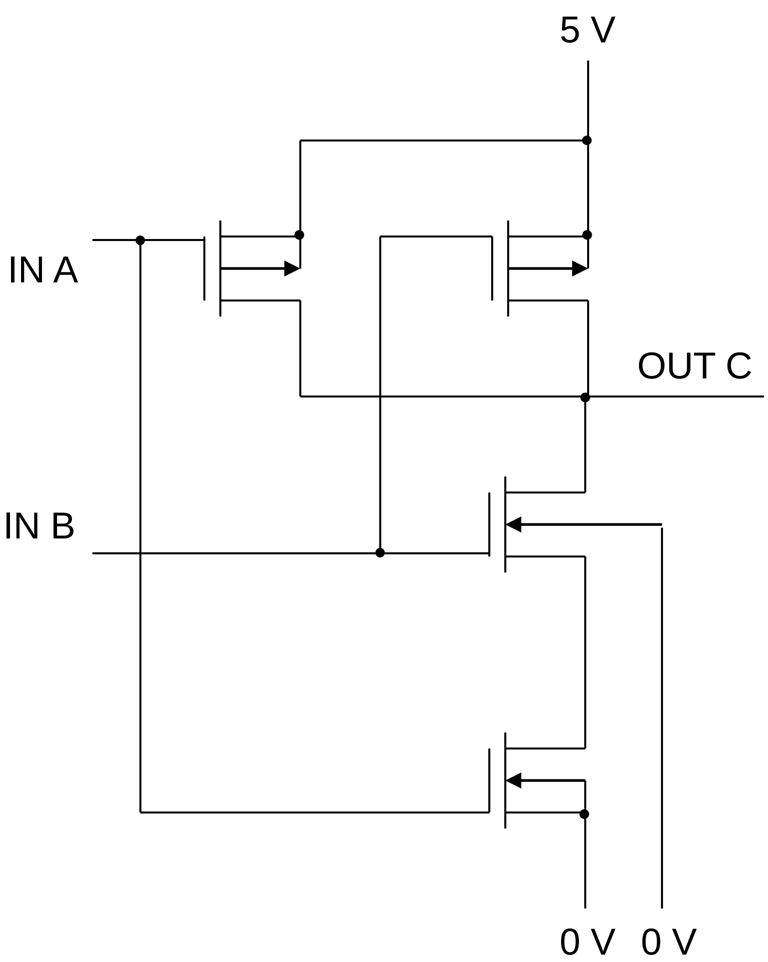
A	C
0	1
1	0



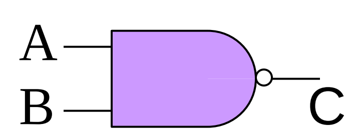


- 0 V input turns OFF lower (n-channel) FET, turns ON upper (p-channel), so output is connected to +5 V
- 5 V input turns ON lower (n-channel) FET, turns OFF upper (p-channel), so output is connected to 0 V
  - Net effect is logic inversion: 0 → 5; 5 → 0
- Complementary MOSFET pairs → CMOS

A NAND gate from scratch:



- Both inputs at zero:
  - lower two FETs OFF, upper two ON
  - result is output HI
- Both inputs at 5 V:
  - lower two FETs ON, upper two OFF
  - result is output LOW
- IN A at 5V, IN B at 0 V:
  - upper left OFF, lowest ON
  - upper right ON, middle OFF
  - result is output HI
- IN A at 0 V, IN B at 5 V:
  - opposite of previous entry
  - result is output HI



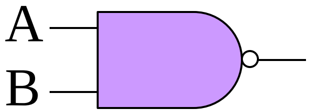
NAND

A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

All Logic from NANDs Alone

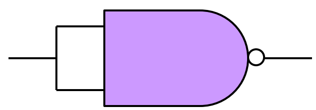
NAND

A	B	C
0	0	1
0	1	1
1	0	1
1	1	0



NOT

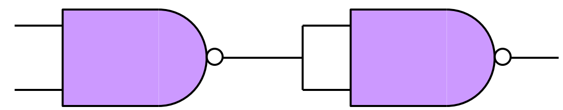
A	C
0	1
1	0



AND

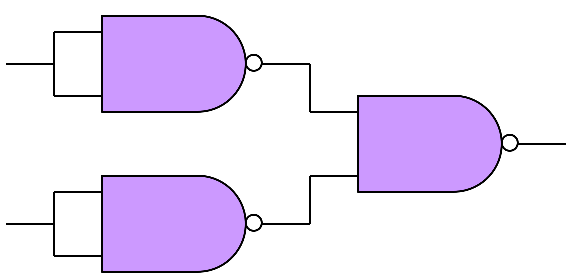
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

invert output (invert NAND)



OR

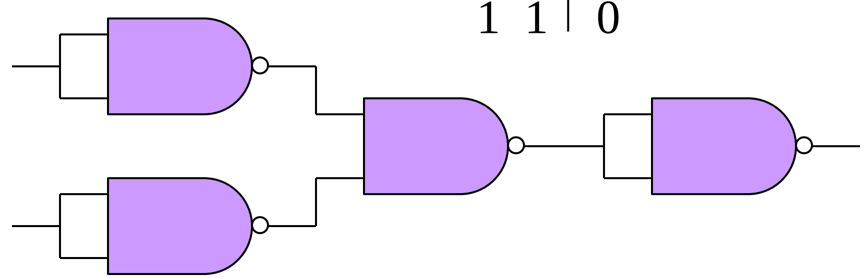
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1



invert both inputs

NOR

A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

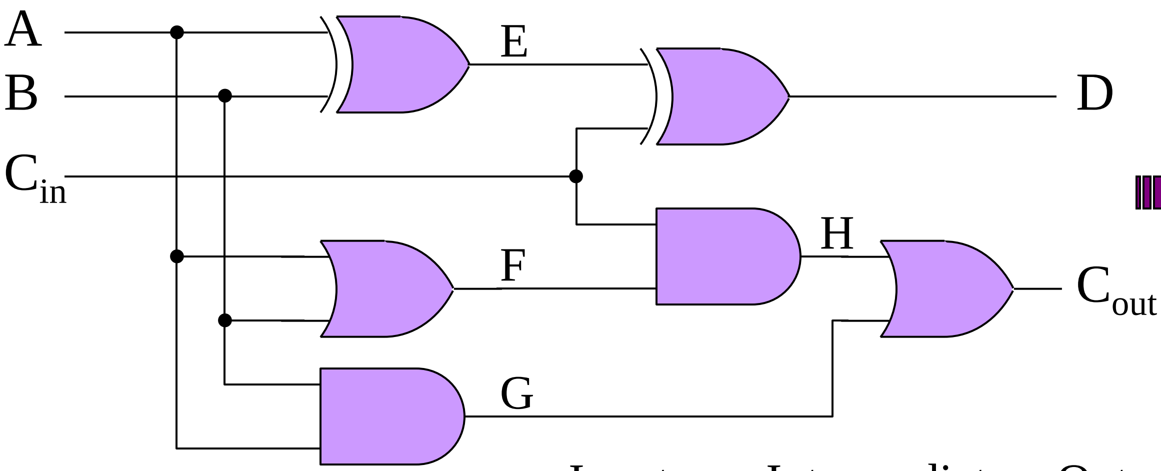


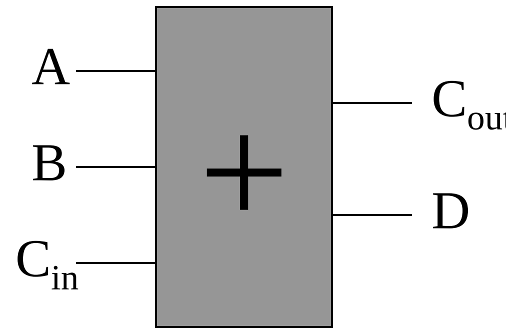
invert inputs *and* output (invert OR)

Rule the World

- Now you know how to build ALL logic gates out of n-channel and p-channel MOSFETs
  - because you can build a NAND from 4 MOSFETs
  - and all gates from NANDs
- That means you can build computers
- So now you can rule the world!

Binary Arithmetic in Gates





"Integrated" Chip

Input			Intermediate				Output	
A	B	C_{in}	E	F	H	G	D	C_{out}
0	0	0	0	0	0	0	0	0
0	1	0	1	1	0	0	1	0
1	0	0	1	1	0	0	1	0
1	1	0	0	1	0	1	0	1
0	0	1	0	0	0	0	1	0
0	1	1	1	1	1	0	0	1
1	0	1	1	1	1	0	0	1
1	1	1	0	1	1	1	1	1

Computer technology built up from pieces

- The foregoing example illustrates the way in which computer technology is built
  - start with little pieces (transistors acting as switches)
  - *combine* pieces into functional blocks (gates)
  - *combine* these blocks into higher-level function (e.g., addition)
  - *combine* these new blocks into cascade (e.g., 8-bit addition)
  - blocks get increasingly complex, more capable
  - Grab previously developed blocks and run
  - Let a computer design the gate arrangements (eyes closed!)

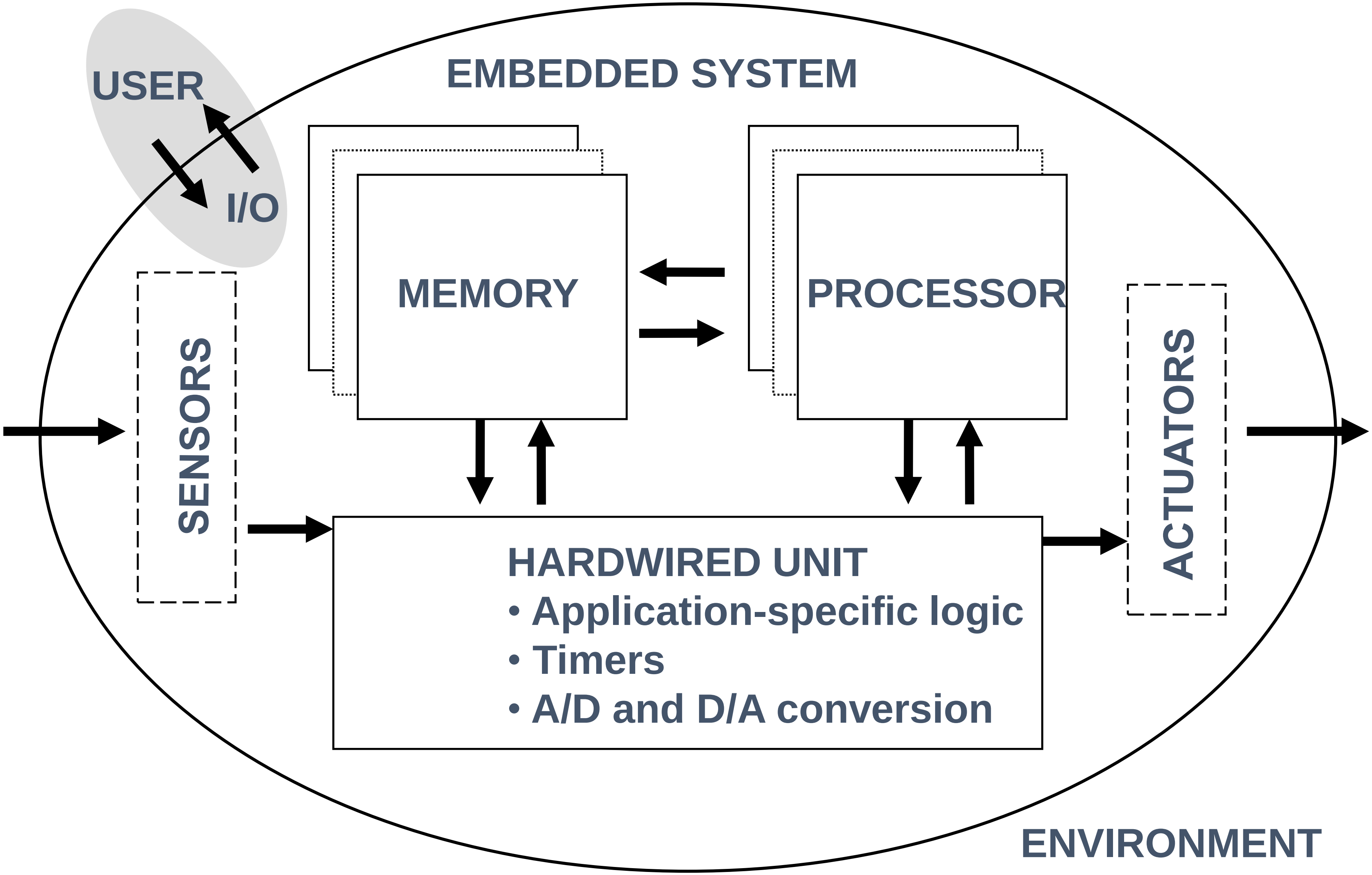
Embedded System

- “Any sort of device which includes a programmable computer but itself is not intended to be a general-purpose computer”

Wayne Wolf

Embedded Systems

- What are examples of embedded systems?

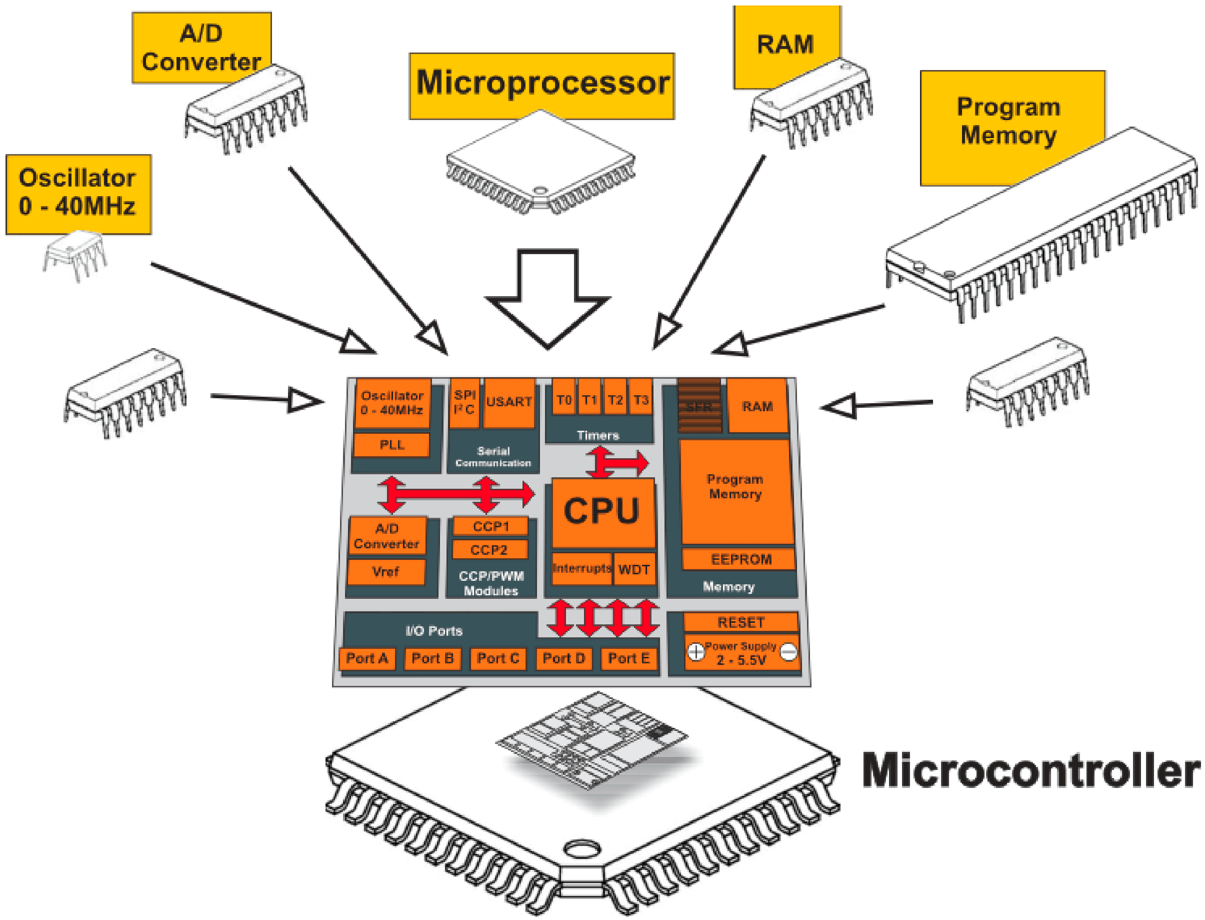


USER
I/O
EMBEDDED SYSTEM
MEMORY
PROCESSOR
SENSORS
ACTUATORS
HARDWIRED UNIT
• Application-specific logic
• Timers
• A/D and D/A conversion
ENVIRONMENT

Embedded Systems

- Actuators - (e.g., mechanical components)
- Sensors - input data (e.g., accelerometer for airbag control)
- Data conversion, storage, processing
- Decision-making

Microcontroller



Microcontroller

- What metrics we need to consider?
  - Power consumption
  - Clock frequency
  - IO pins
  - Memory
  - Internal functions
  - Others

Hard Real-time

- System designed to meet all deadlines
- A missed deadline is a design flaw
- For examples: ABS brake, nuclear reactor monitoring system
- System hardware (over) designed for worst-case performance
- System software rigorously tested

Firm Real-time

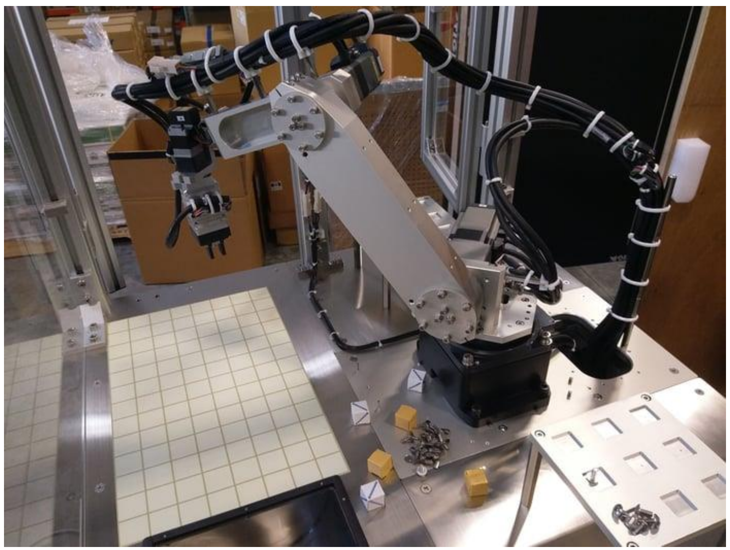
- System designed to meet all deadlines, but occasional missed deadline is allowed
    - Sometimes statistically quantified (e.g. 5% misses)
- For examples: multimedia systems
- System hardware designed for average case performance
- System software tested under average (ideal) conditions

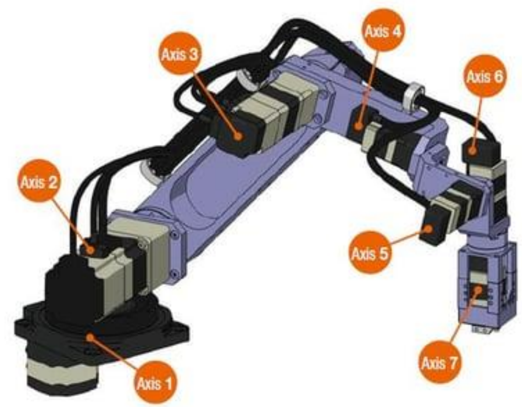
Soft Real-time

- System designed to meet as many deadlines as possible
  - Best effort to complete within specified time, but may be late
- For examples: network switch or router
- System hardware designed for average case performance
- System software tested under averaged (ideal) conditions

Embedded Systems

- Robot example





■ Motor Component List

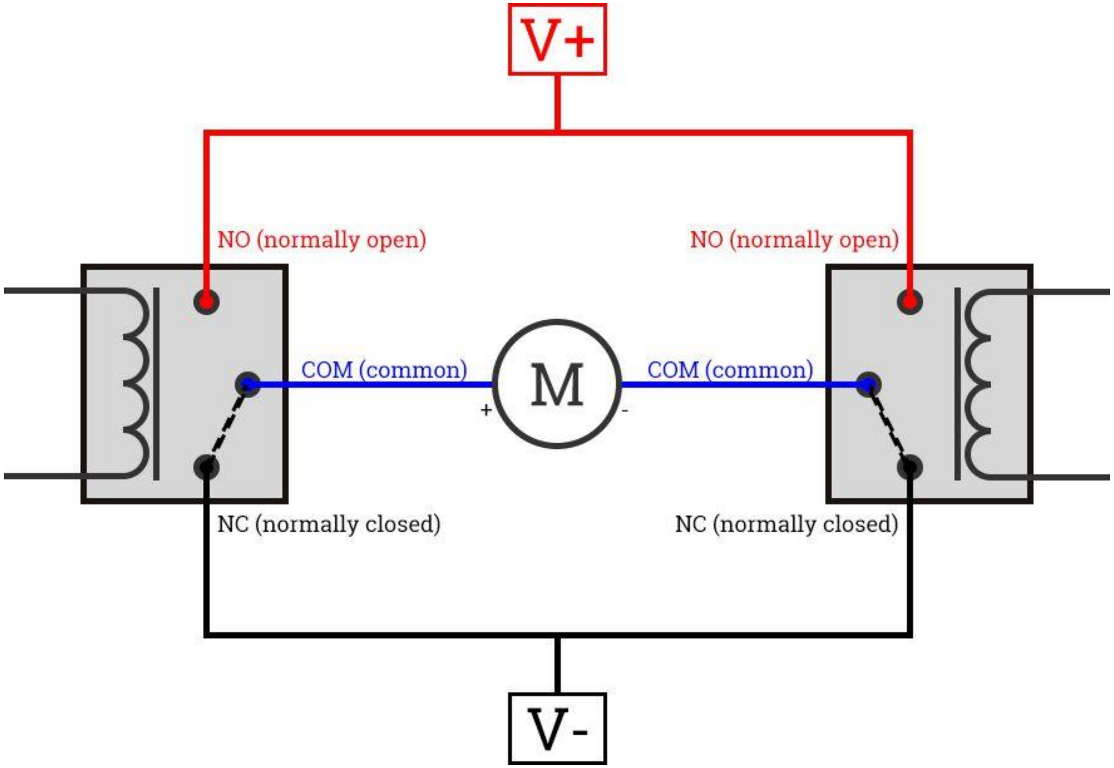
Axis	Motor/Actuator Product Model
Axis 7	AZM24AK
Axis 6	AZM24AK-HS50
Axis 4 Axis 5	AZM24AK-HS100
Axis 3	AZM46MK-HS100
Axis 2	AZM66MK-HS100
Axis 1	DGM130R-AZAK

Embedded Systems

- Motor control:
  - Directly from microcontroller
  - Using switch

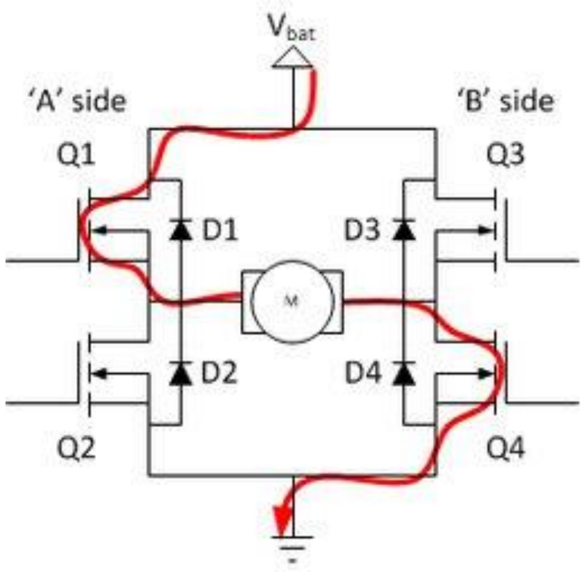
Embedded Systems

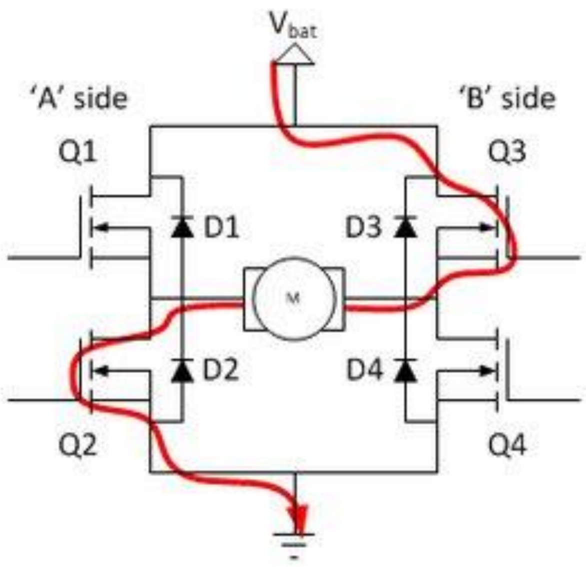
- Relay



Embedded Systems

• H-Bridge



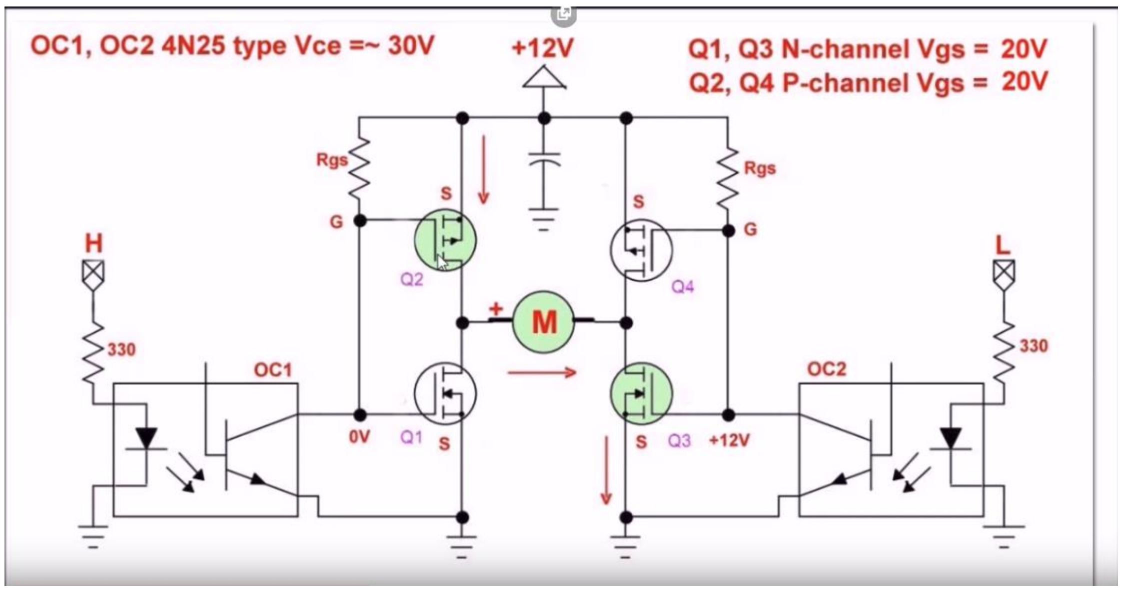


Embedded Systems

- High payload challenge

Embedded Systems

- Opto-coupler (Opto-isolator)

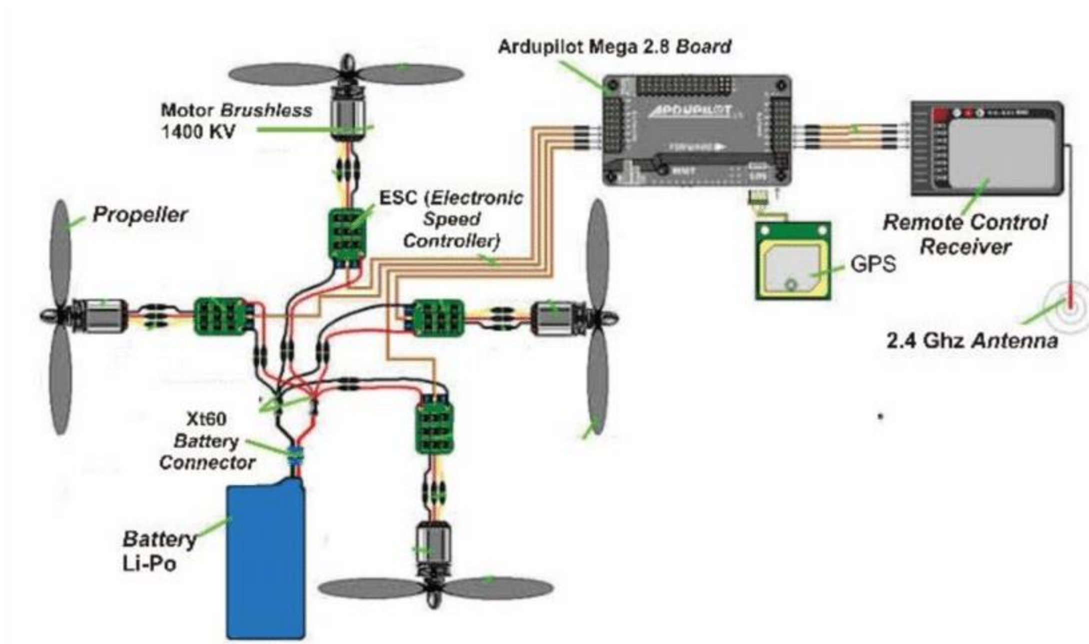


Embedded Systems

- Frequency response

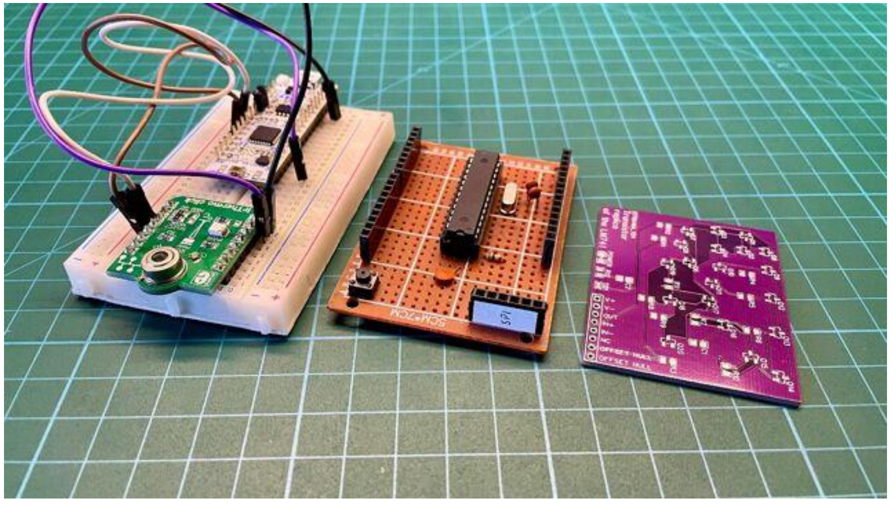
Embedded Systems

- Quadcopter

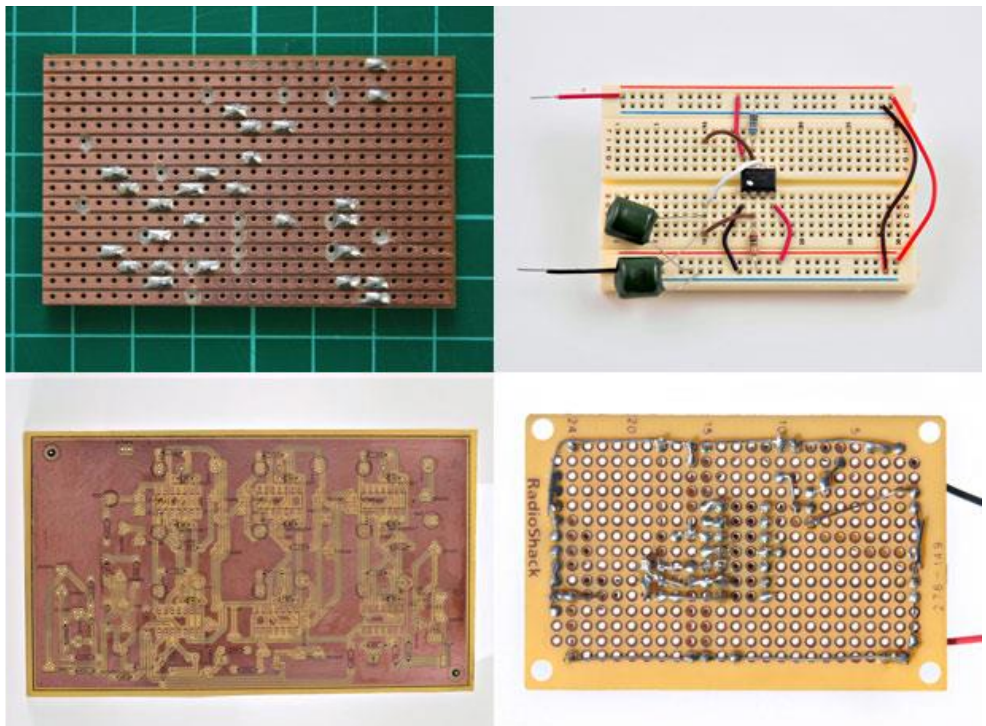


Nugraha, M.I., Utomo, A.T., Taufik, A., Tandioga, R. and Syam, R., 2019, October. Development of Quadcopter for Tracking Object Using Image Processing. In IOP Conference Series: Materials Science and Engineering (Vol. 619, No. 1, p. 012004). IOP Publishing.

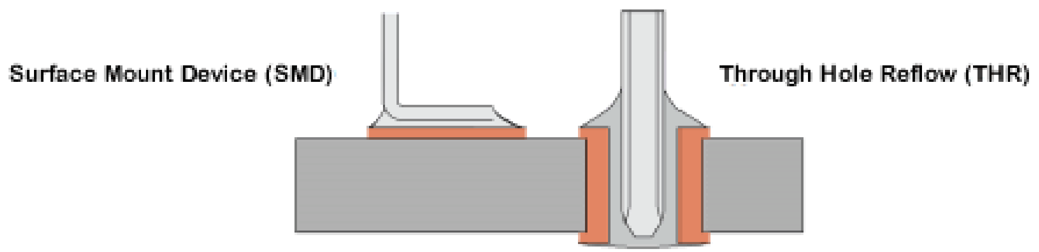
Make your circuit



Make your circuit



Make your circuit



References

- References:
  - Horowitz and Hill: *The Art of Electronics*
  - Lab manual by Hayes and Horowitz (far more practically-oriented)
  - Texas Instruments
  - UCSD: Physics
  - Hunter Freberg
  - Johann Tang – Oriental Motors
  - Nugraha, M.I., Utomo, A.T., Taufik, A., Tandioga, R. and Syam, R., 2019, October. Development of Quadcopter for Tracking Object Using Image Processing. In IOP Conference Series: Materials Science and Engineering (Vol. 619, No. 1, p. 012004). IOP Publishing.