Introduction to Biomedical Engineering

Section 1: Basic electronics

Lecture 1.1: Diodes and Transistors

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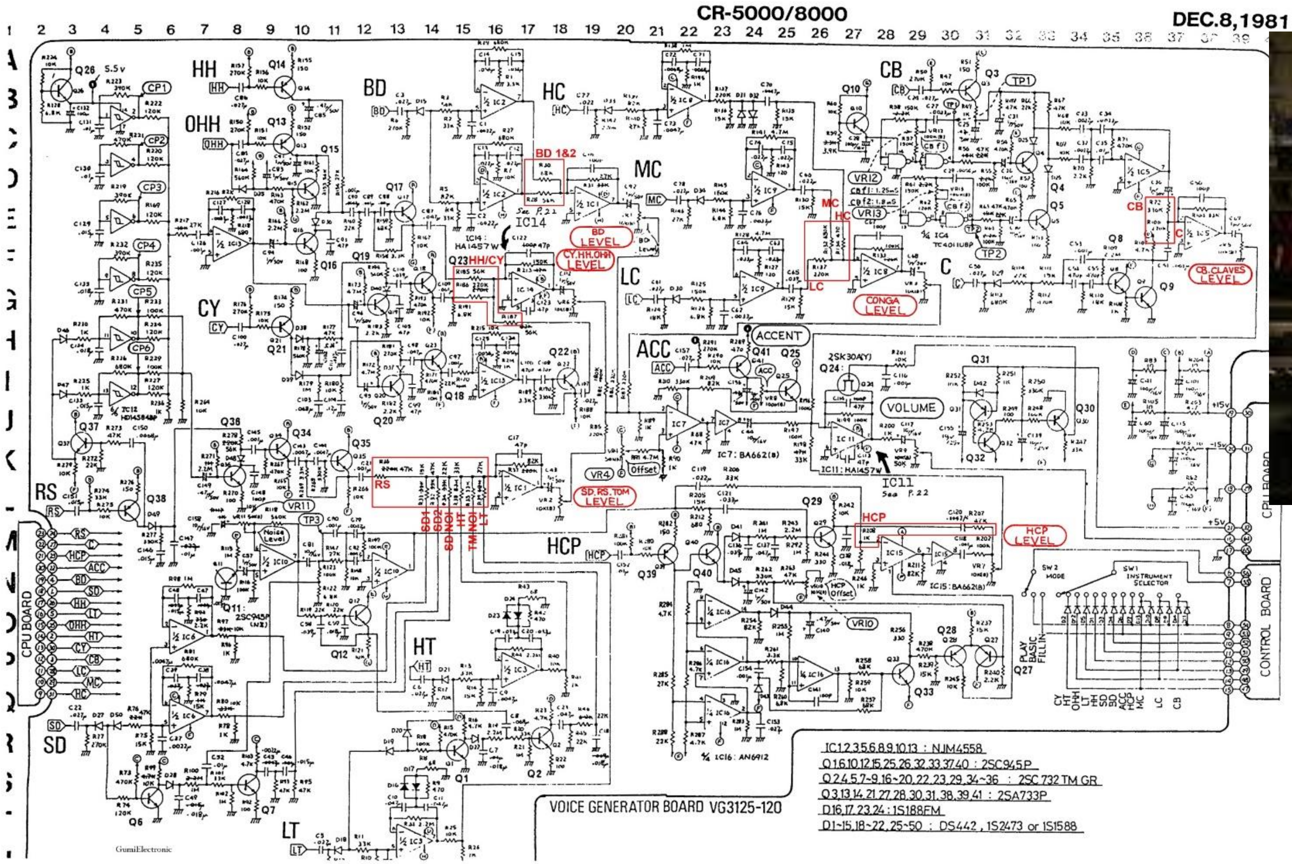
Electronic engineering vs. Common sense engineering

Spot the electronic engineer….

Electronic engineering vs. Common sense engineering



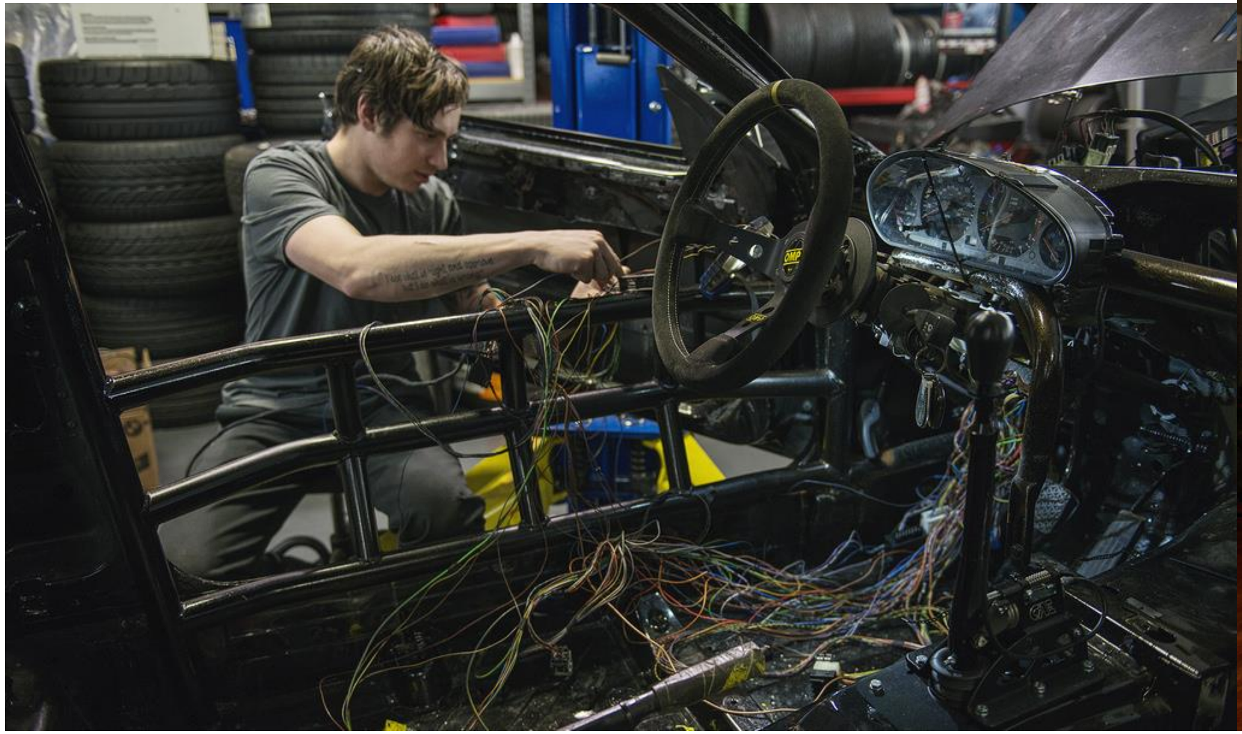
Impenetrable diagrams

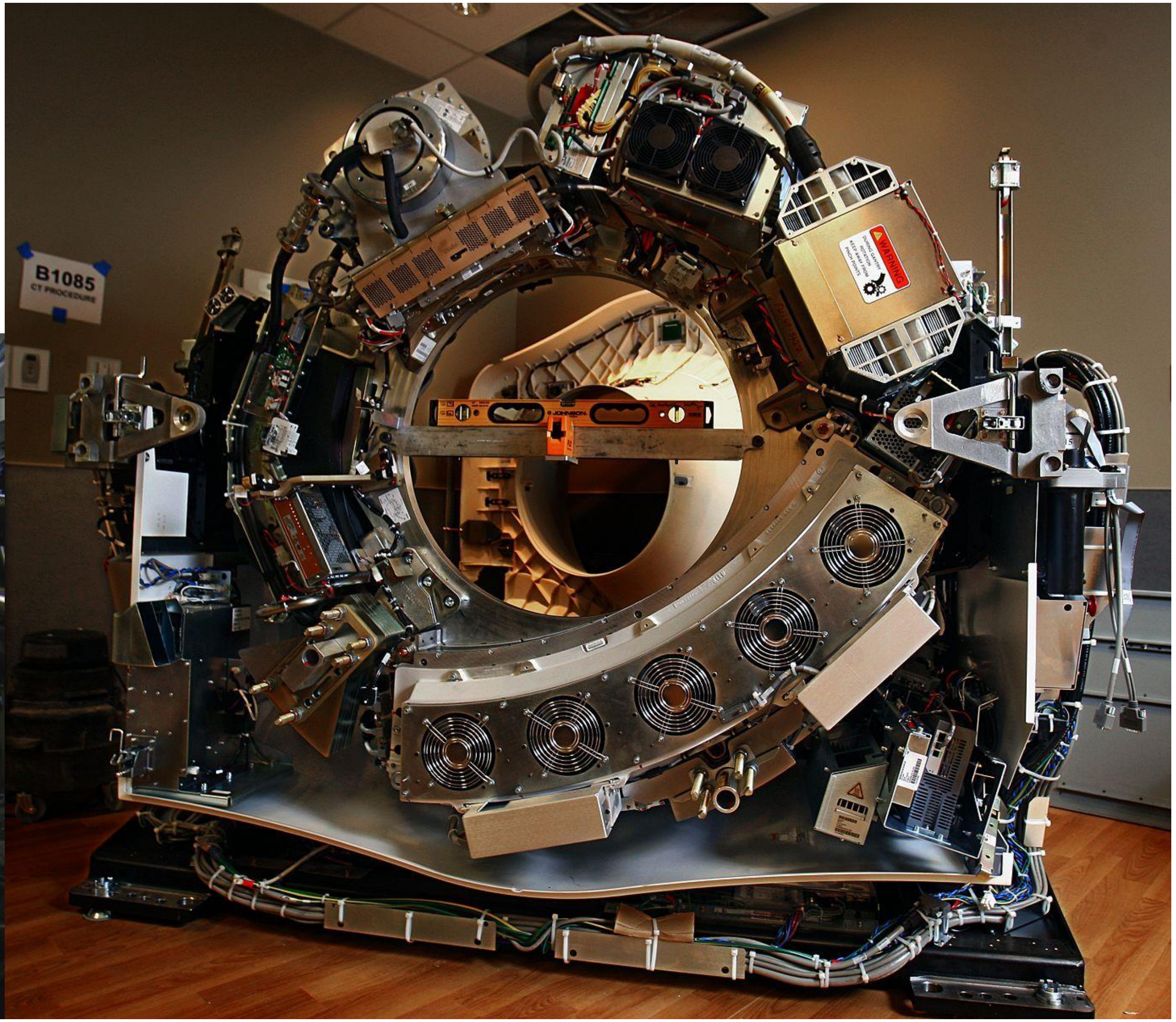
Workshops with
no natural light

JARGON

Is electronics even relevant?

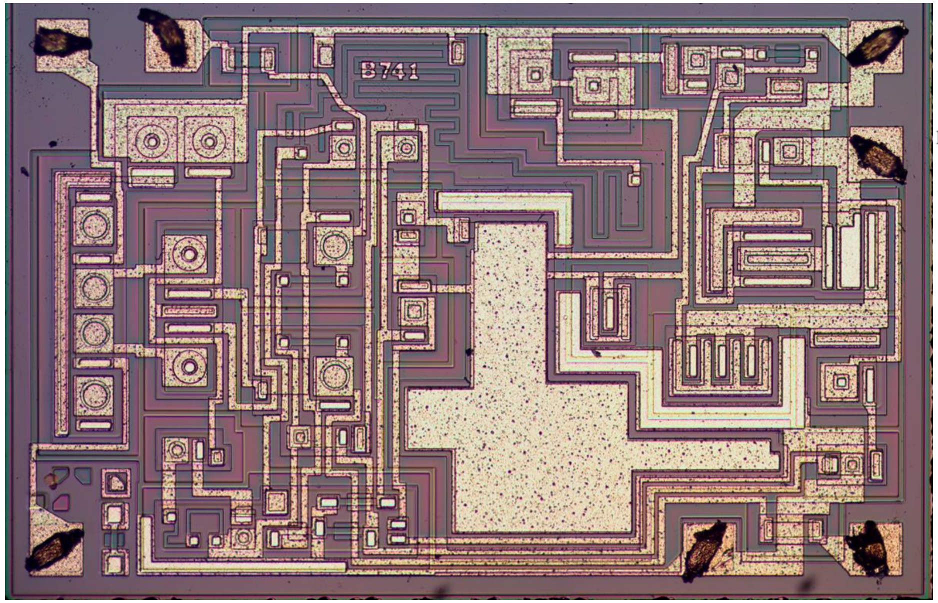
Think about what any contemporary engineering product looks like…

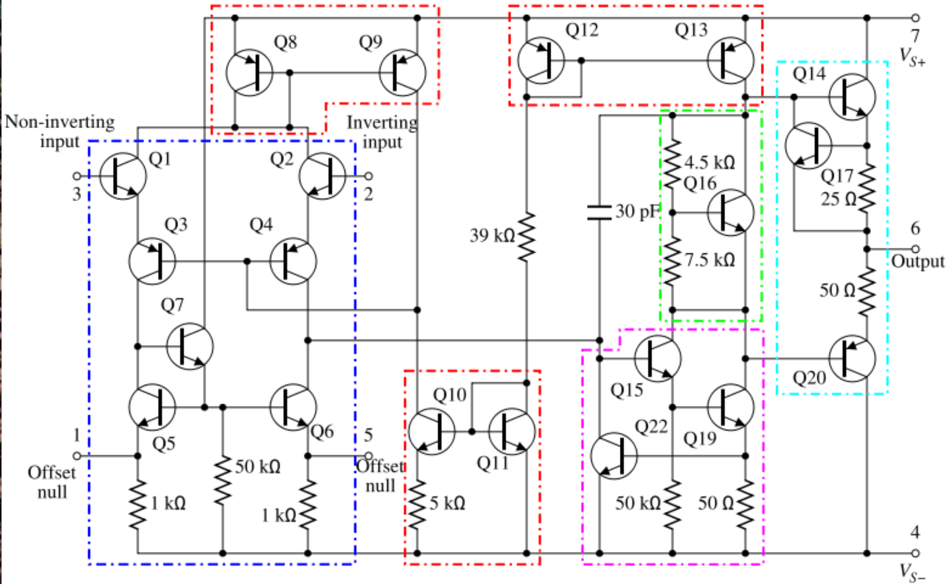


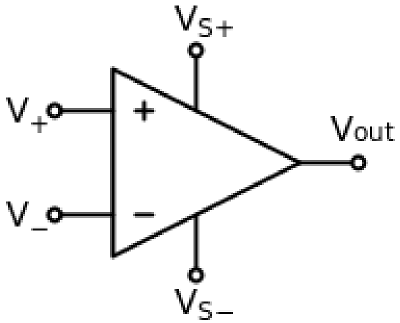


We don’t have to become Electronic Engineers…

We can consider layers of *abstraction*. Each building upon the previous one







$$V_{out} = A_{OL}\,(V_+ - V_-)$$

Silicon Chip

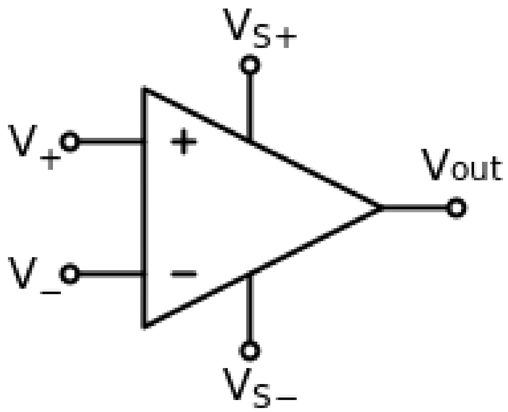
Internal circuitry

Op amp model

Still necessary to appreciate the limitations of these abstractions as we will need them to understand the trade-offs during design.

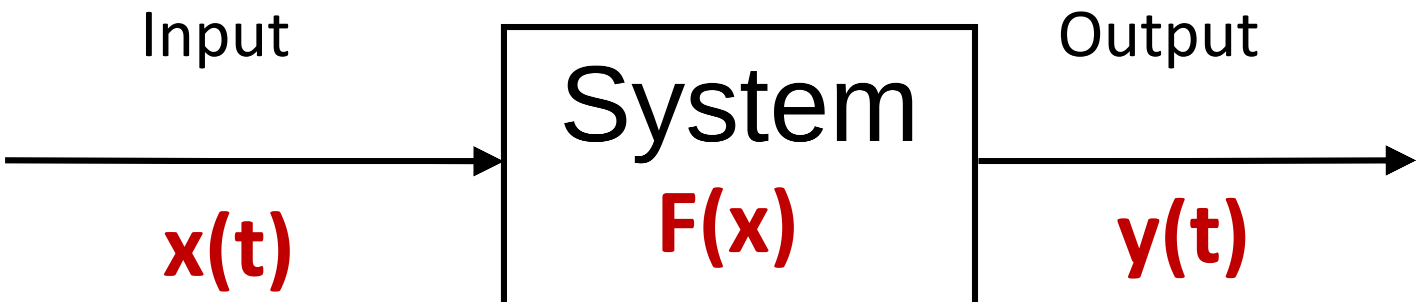
No really. We don't have to become Electronic Engineers…

Formally these abstractions can be written mathematically as *transfer functions*



$$V_{\text{out}} = A_{OL}\,(V_+ - V_-)$$

Op amp model



Mathematical
model e.g. ODEs

We don't typically use the time domain equations, instead we use the *Fourier* or *Laplace* domain. We will look at these in a later lecture

$$G(s) = \frac{V_0(s)}{V_i(s)}$$

Analog(ue) vs. Digital Signals

vs

Analogue

Continuous signal

f(t) exists for *any* t, and value of f(t) could be *any* number

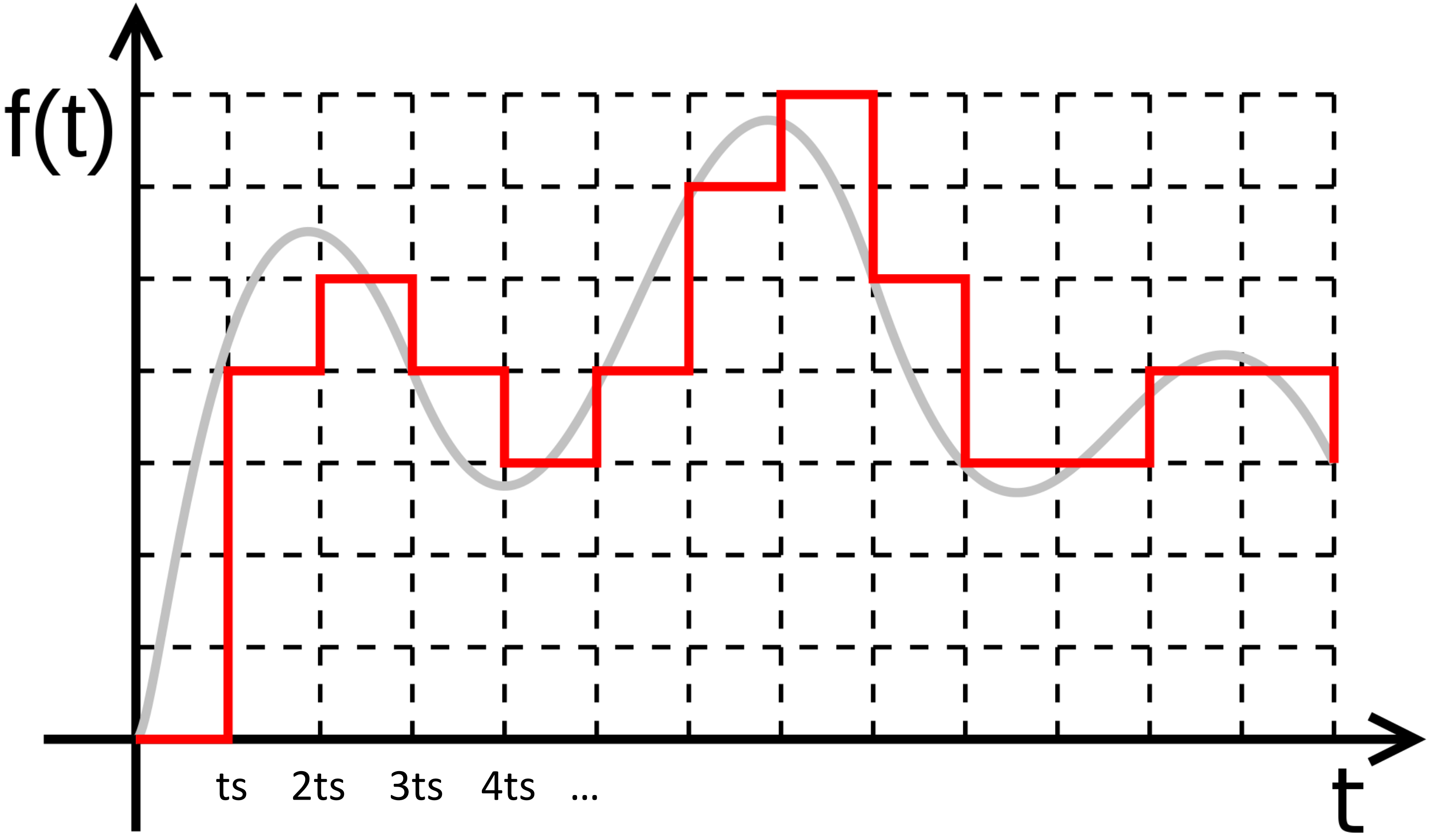
Digital

Discrete signal

f(t) exists only for discrete integer values of ts – the sampling period. Value of f(t) only discrete integers

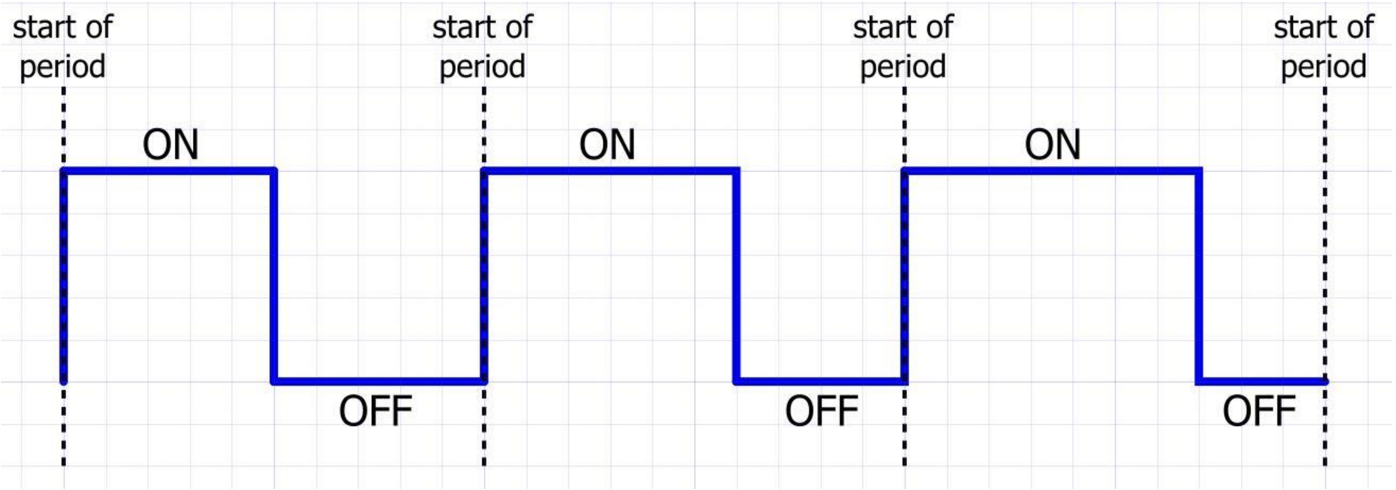
“real world” vs

“things computers like”

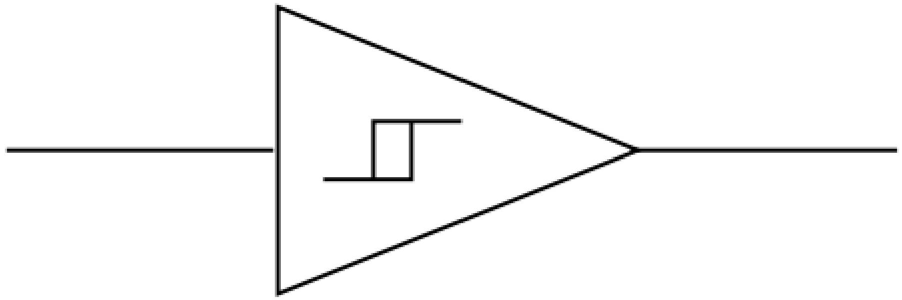


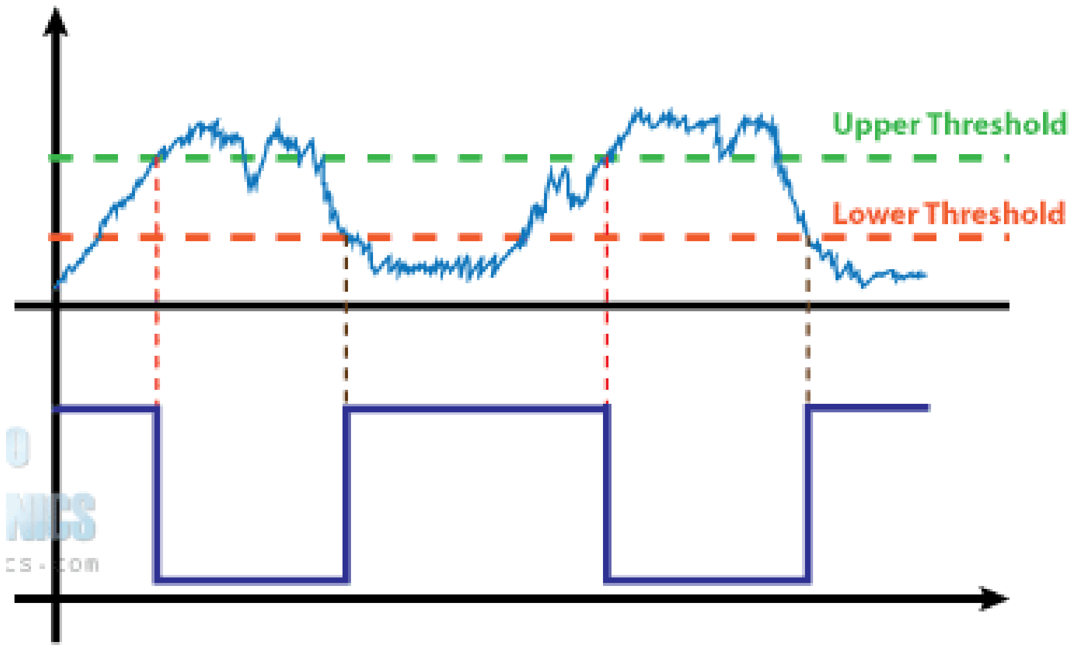
Digital electronics - pulses

The most common digital signals have only two levels - On/Off, or 0/1 or 0V/5V etc.



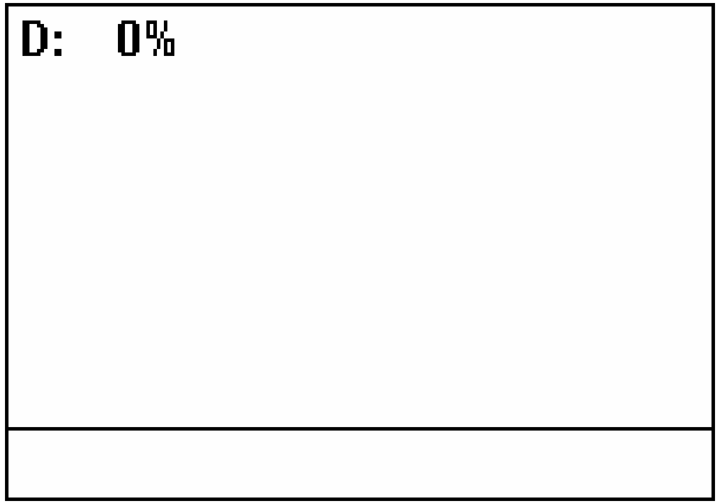
With the correct circuitry, often included in ICs, the signals are *very* robust to noise *i.e.* 0s stays 0s and 1s stay 1s





The most common circuit is called a Schmitt Trigger, they are on every Arduino digital pin

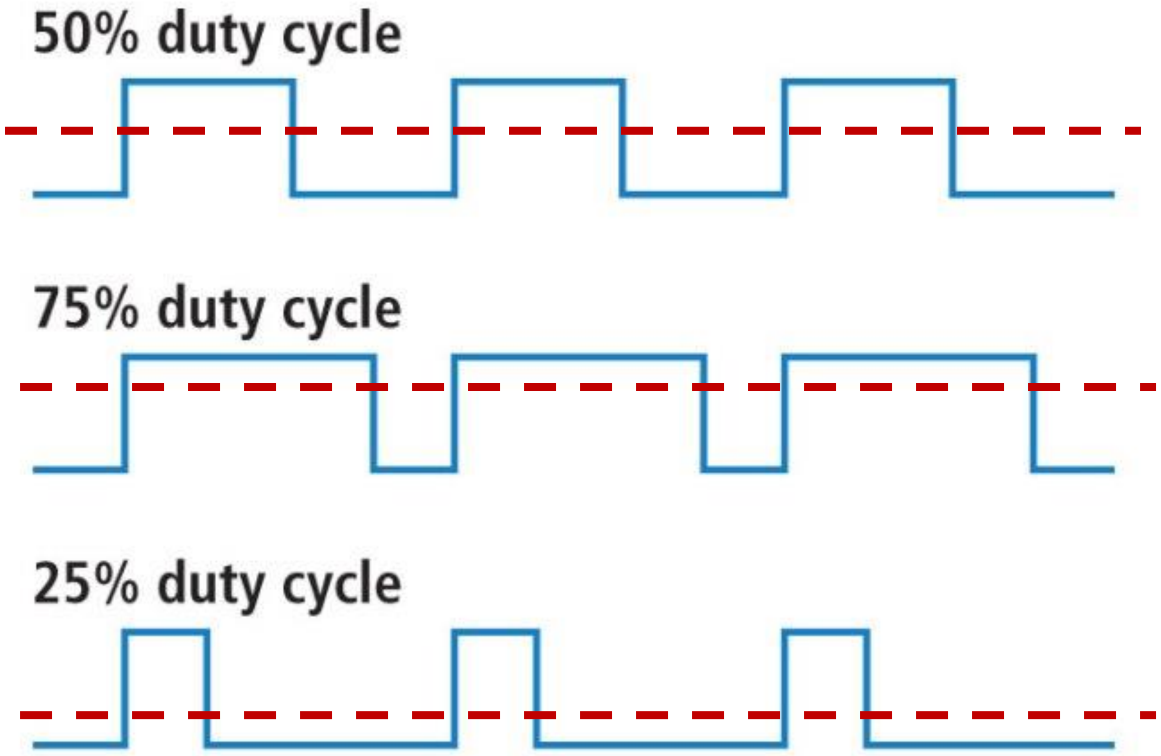
Digital electronics – Duty Cycle



Rather than a simple square wave, the ratio of on to off can also be varied – the *duty cycle.*

$$D = \frac{PW}{T} \times 100\%$$

T is period
PW is pulse width



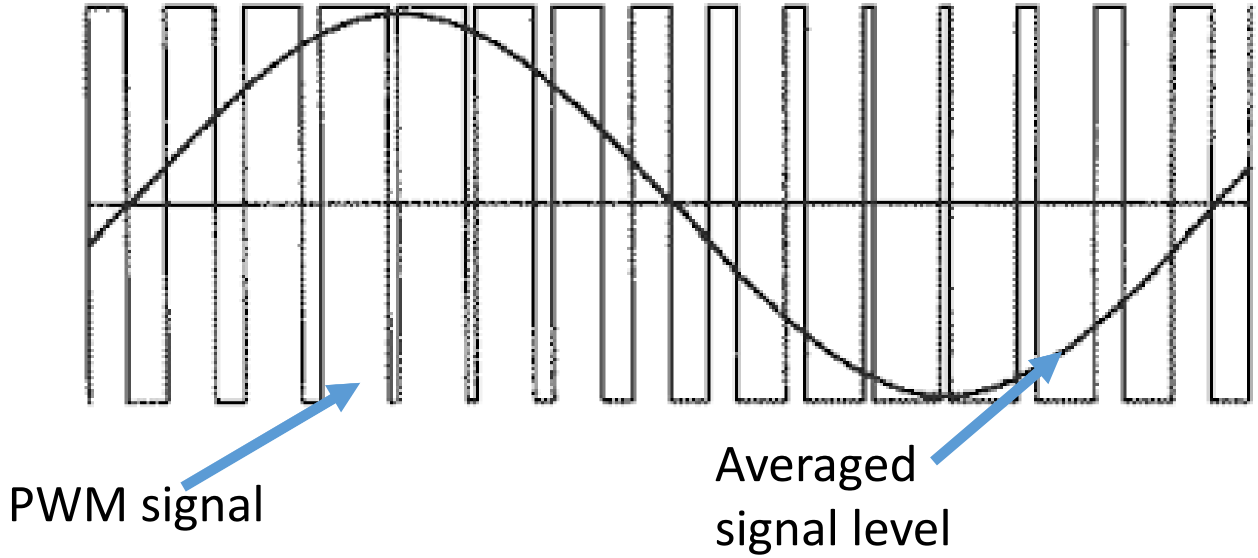
What is important is the *averaged signal.*
We use a pulse frequency that is either:

- Much faster than the system can react – like a motor or a heating element
- Much faster than is noticeable – like PWM on LEDs

Digital electronics – Pulse Width Modulation

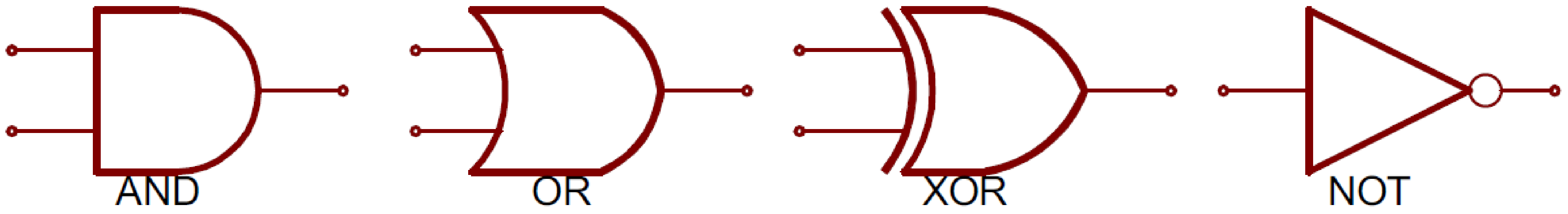
Controlling the duty cycle is known as *pulse width modulation (PWM).* Very useful for controlling things beyond “on” and “off” when using digital electronics

Arduino has special PWM~ pins which can vary the duty cycle much faster. This way you transmit more complicated signals

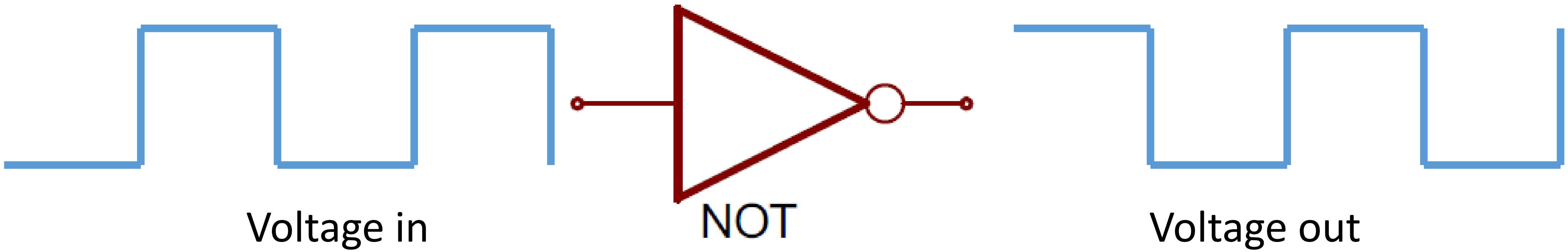


Digital electronics – Logic gates

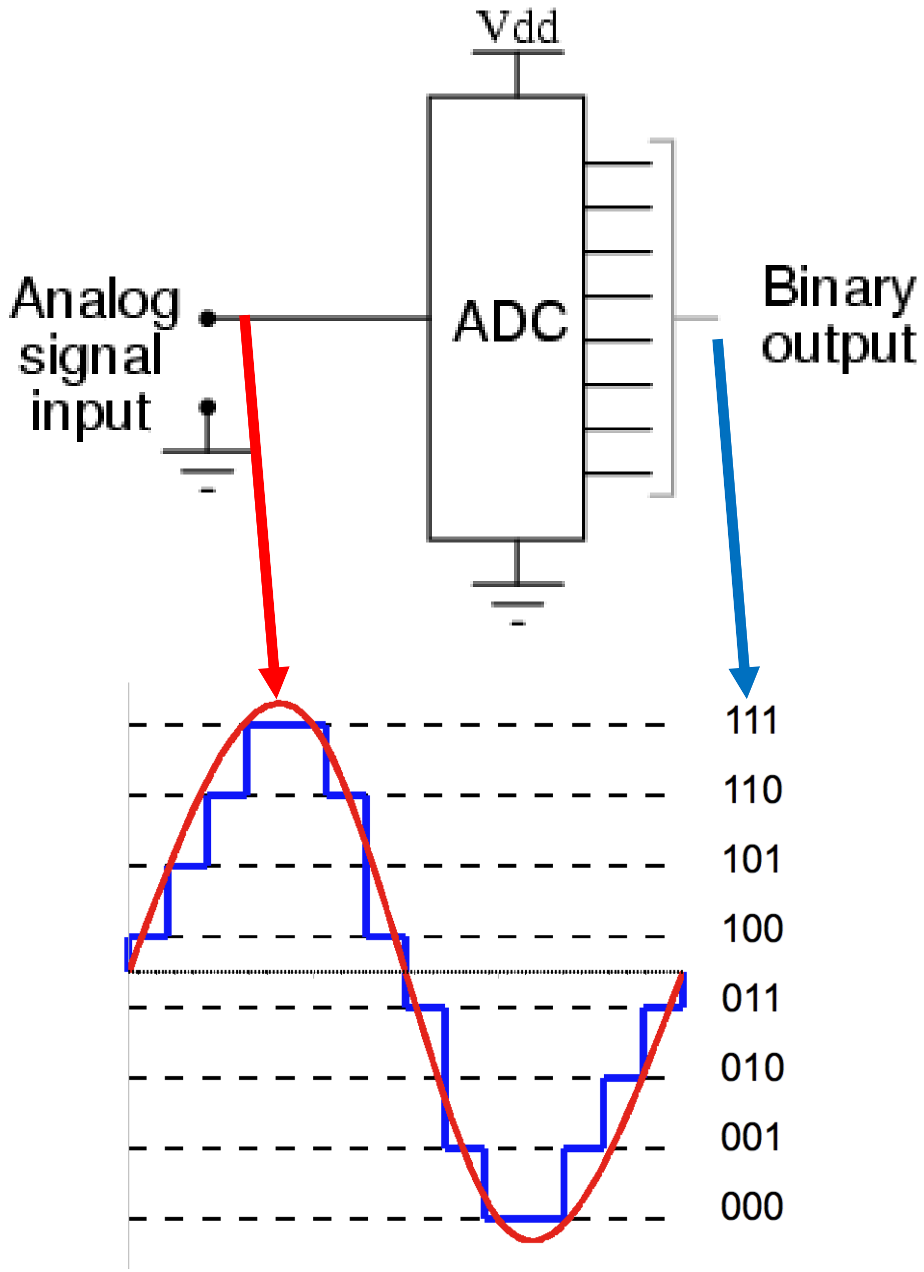
Digital logic underpins modern electronics and computing, enabling calculations in binary

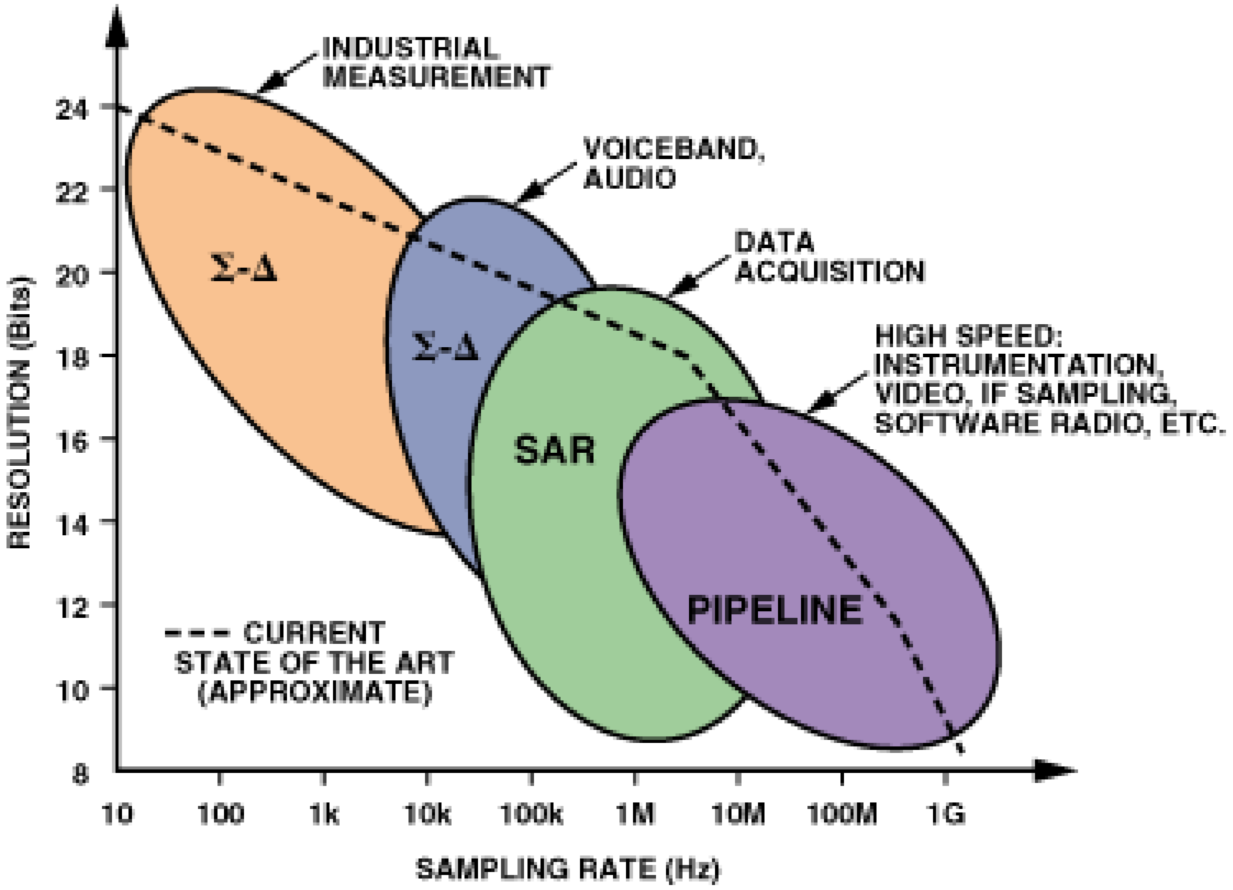


The simplest of these elements is the NOT gate or inverter, which flips the sign of the input signal



Real world to computers - Analogue to Digital converter

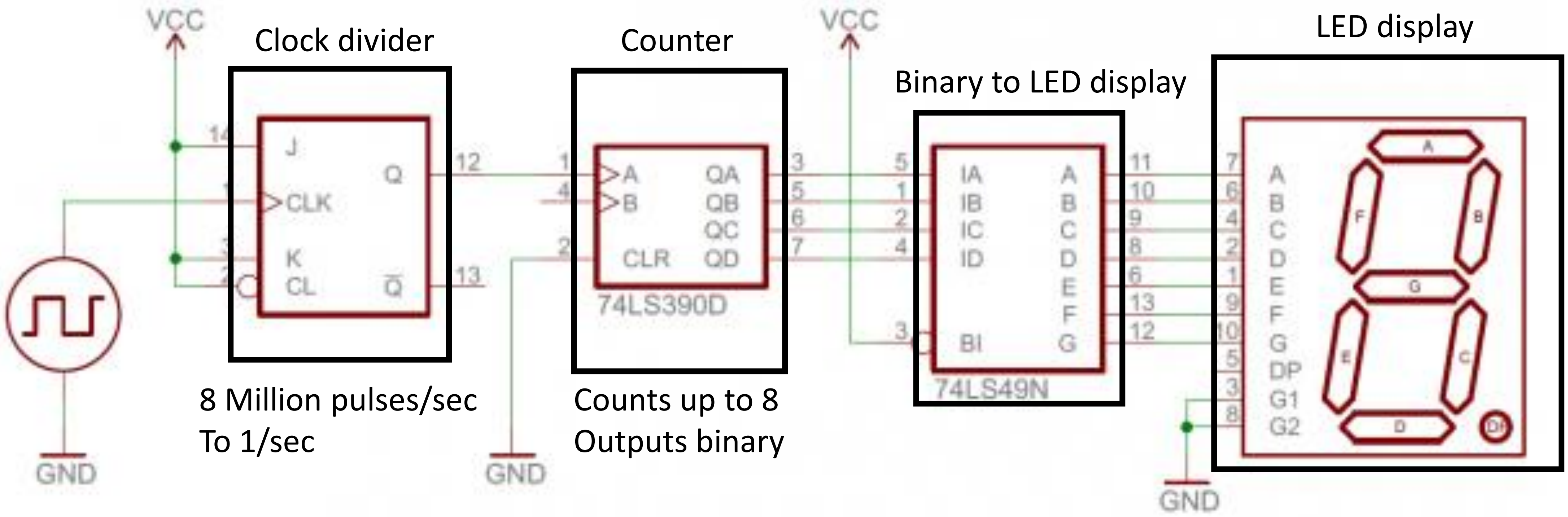


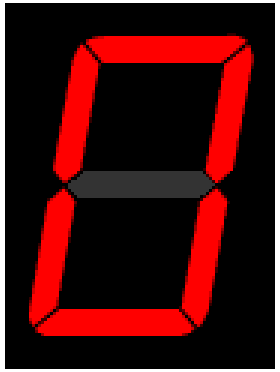


There are different types of ADC:
Most important thing is the trade off with speed and resolution (and power)

Analogue vs. Digital electronics

Operate using discrete signals, with binary signalling along the wires i.e. “just” on/off pulses



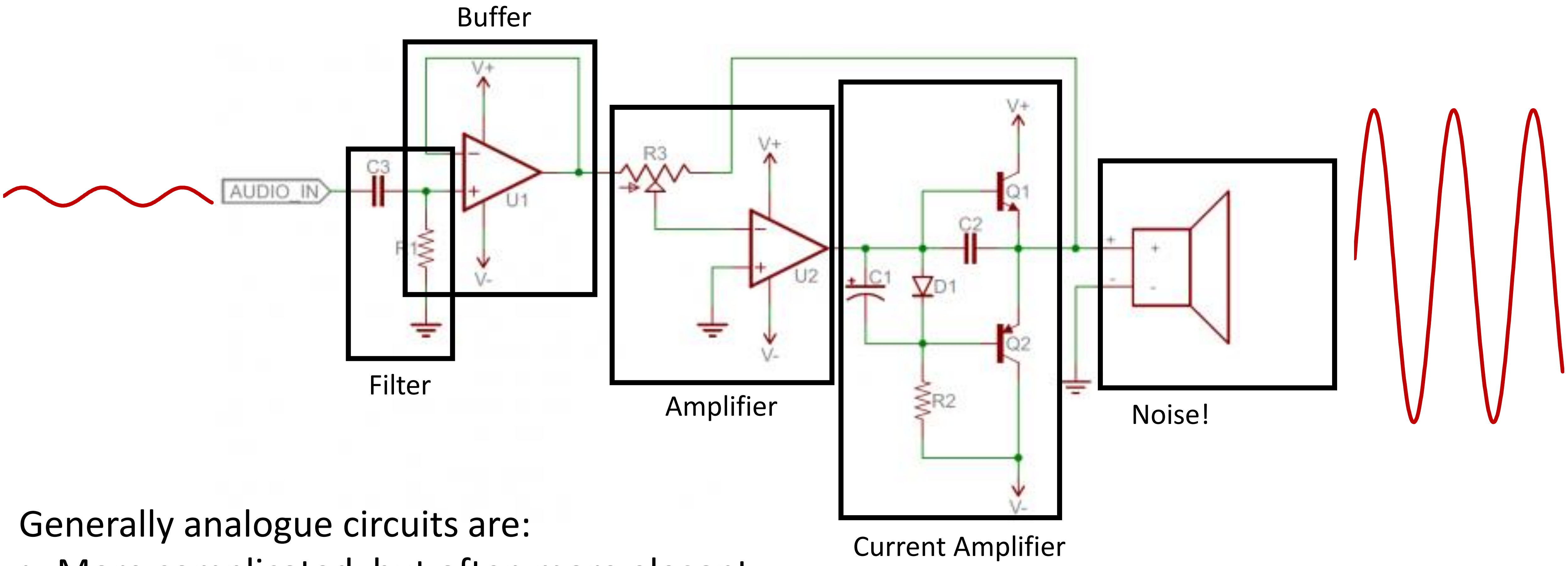


Generally digital circuits are:

- Easier to design (!)
- More expensive and require more power to do the same job (if job can be done in analogue)

Analogue electronics

Majority of components we have seen are *inherently* analogue.
So if you don’t see any blocks representing IC’s its probably an analogue circuit



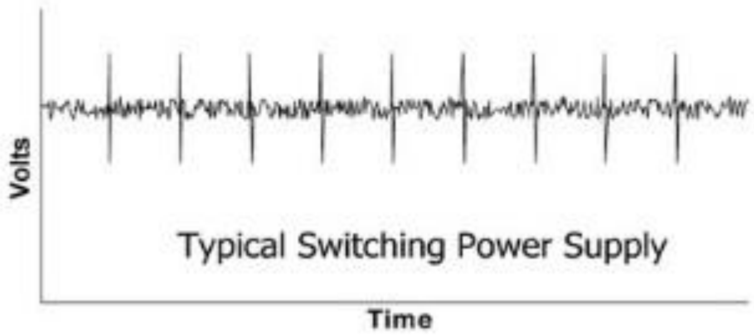
Generally analogue circuits are:

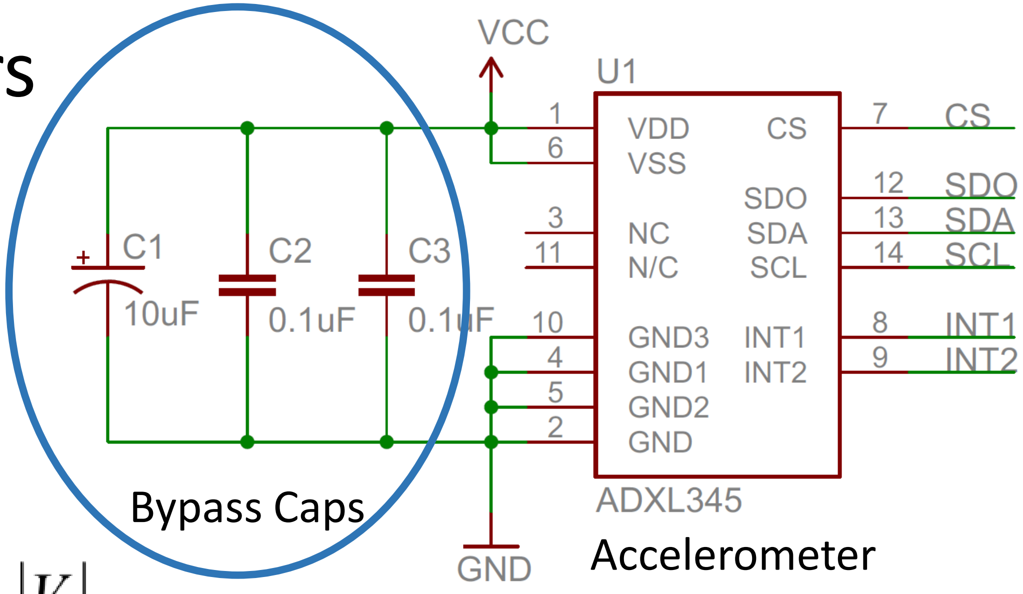
- More complicated, but often more elegant
- More susceptible to noise

Simplifying schematics – Bypass capacitors

Capacitors between supply (Vdd/Vss/Vcc) and ground pins

Very common in digital circuits, reduce noise in power supply to other components, particularly sensor ICs and amplifiers.

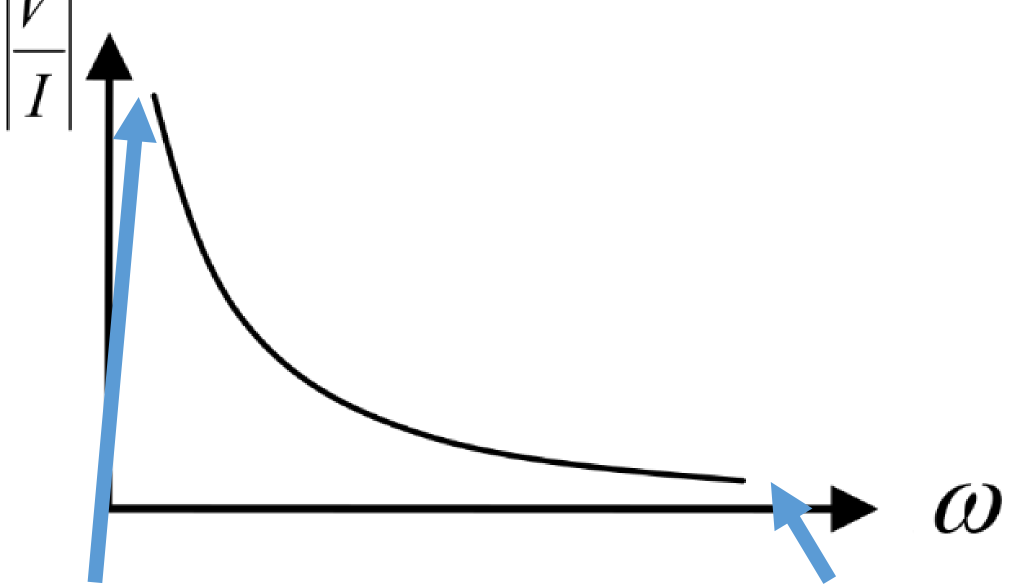




Want the DC (0 Hz) component, not any of the high frequency stuff

Consider the impedance of an ideal capacitor:

$$Z_C = \frac{1}{j\omega C}$$



Low freq $\omega \approx 0$

So $Z_c \approx \infty$

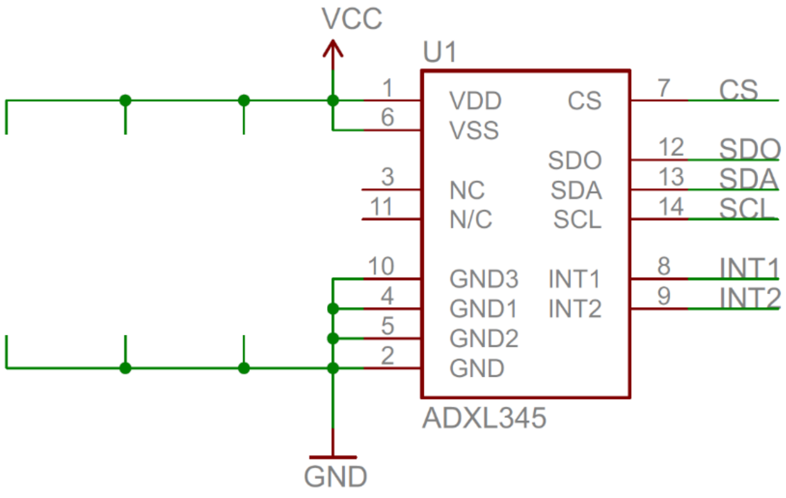
High freq $\omega \approx \infty$

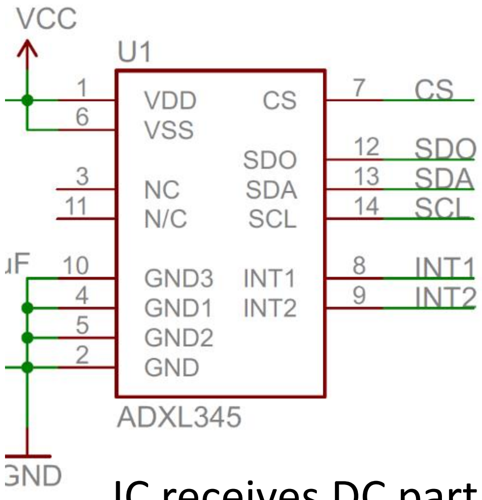
So $Z_c \approx 0$

Simplifying schematics – Bypass capacitors

"active" components

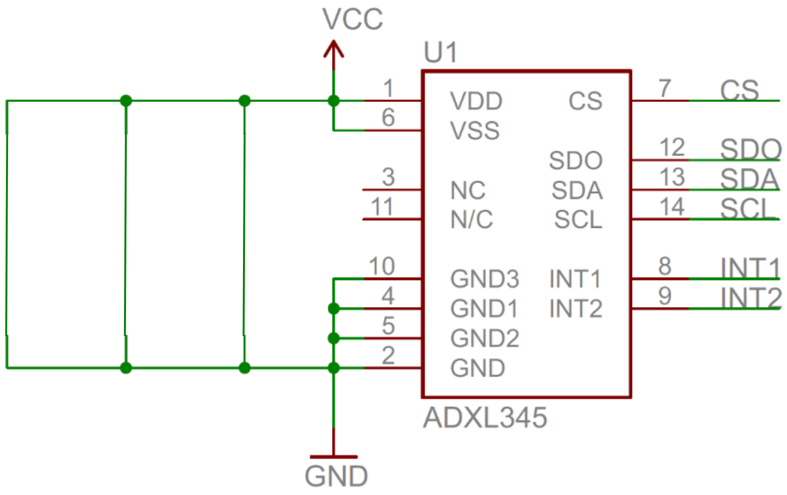
At low freq, $Z_c \approx \infty$
- caps are open circuits
- *No* current through them, can be neglected

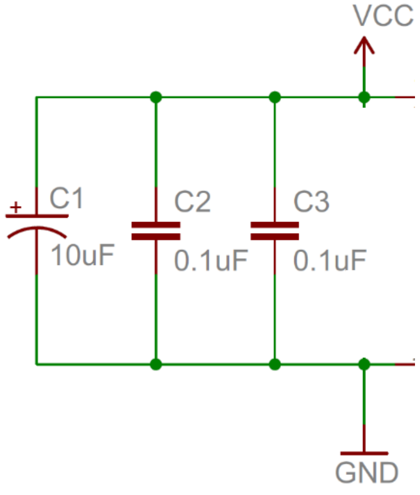




IC receives DC part

At high freq, $Z_c \approx 0$
- caps are closed circuits
- *All* current through them, all else can be neglected

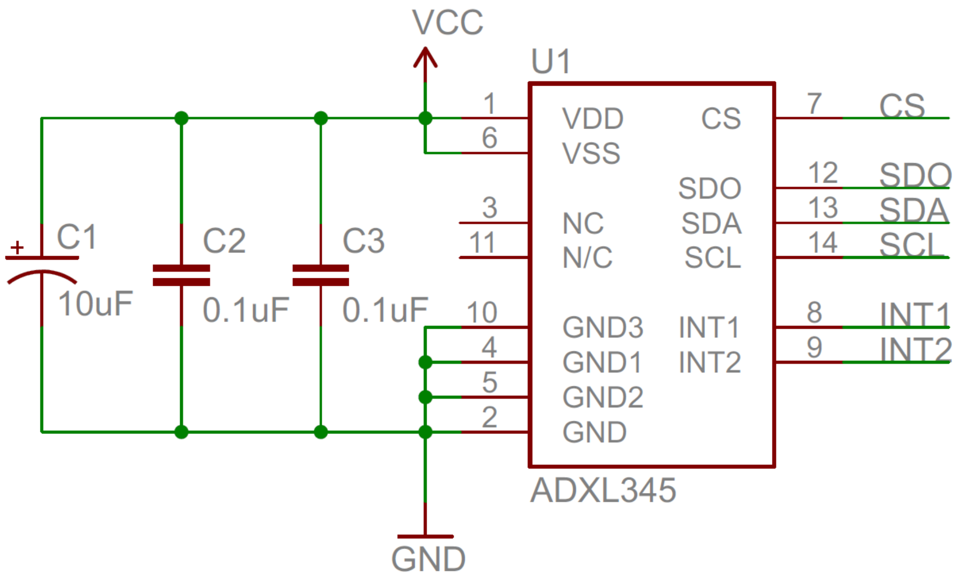




Noise goes through caps only

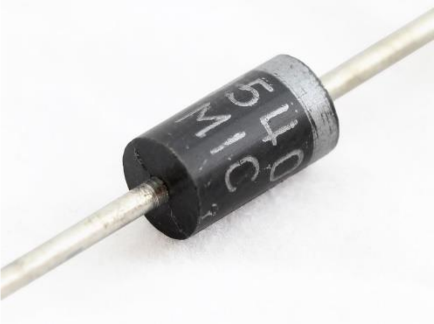
Simplifying schematics – Bypass capacitors

Now we know the job these capacitors are doing, we can just ignore them when looking at schematics



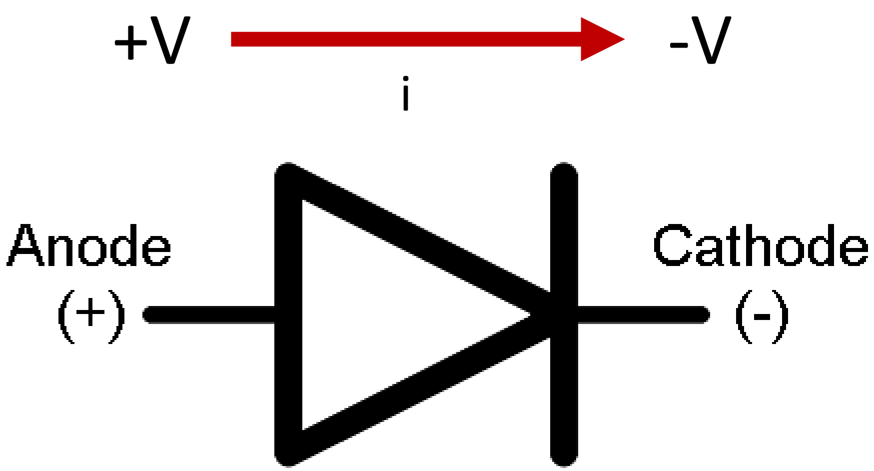
On circuits with mostly digital components, this may mean reducing the number of important parts by half. Yay!

Diodes – controlling current direction

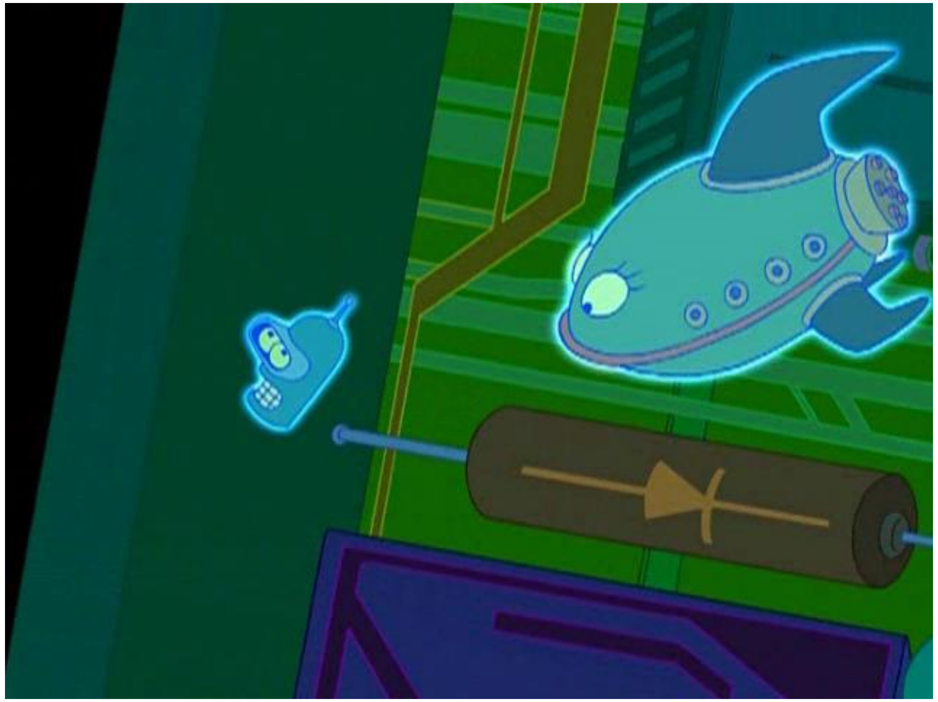


Diodes are semiconductor (i.e. made of silicon) components which only allow current to flow in a single direction, known as the *forward* direction.

If voltage across diode is positive
Current can flow, diode is "*forward biased*"



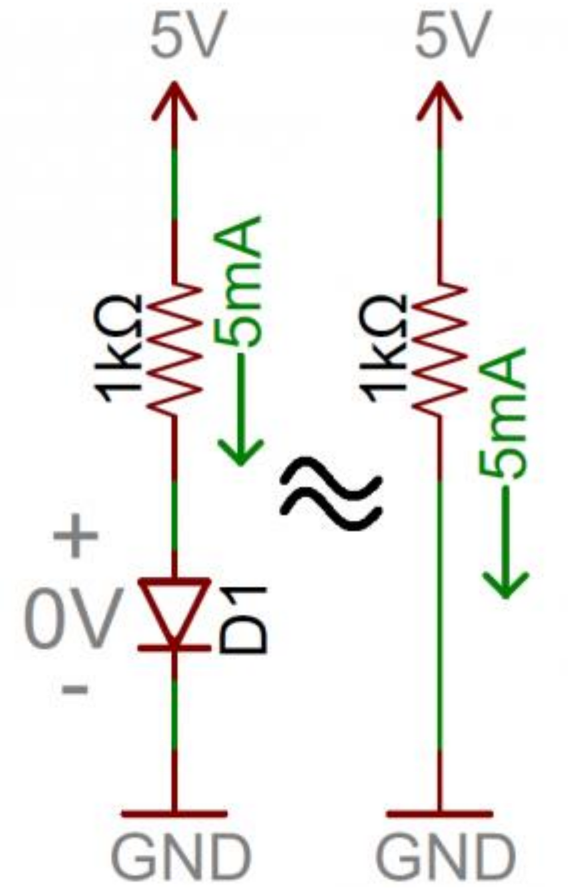
If voltage across diode is negative
Current cannot flow, diode is "*reverse biased*"



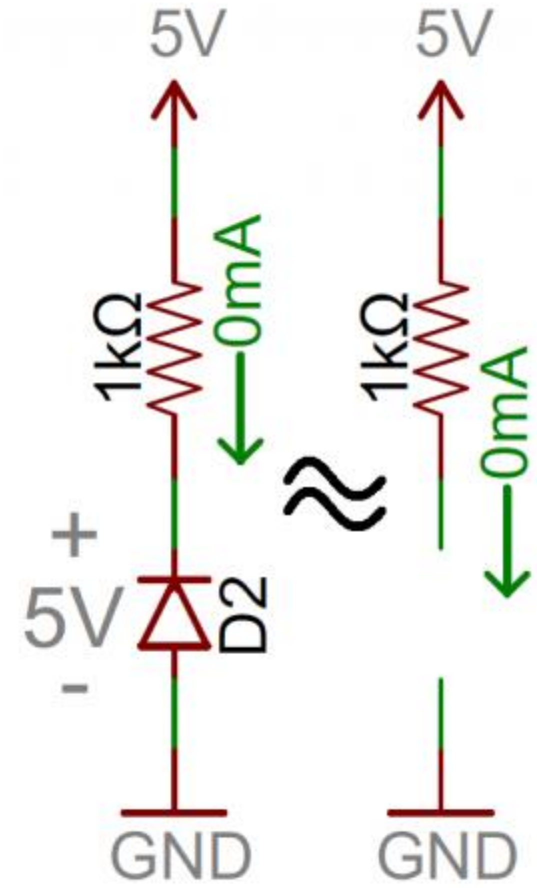
If you get the "joke" then you have understood this slide

Diodes – simplifying circuits

Ideally zero resistance in one direction, and ideally infinite resistance in the other.
So we can simplify when analysing the circuits



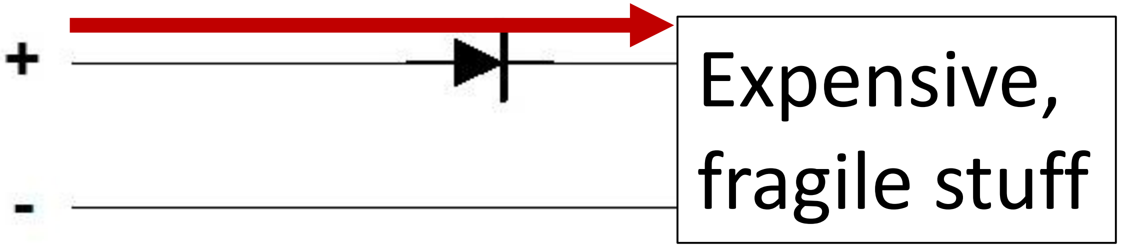
Forward biased (positive voltage)

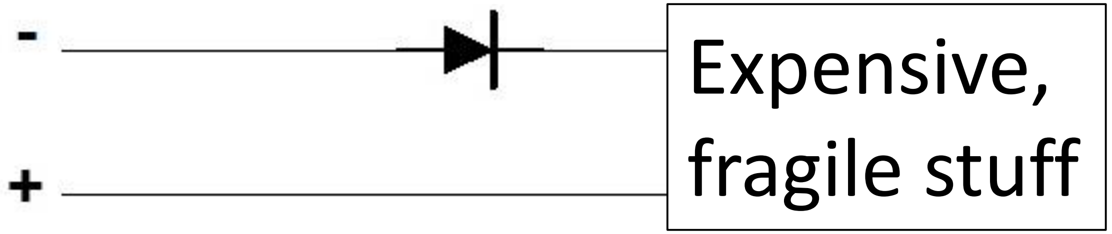


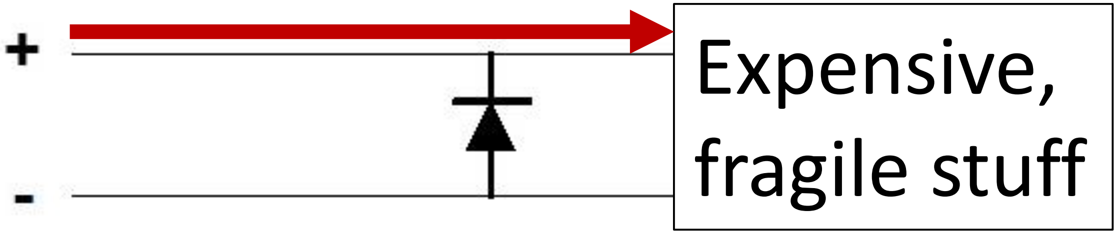
Reverse biased (negative voltage)

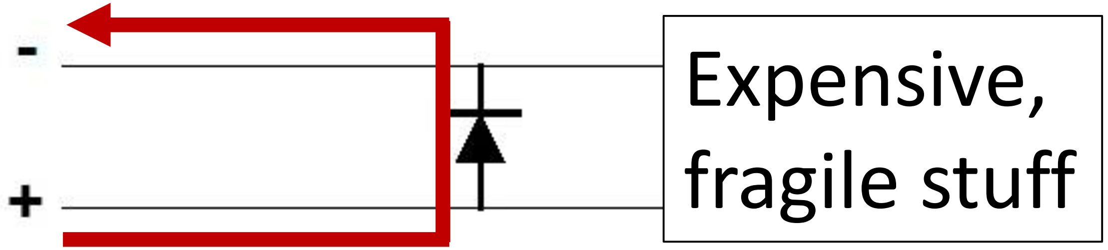
Diodes – circuit protection

One simple use for diodes is circuit protection. Preventing damage when power supplies are connected incorrectly, or break for some reason







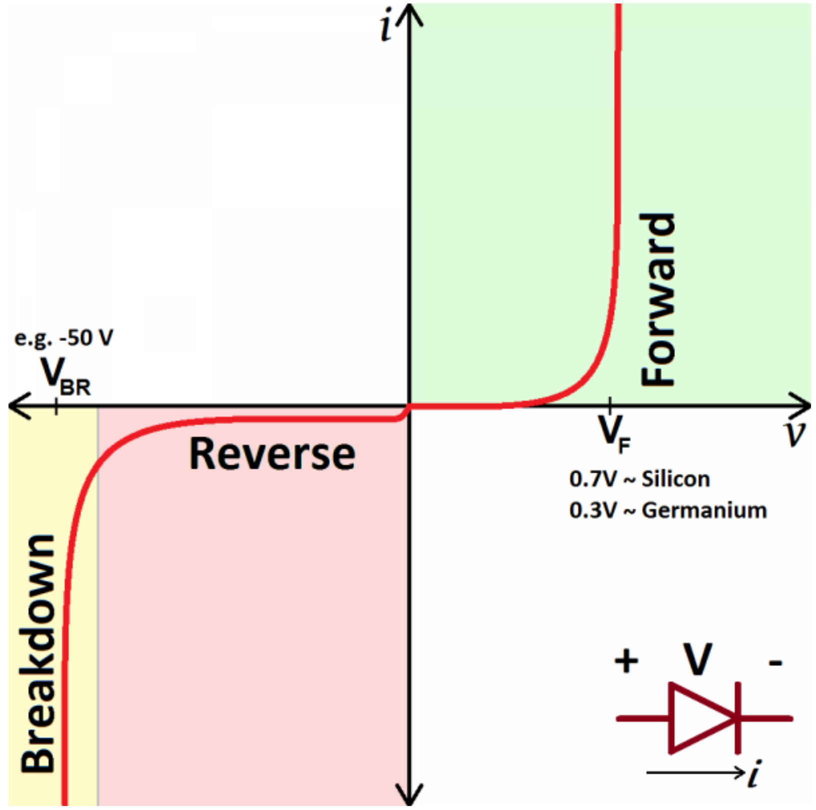


When connected correctly, an ideal diode will have no effect on circuit

When polarity is swapped, series diode stops all current flow, parallel diode short circuits current to ground instead

Diodes in reality

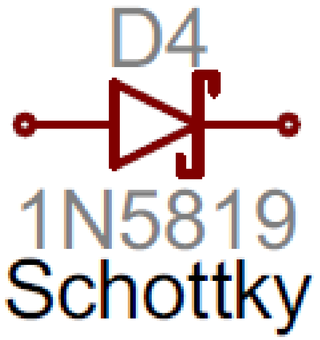
Real diodes require a certain voltage to be reached before they will conduct current – “Forward voltage”.

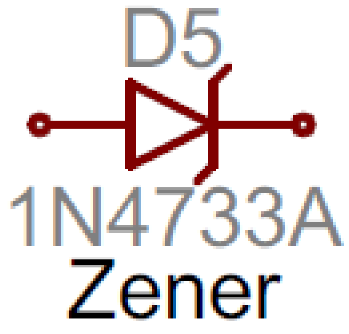


Also a negative voltage at which they will conduct current in the negative direction – “Breakdown voltage”.

Limited amount of current!

Funny looking symbols



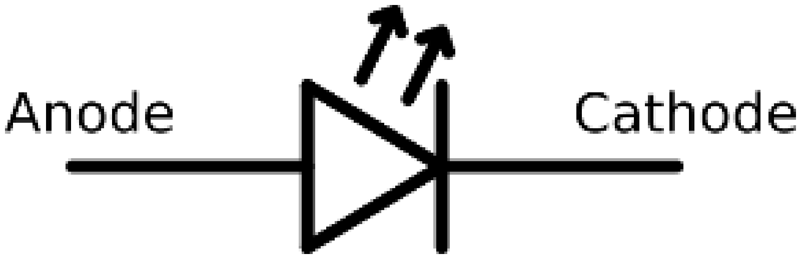


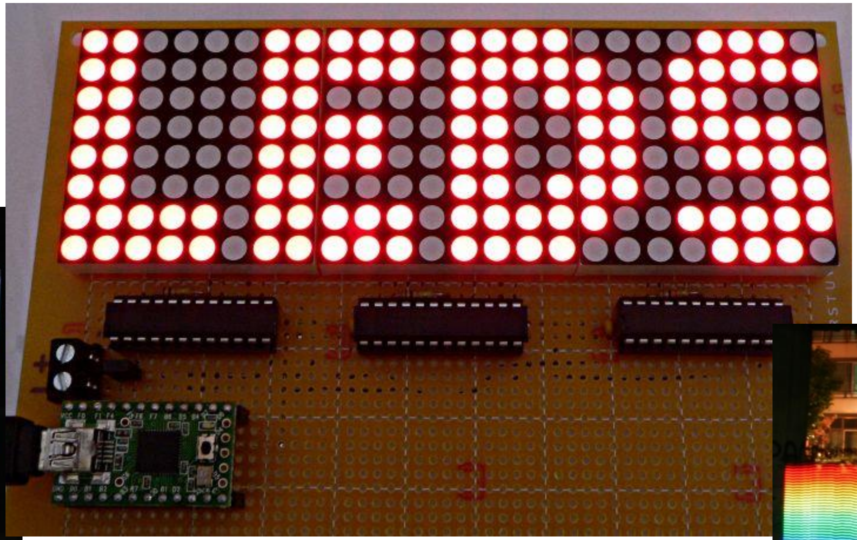
These diodes exploit these properties, but have specific uses.

Enough to know “That’s a diode, I’ll google what it does when I see it”

Light emitting diodes - LEDs

Ubiquitous type of diode which emit light when forward biased, via electroluminescence



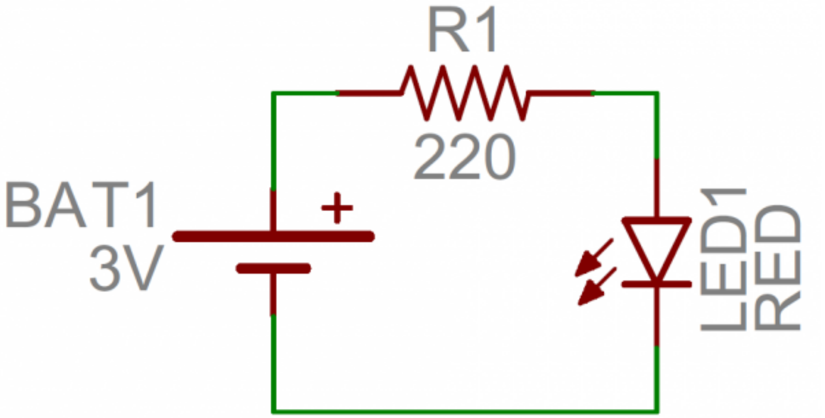


Everyone’s first Arduino project. An obsession of engineers. The more the better!

LEDs – current limiting resistor

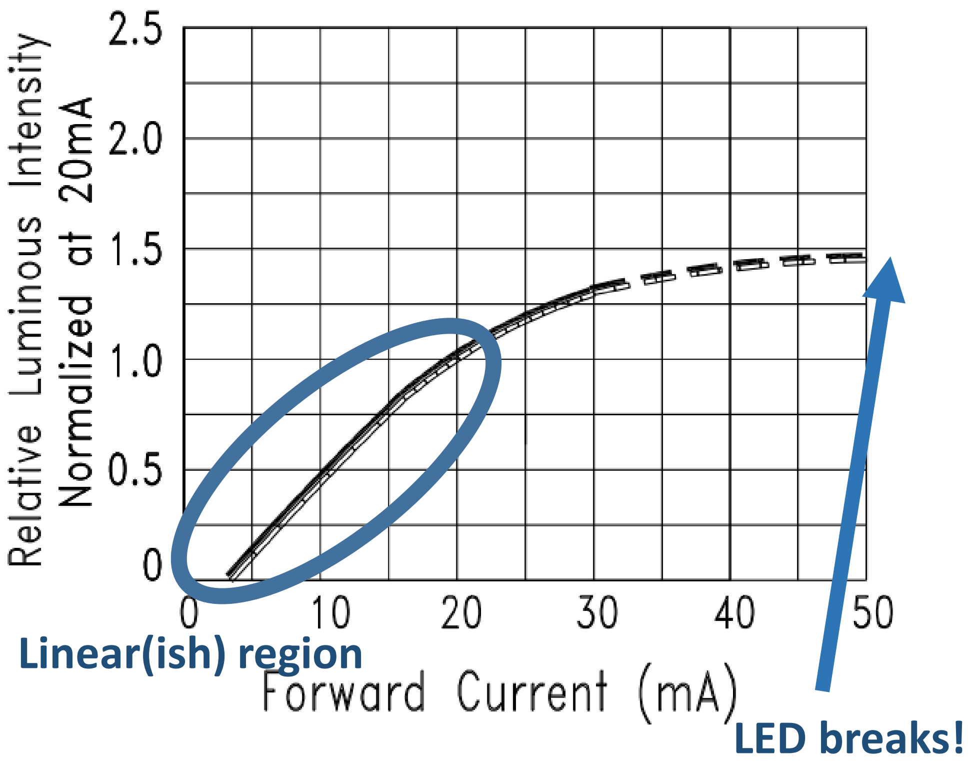
Luminosity is proportional to the *current* flow.
Significantly lower max current than other diodes, normally ~ 20mA vs ~>1 A

For simple on/off indicator applications:
A current limiting resistor is enough



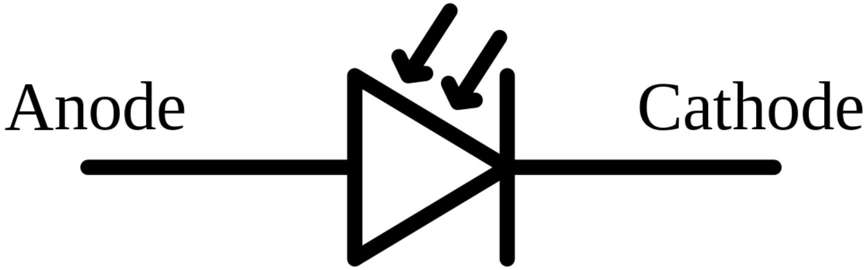
But

- Luminosity changes as power fluctuates
- Not all LEDs have exact forward voltage, so actual current changes
- Difficult to control brightness (pwm) in linear fashion



Better to control current directly.
Block 2 Current Driver in Lab

Photodiode



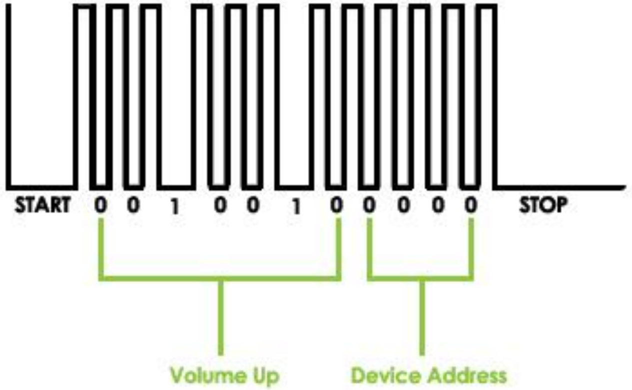
Special type of diode that convert light into current, via the *photoelectric effect*

High current, but reacts slowly. Great for solar cells

OR

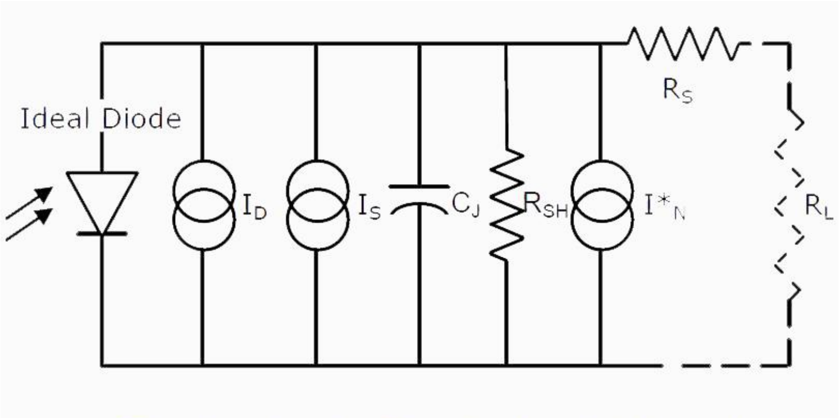
Low current, very fast switching, suited to sensors

These are used in receivers for remote controls

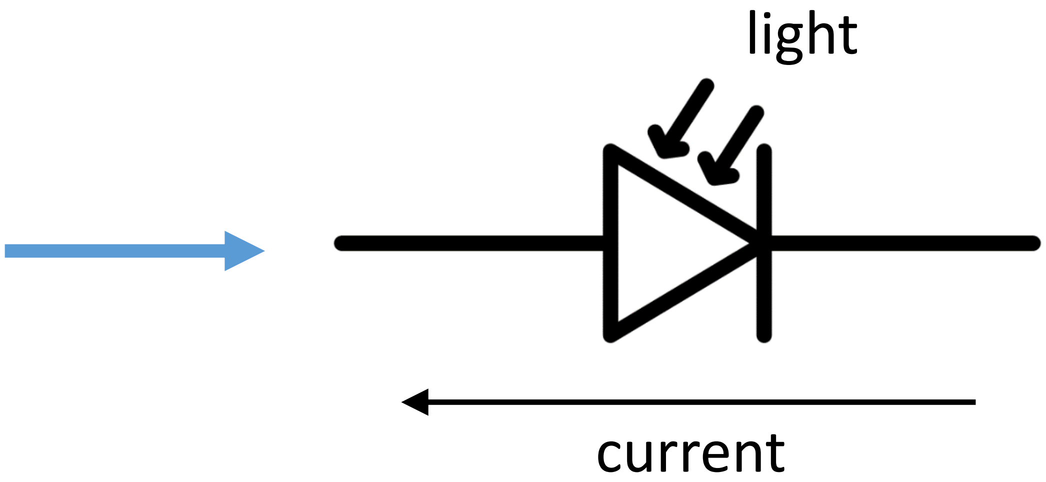


Photodiode

Current produced is (essentially) **linearly** dependent upon the incident light
Meaning we can simply greatly!

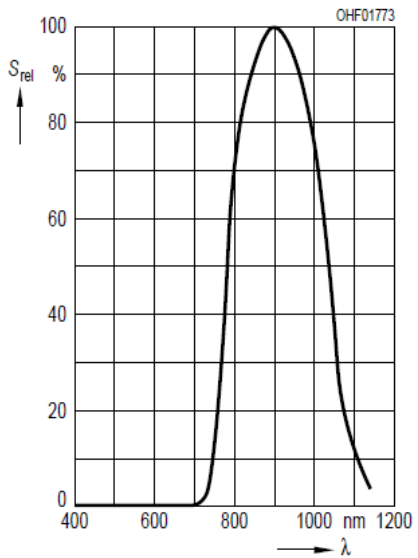


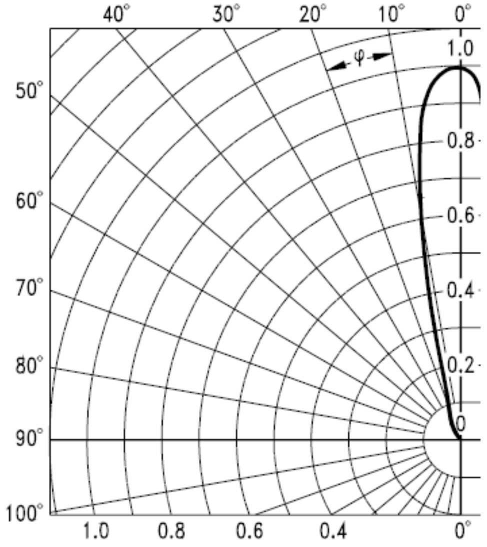
Photodiode Equivalent Circuit



The sensitivity is both wavelength dependent and directional

Same is true for LEDs

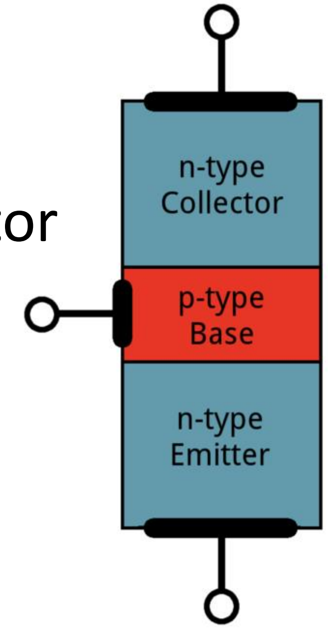


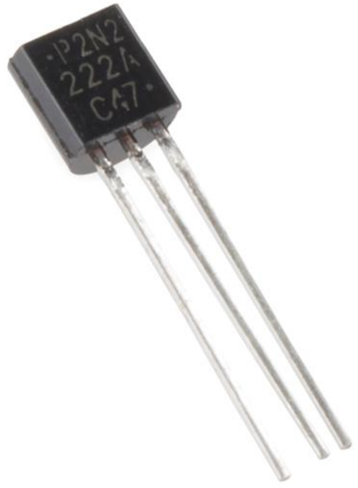


Transistors

A semiconductor device which can act as either an insulator or conductor, depending upon the control signal applied

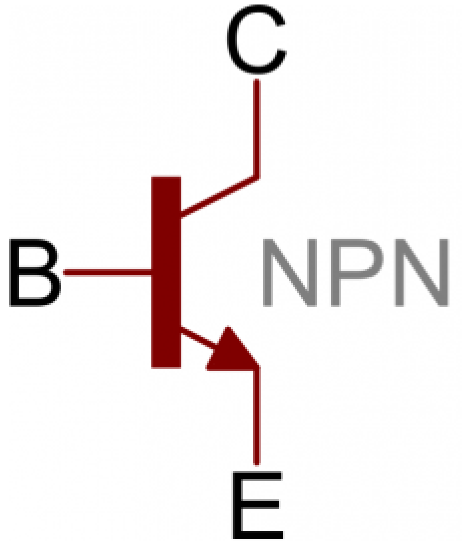
Without understanding the semiconductor physics, a transistor can be considered as functioning as a control valve for the current passing through it.
Or as a *variable, adjustable resistor.*



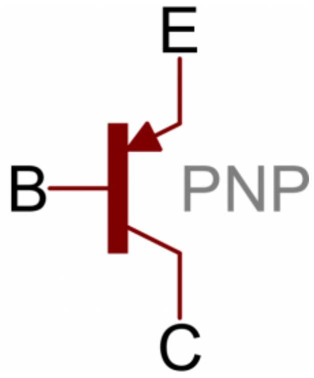


bi-polar junction transistor (BJT)
the simplest transistor

By changing the current here



We control much greater current through here



PNP is fipped -
More base current means *less* output current

Two main applications: **"switching"** (digital electronics) or **"amplification"** (analogue electronics)

Transistors – switching applications

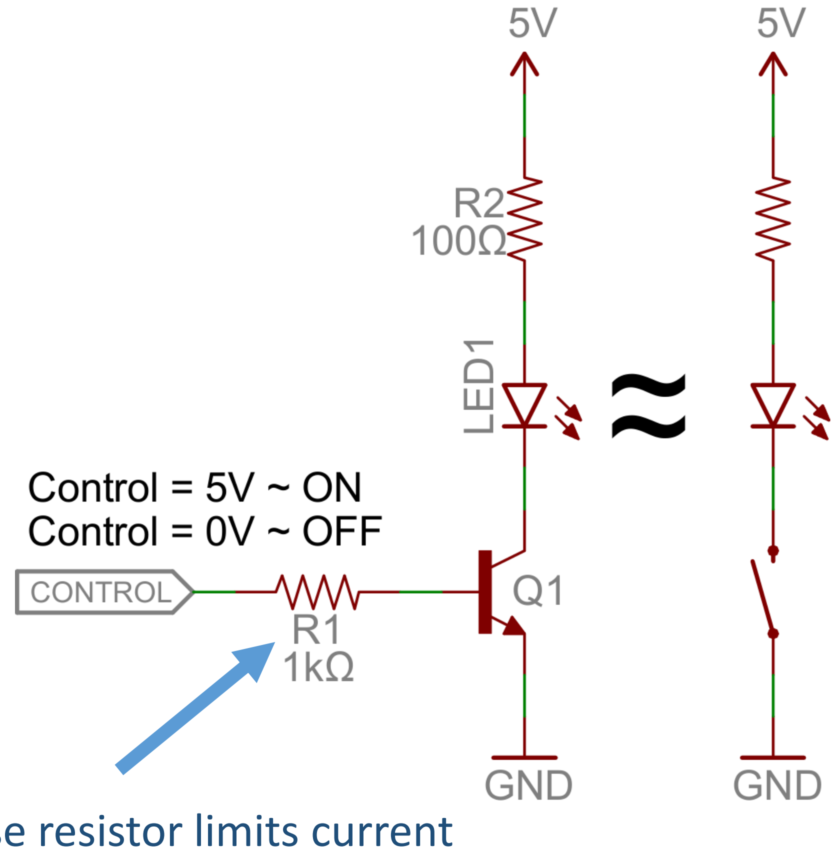
Used to control the flow of current to another part of the circuit – *i.e.* as an electric switch

High control voltage

- Transistor is fully “on”
- Ideally zero resistance
- Known as “saturation”

Low control voltage

- Transistor is fully “off”
- Ideally infinite resistance
- Known as “cut-off”



Microcontroller pins have max ~10mA current.
So transistors used to turn on devices with higher current draw

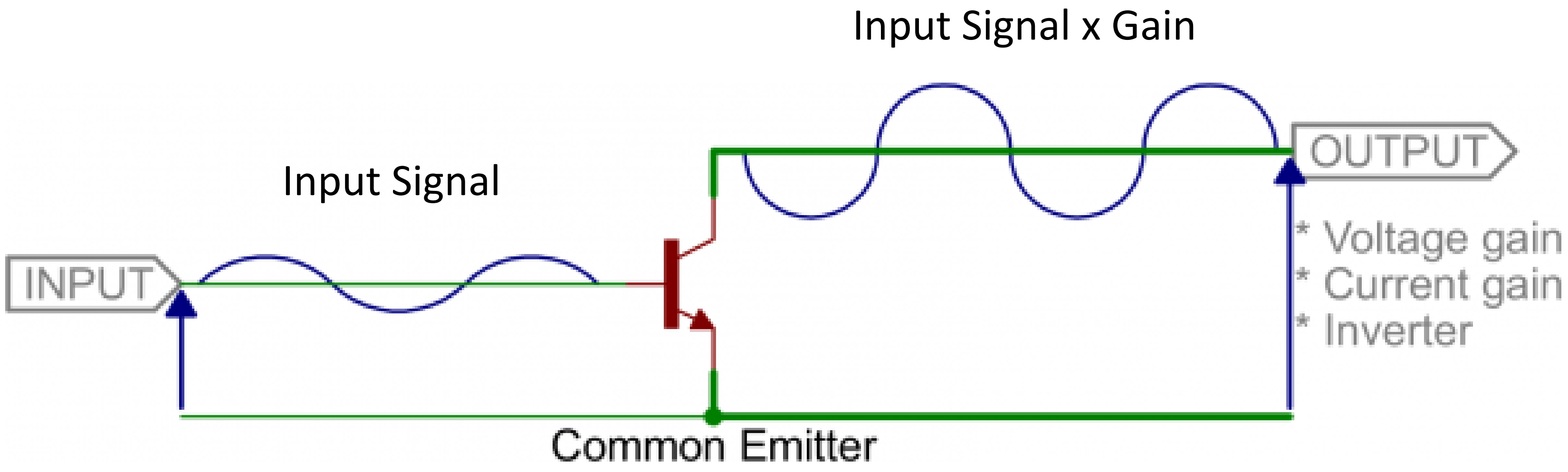
Real transistor has limits on:

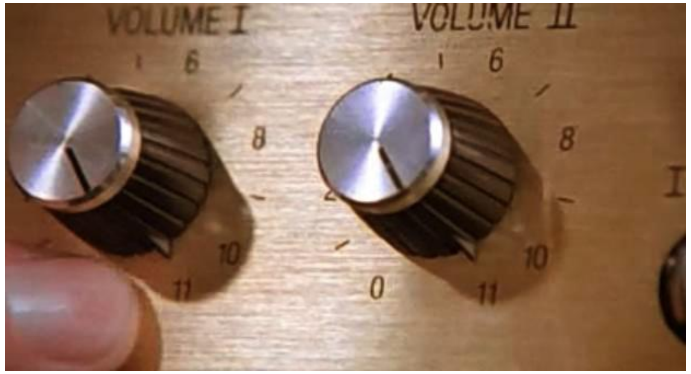
- Switching speed
- Maximum current
- Minimum resistance

If input is from a digital source, e.g. Arduino pin, then its probably being used as a switch

Transistors – amplifier applications

Turning a low power analogue signal into a higher power one.
Transistor neither fully “on” or “off”, but output current *proportional* to input base current (known as “active” mode)





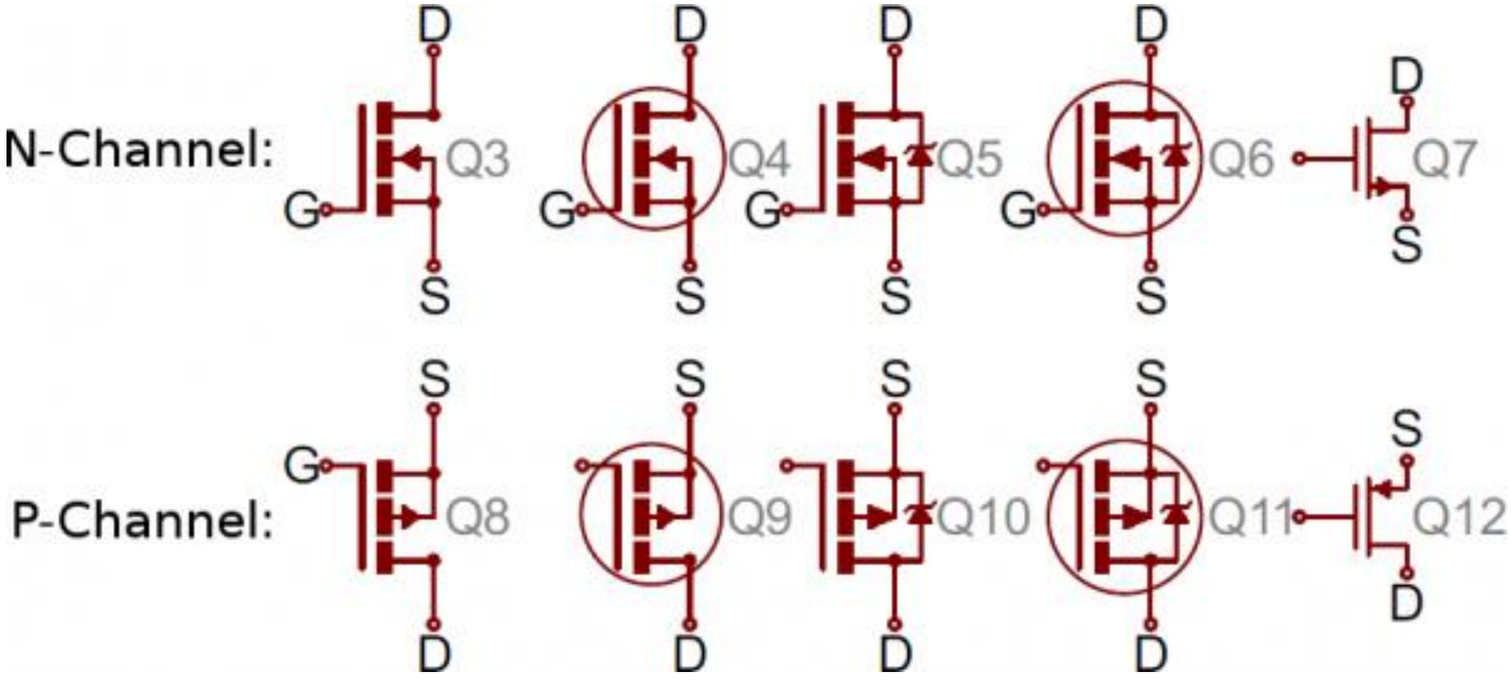
BJT gain: hFE or β
Typical max gain 10 to 500

Can be arranged to amplify V or I, or convert V to I or I to V (transimpedance amps – next week & Block 3 in lab)

If input is analogue signal, e.g. sensor or op-amp, then its probably being used as an amplifer

Transistors – other types

There are other types of transistors known as FETs and MOSFETS



Semiconductor elements are different, and are *voltage controlled*

Lower power consumption but slower switching speed compared to BJT

Again, enough to know they perform similar tasks, and EE guys picked it over a BJT for a reason

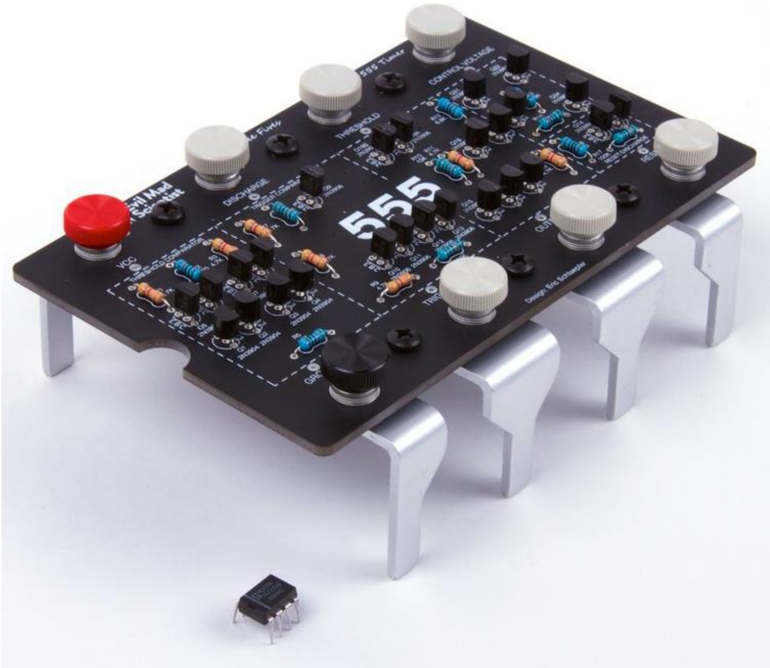
Mixed Digital and Analogue – 555 Timer

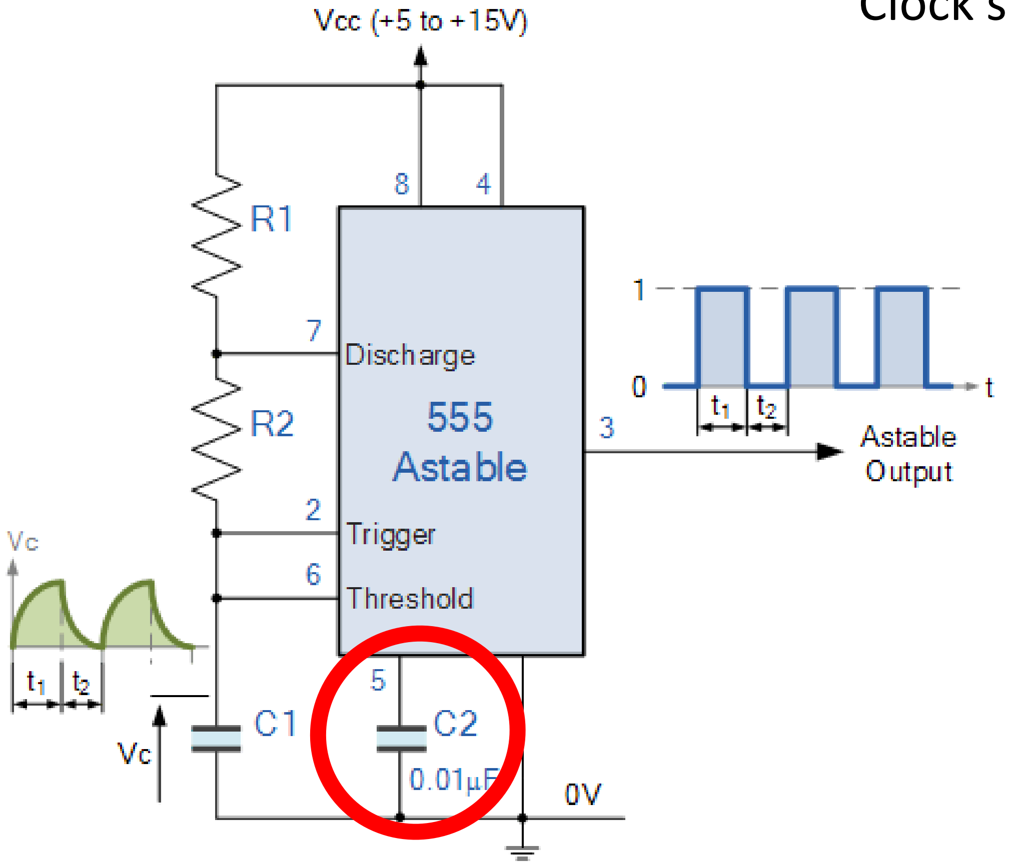
Uses analogue components to generate a digital signal
a square wave of a programmable duty cycle and frequency

Cheap synths

Clock signals

Inside is actually quite complicated…





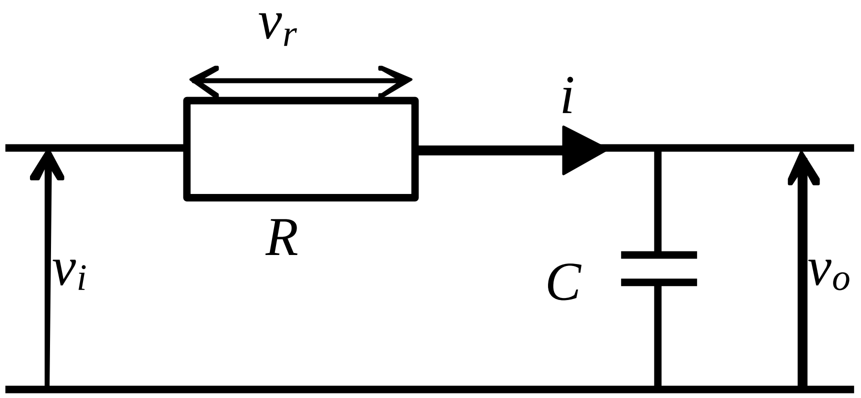
But we can consider the IC as a block only

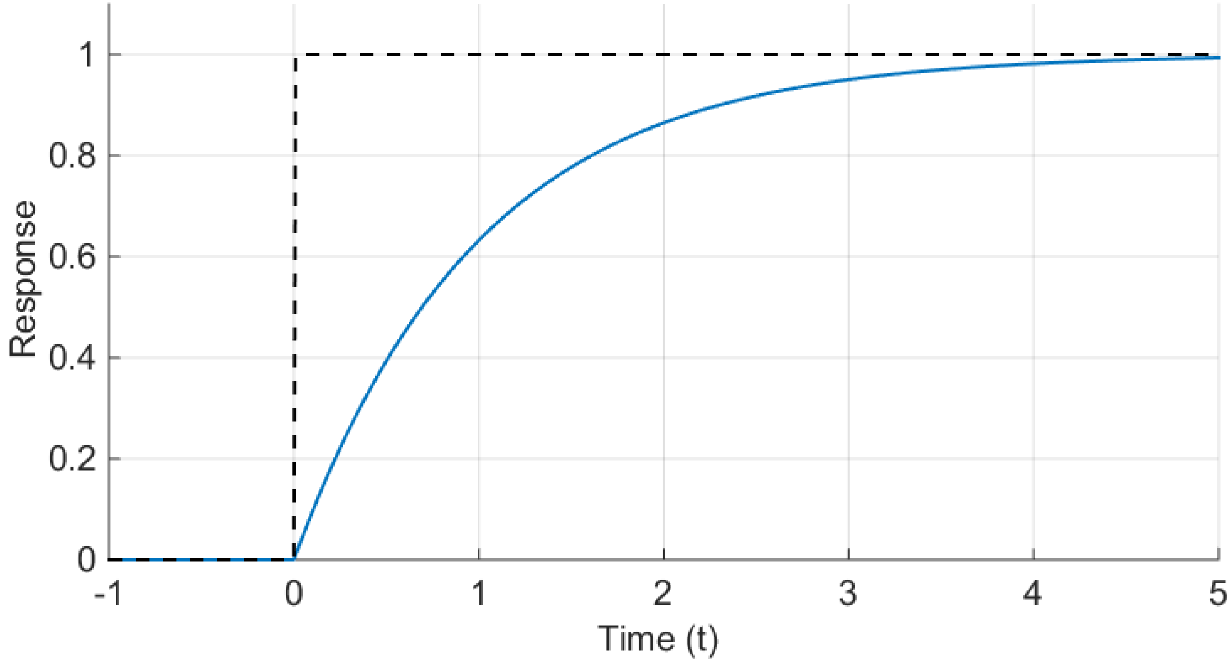
Bypass cap. So we can ignore!

Mixed Digital and Analogue – 555 Timer

When voltage applied across a capacitor, the capacitor charges at rate dependent on current flow

Exponential rise thus set by R and C





1st order ODE
$$v_i(t) = RC\frac{dv_o}{dt} + v_o(t)$$

Solution (time domain)
$$v_o = v_i\left(1 - e^{\left(\frac{-t}{RC}\right)}\right)$$

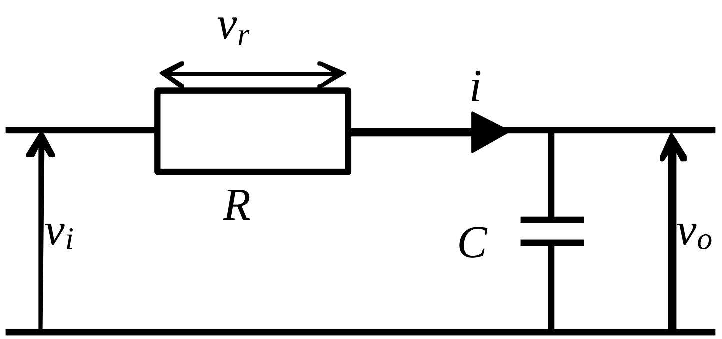
$$G(s) = \frac{V_0(s)}{V_i(s)} = \frac{1}{RCs+1} = \frac{\alpha}{Ts+1}$$

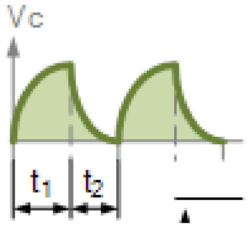
Transfer function in Laplace domain

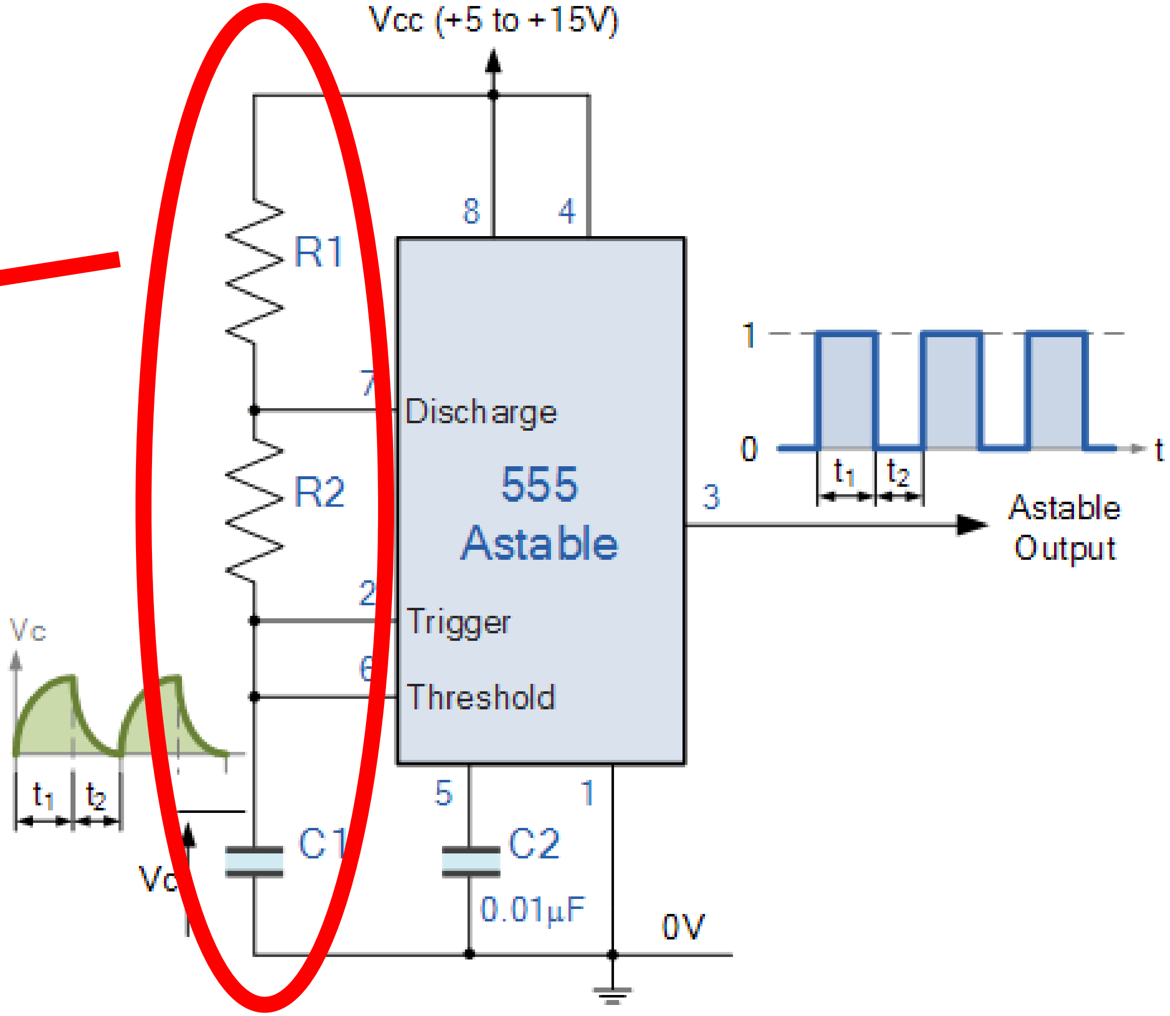
RC determines the *time constant T* which controls the rise time

Mixed Digital and Analogue – 555 Timer

An identical circuit formed from *R1, R2* and *C1* in the 555 timer circuit.
User programmable charge and discharge rate of capacitor.







Without the 555 timer doing anything,
all this can do is charge up to the voltage V_{CC}

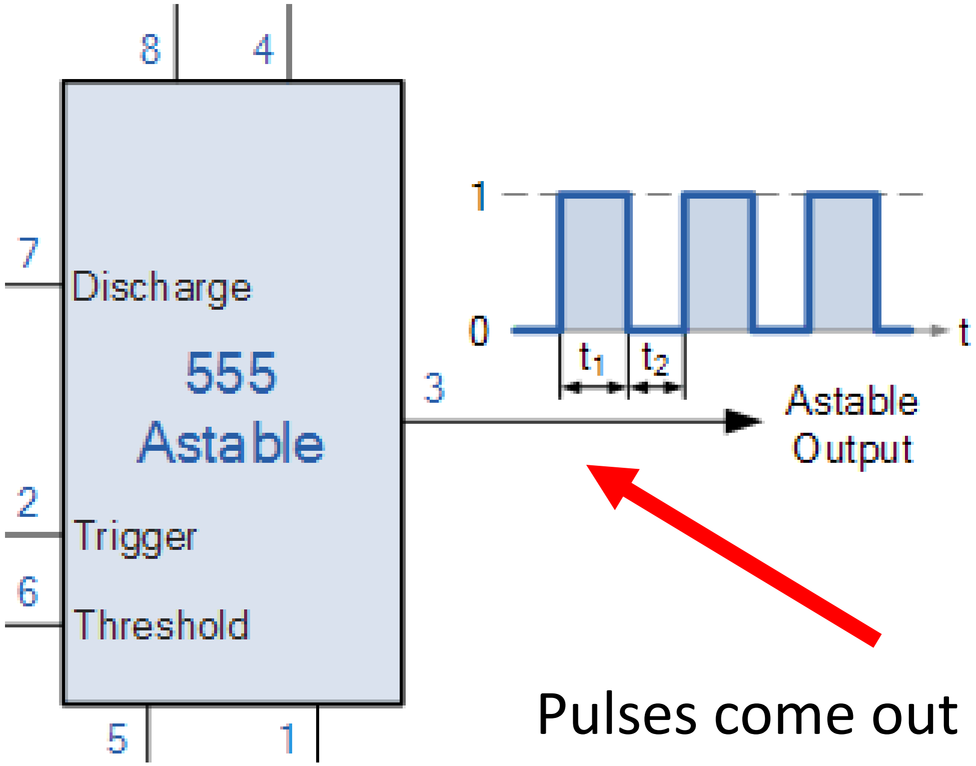
Mixed Digital and Analogue – 555 Timer

Three pins *discharge, Trigger* and *Threshold* determine what the voltage is on the *output* pin.

Either disconnected, or connected to ground when output is *low.* Used to *discharge* the capacitor C1

When voltage on this pin goes *below* 1/3 V_{CC}, the output flips from LOW to HIGH

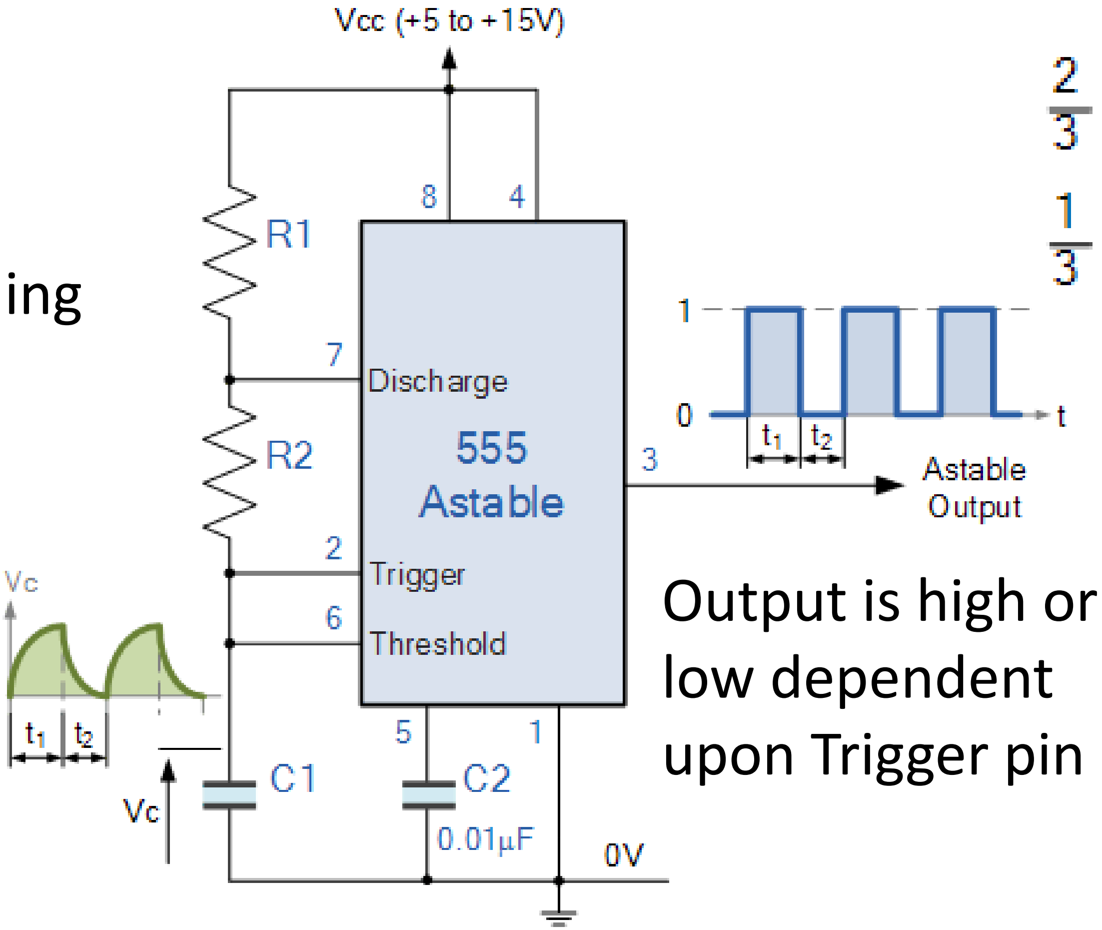
When voltage on this pin goes *above* 2/3 V_{CC}, the output flips from HIGH to LOW



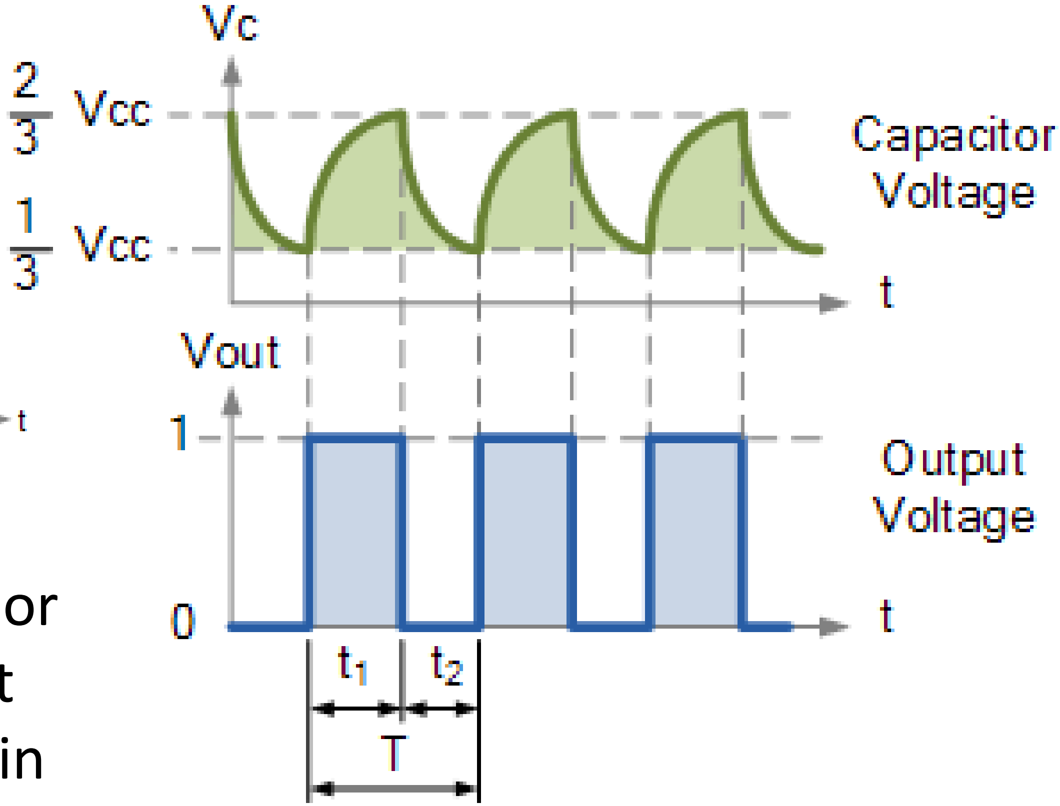
Pulses come out here

Mixed Digital and Analogue – 555 Timer

Discharge pin is connected to ground, depending upon voltage at Threshold pin



Output is high or low dependent upon Trigger pin



$$t_1 = 0.693(R_1 + R_2)C_1$$

$$t_2 = 0.693R_2C_1$$

The duty cycle and period can be controlled by choosing only 3 components

Thank you for your attention!

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