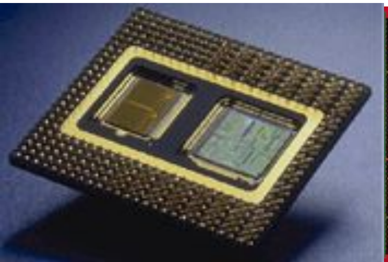
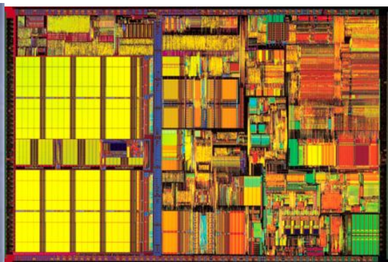
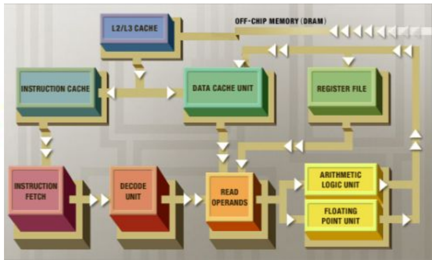
Analog to Digital Conversion

Dov Kruger
Department of Electrical and Computer Engineering
Rutgers

Adapted from Brian Ackland's slides. Some images from wikimedia, and Electronics Tutorials

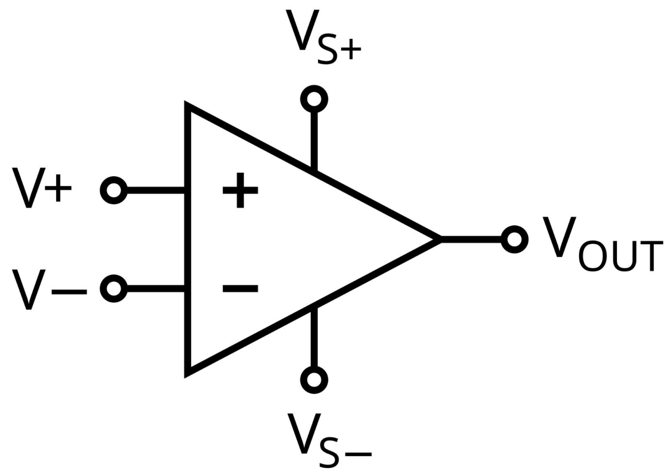
The Real World of Analog

- A microprocessor deals exclusively with digital data
  - finite precision storage of information (bits)
- The world is analog
- Convert from binary to analog voltage
  - Digital to Analog (DAC)
- Convert from analog to digital
  - Analog to Digital (A/D or ADC)

Fundamentals: Op Amp

We won't cover operational amplifiers, but you should at least know what they are

- Multiple transistors to create an amplifier
- Very high input impedance (resistance)
- Very high amplification (~ 10^6) called Gain (G)
  - $V_{out} = G(V^+ - V^-)$
- Not very repeatable
- Two "identical" op-amps may differ by +/- 50k gain



Op-Amps Used for…

Building Amplifiers

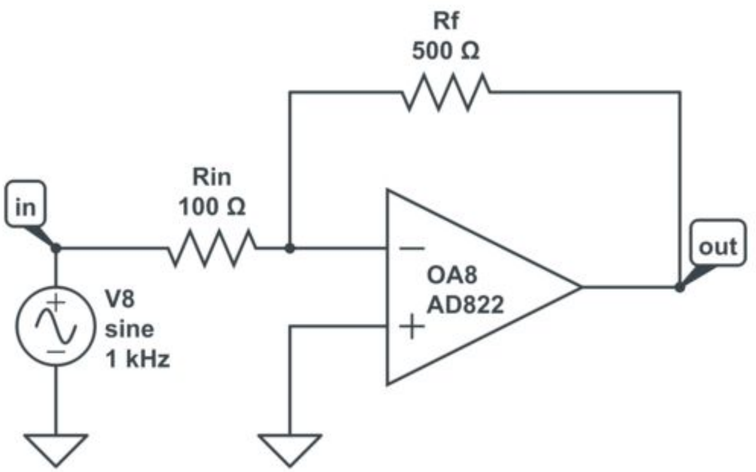
- Analogy: Furnace in a heating system
- Furnace does not maintain exact temp
- We create a feedback loop
- Furnace turns on when it's too cold, off when it's too hot

Building Comparators (compare two voltages)

Inverting Amplifier

The inverting Amplifier uses two resistors to create a feedback loop

$V_{out} = GV_{in}$ $G = -R_f/R_{in}$

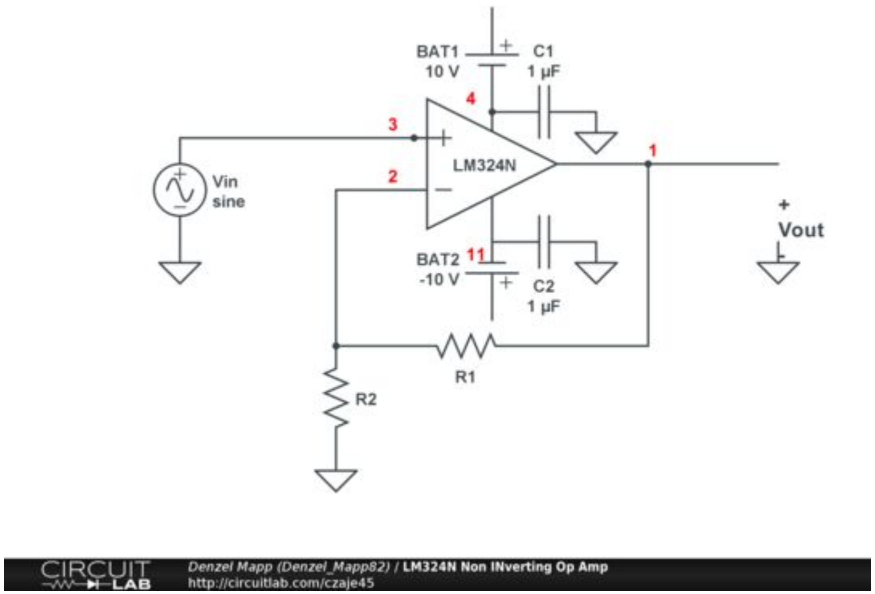


Humberto Evans (hevans) / **Inverting Amplifier with specific gain an using an op-amp**
http://circuitlab.com/c92826hksjz5c

Non-Inverting Amplifier

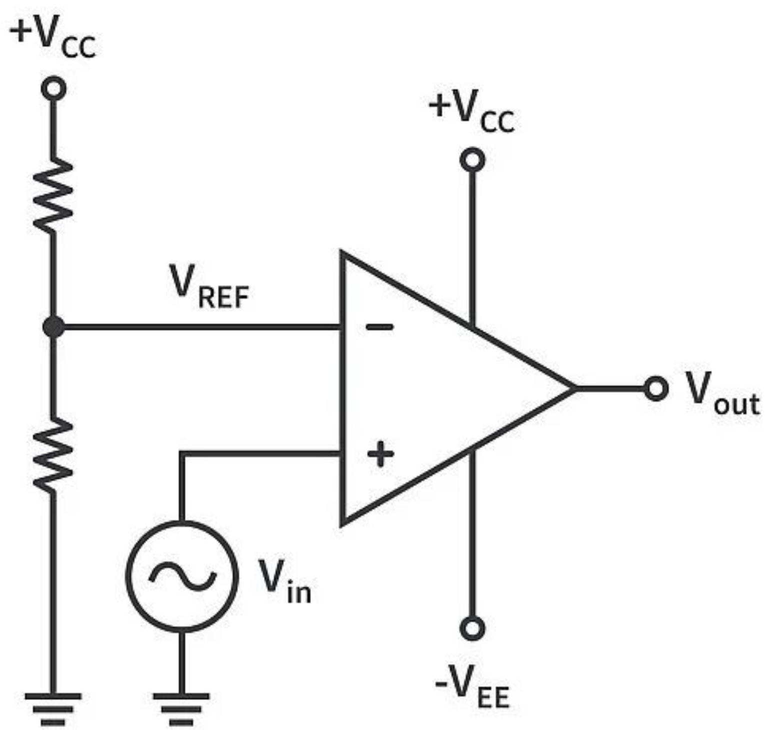
The non-inverting Amplifier does not negate but amplifies noise

$V_{out} = GV_{in}$, $G=(R_1/R_2+1)$



Comparator

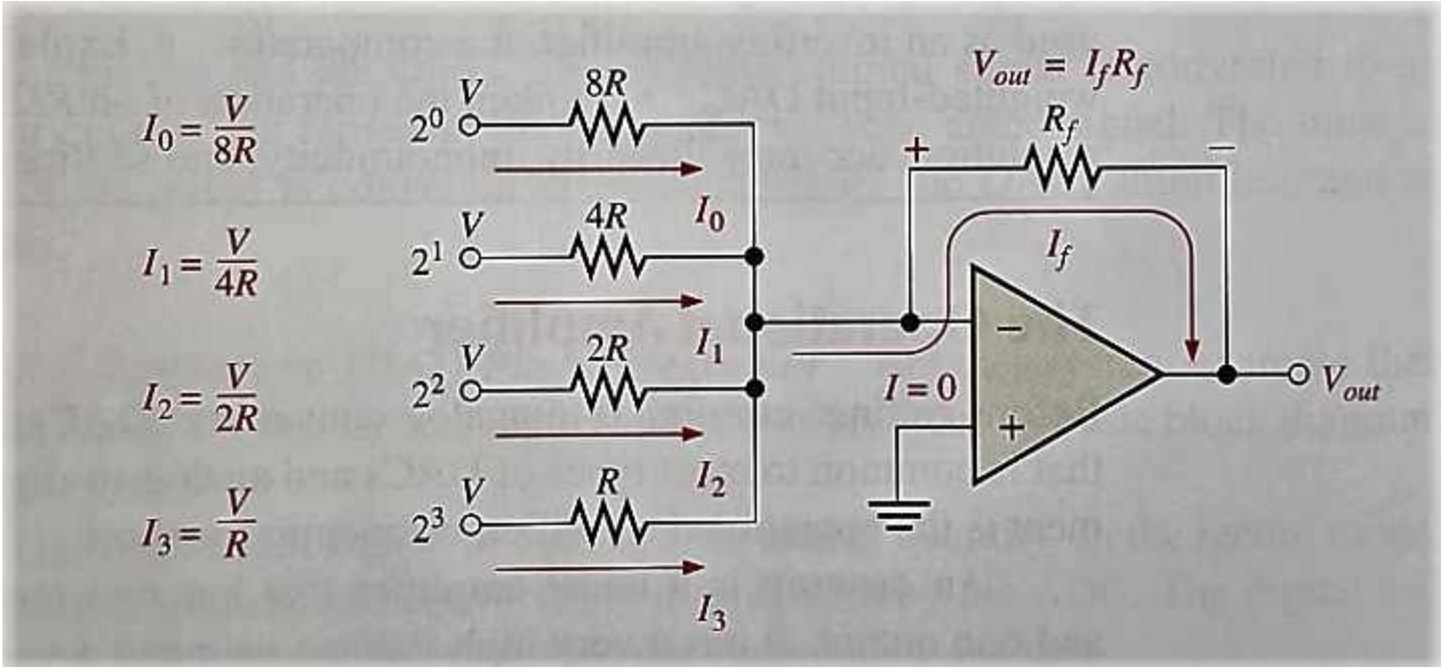
When v_{ref} is higher than V_{in} $\quad V_{out} = V_{cc}$
When v_{ref} is lower than V_{in} $\quad V_{out} = -V_{EE}$
For digital applications, $V_{EE} = 0$, V_{cc} is our reference voltage



Digital to Analog Converter (DAC)

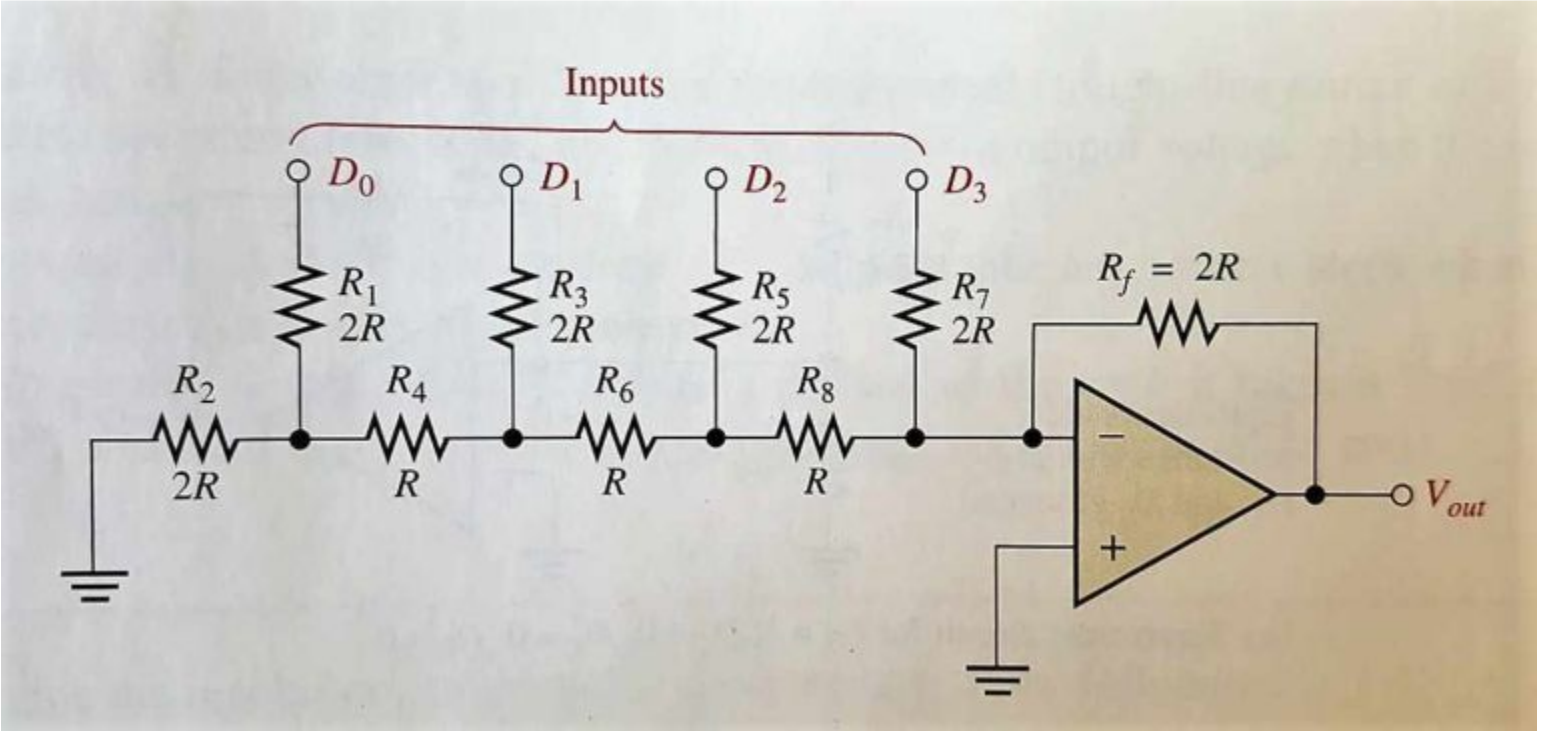
A DAC converts binary to an analog voltage

This diagram shows a conceptual view



R/2R Ladder

Circuit to encode 4 bits to analog using two resistor values



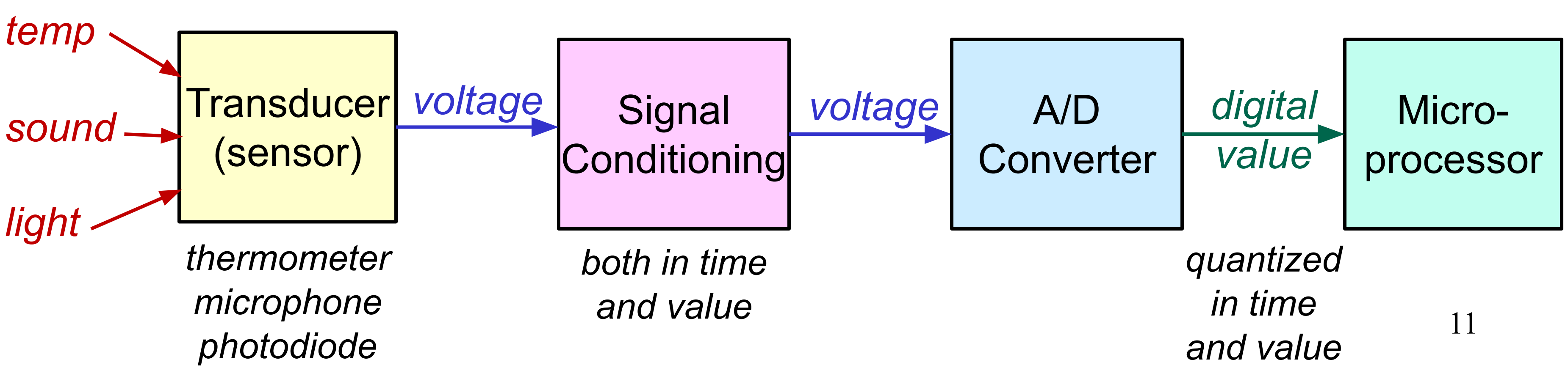
D/A Used for…

Analog audio sound

Old fashioned video

Analog to Digital (A/D) Conversion

- A microcontroller in an embedded application takes inputs from real-world sensors
  - some of these are already digital (e.g. switches, keyboard, mouse)
  - many are analog (e.g. pressure, temperature, light intensity, microphone, airflow, engine speed, oxygen level)
- Analog-to-Digital converter (A/D) transforms analog signal into digital representation usable by microprocessor

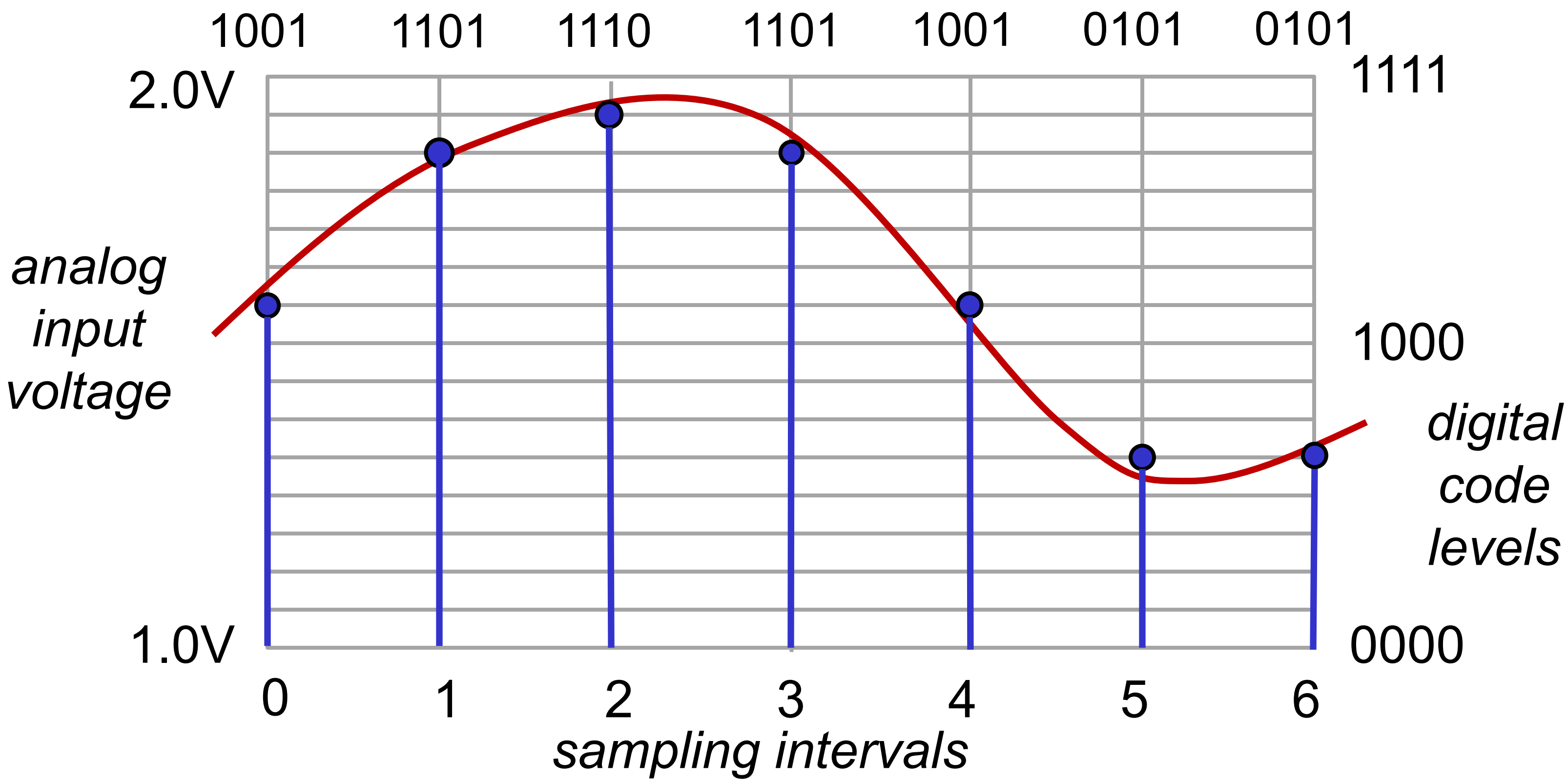


Simplest A/D: 1 bit

With 1 bit, there are only 2 levels

Analog to Digital Conversion

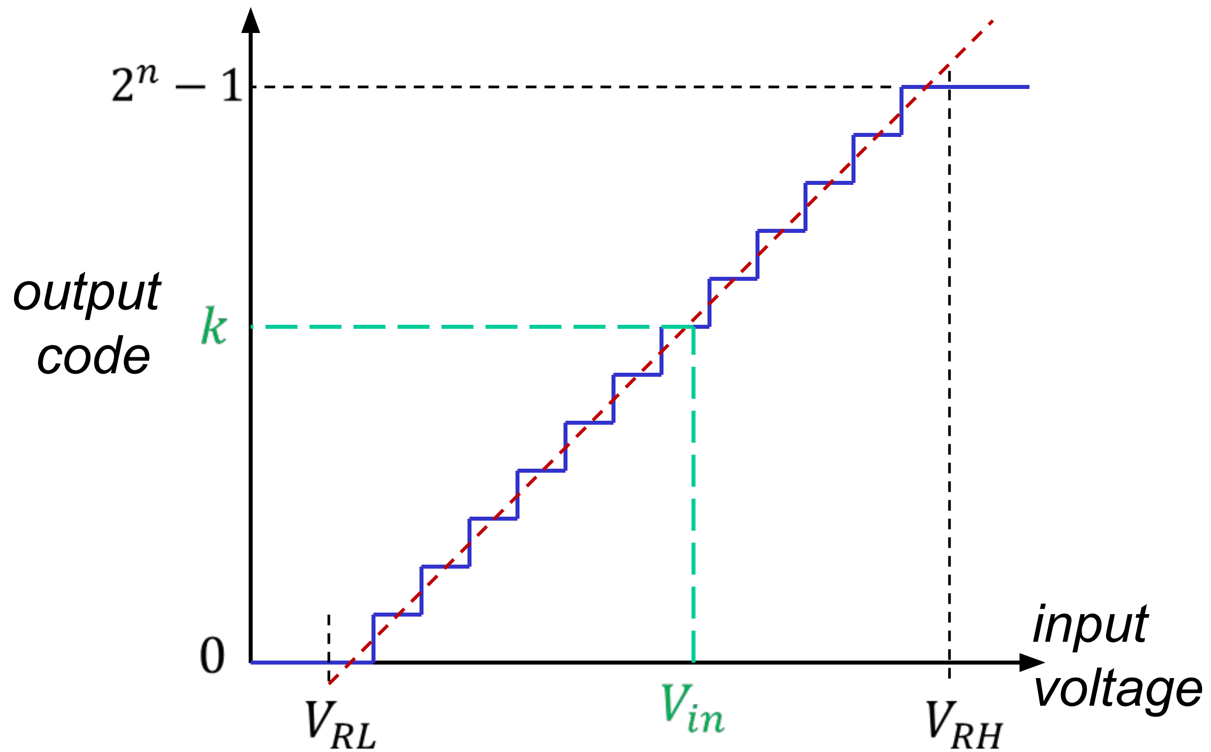
- An A/D converter samples an analog signal at regular intervals and generates a digital code which is its best (closest) approximation to the analog value at that instant

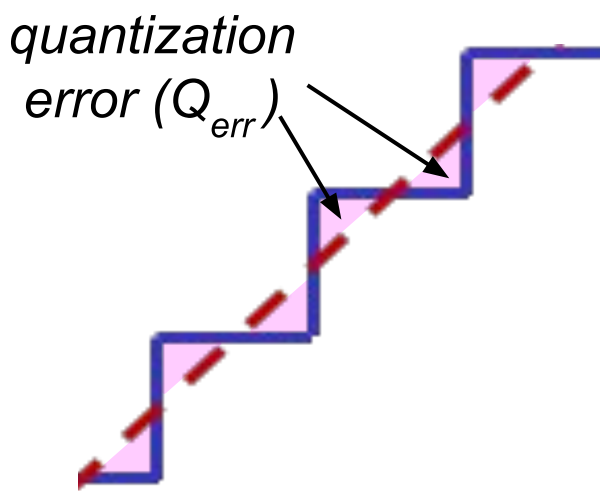


- Analog signal: continuous in time and value
- Digital signal: quantized in time and value

A/D Transfer Function

- An n-bit A/D converter has 2^n possible output codes
- Input voltage range typically defined by two reference voltages V_{RL} and V_{RH}





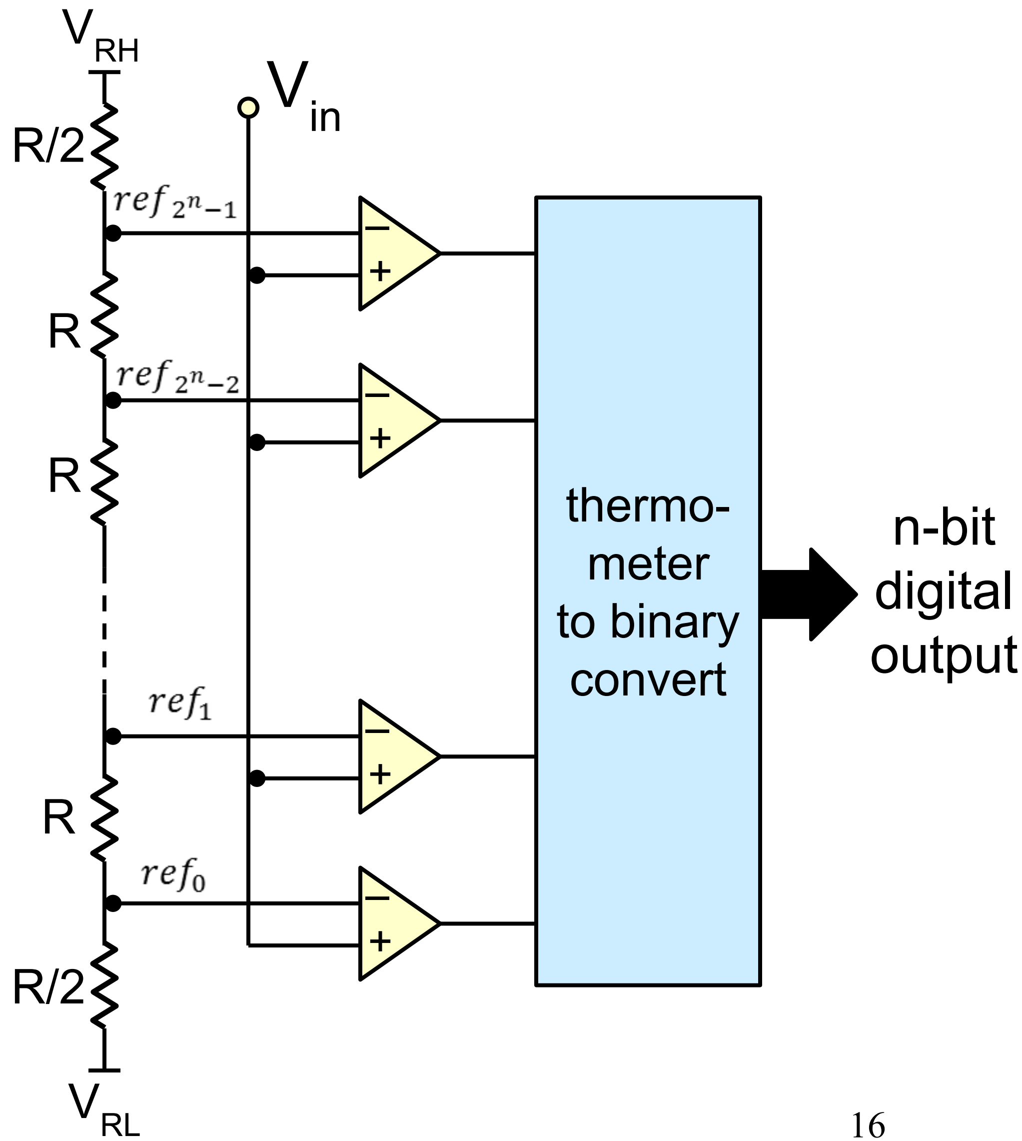
$$V_{in} = V_{RL} + \frac{(V_{RH} - V_{RL}).k}{2^n - 1} \pm Q_{err}$$

A/D Characteristics

- **Resolution**
  - often quoted in terms of # bits (e.g. 12-bit converter)
  - analog resolution is $(V_{RH} - V_{RL})/2^n$

Flash (Parallel) A/D Converter

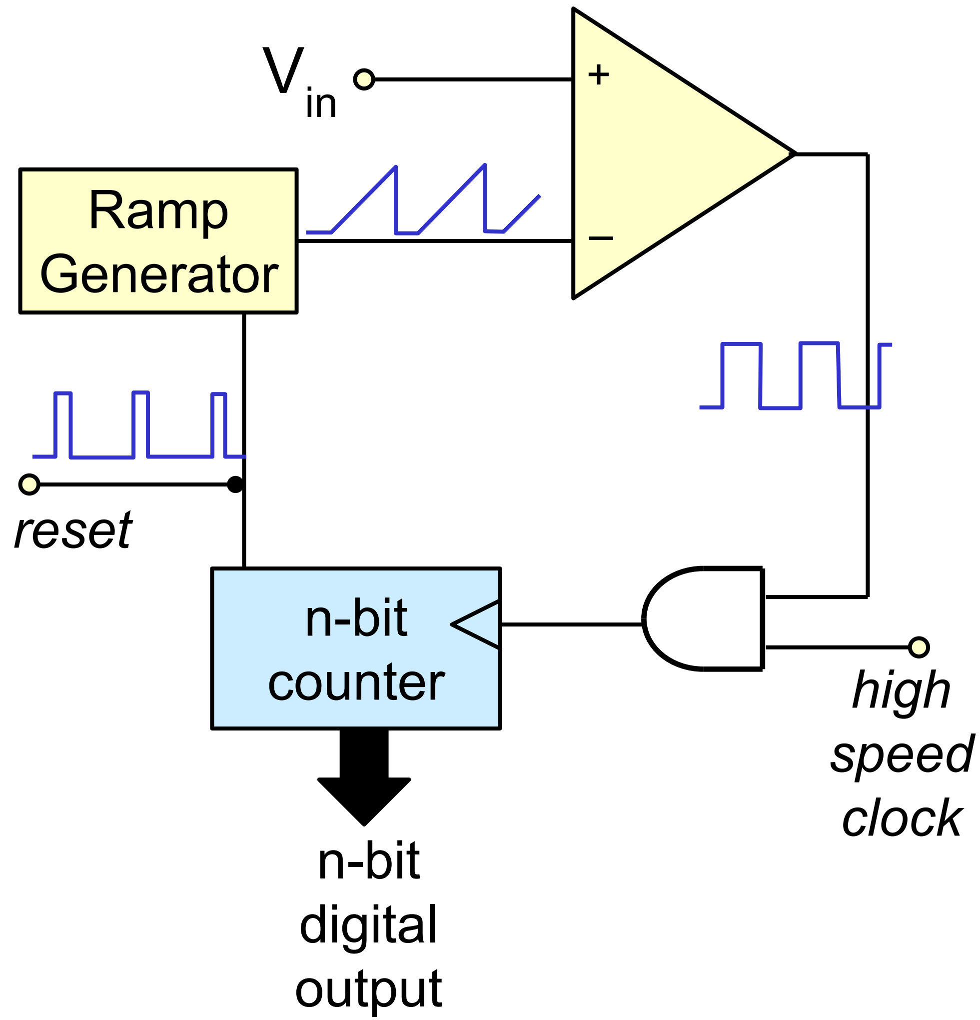
- Resistor ladder generates 2^n reference voltages
- 2^n comparators simultaneously compare input with each reference
- Comparator output k is high if Vin > ref_k
- Conversion logic generates code indicating greatest value of k for which comparator output is high
- Very high speed
- Expensive in area & power
- Limited to ~ 8-bits



Single Slope A/D Converter

- Compares input to linear ramp to generate a pulse width proportional to V_{in}
- Pulse used to gate clock to high speed digital counter
- Simple hardware – popular in low speed applications
- High resolution possible
- Performance limited by:

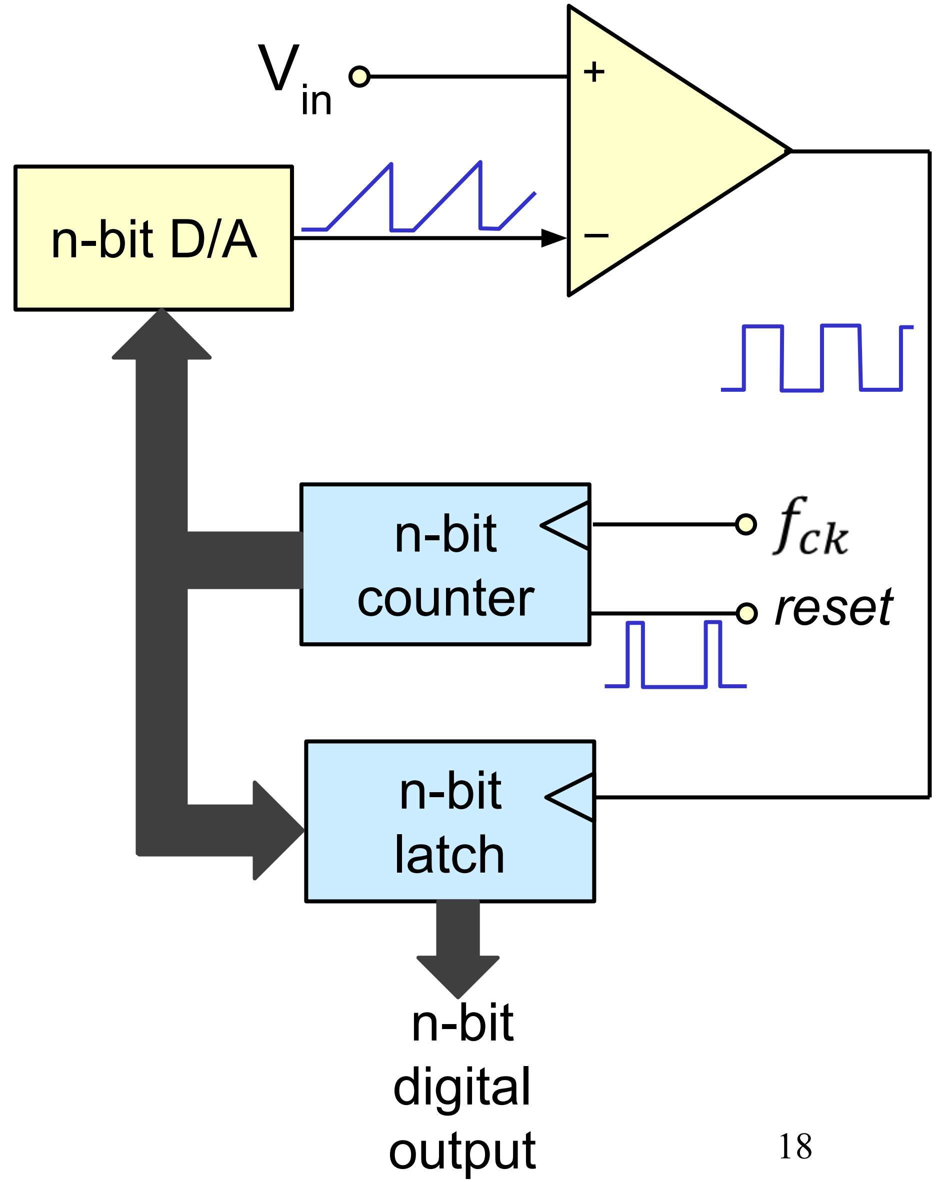
$$f_{ck} = f_{samp} \times 2^n$$



e.g. for f_{samp} = 1 MHz, a 12-bit converter requires f_{ck} = 4 GHz

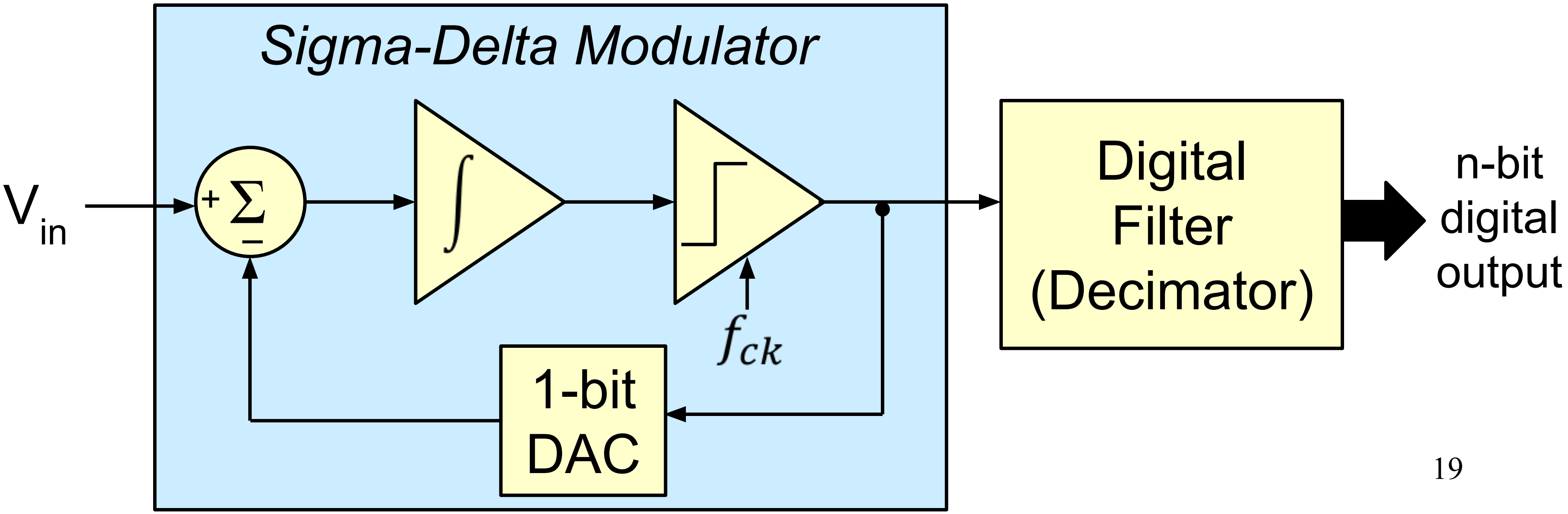
Counter Ramp A/D Converter

- Variant on single-slope converter
- Ramp is generated by counter driving a D/A converter
- When D/A output ramp crosses V_{in}, counter value is captured in n-bit latch
- Does not require precision analog ramp generation
- Precision limited by linearity of D/A



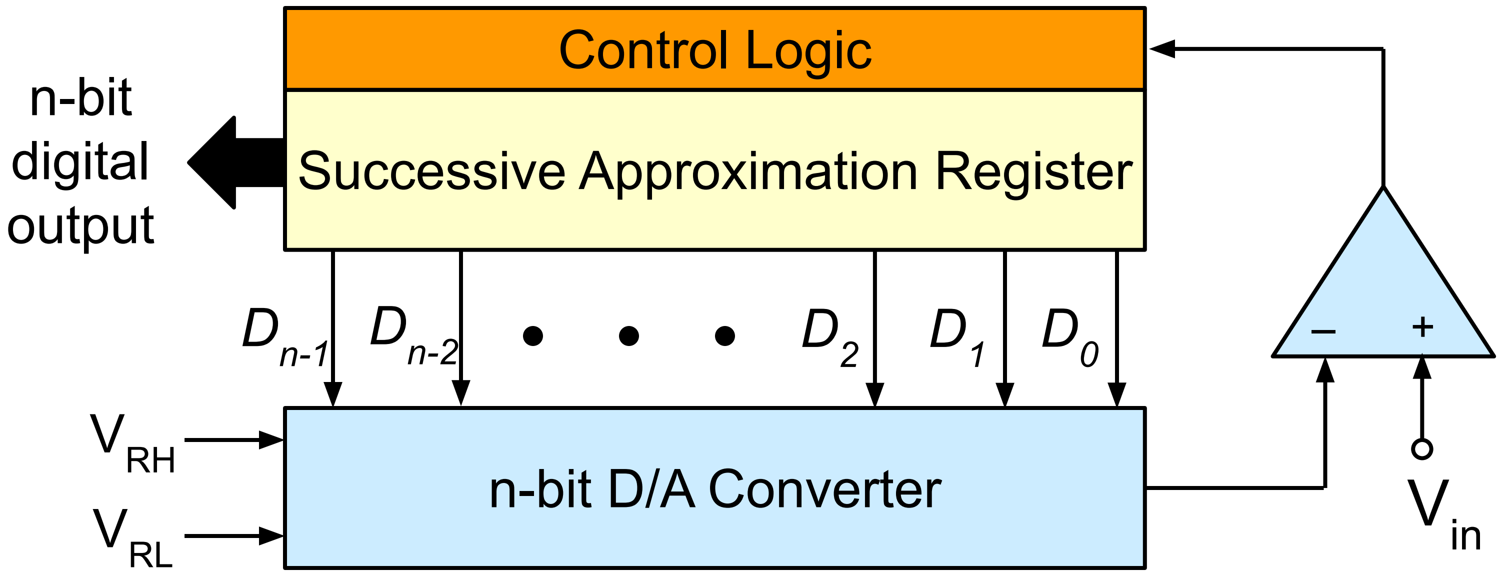
Sigma Delta (Oversampling) A/D Converter

- Sigma-delta modulator consists of summer, integrator, clocked comparator and a 1-bit DAC
- Modulator runs at many times (e.g. 16x – 1000x) the required sampling frequency to produce very high speed 1-bit waveform
- Digital filter coverts this to much slower n-bit digital output
- Since 1-bit DAC is perfectly linear, can produce very high resolution (up to 24-bit)
- Sampling frequency is limited by need to over-sample



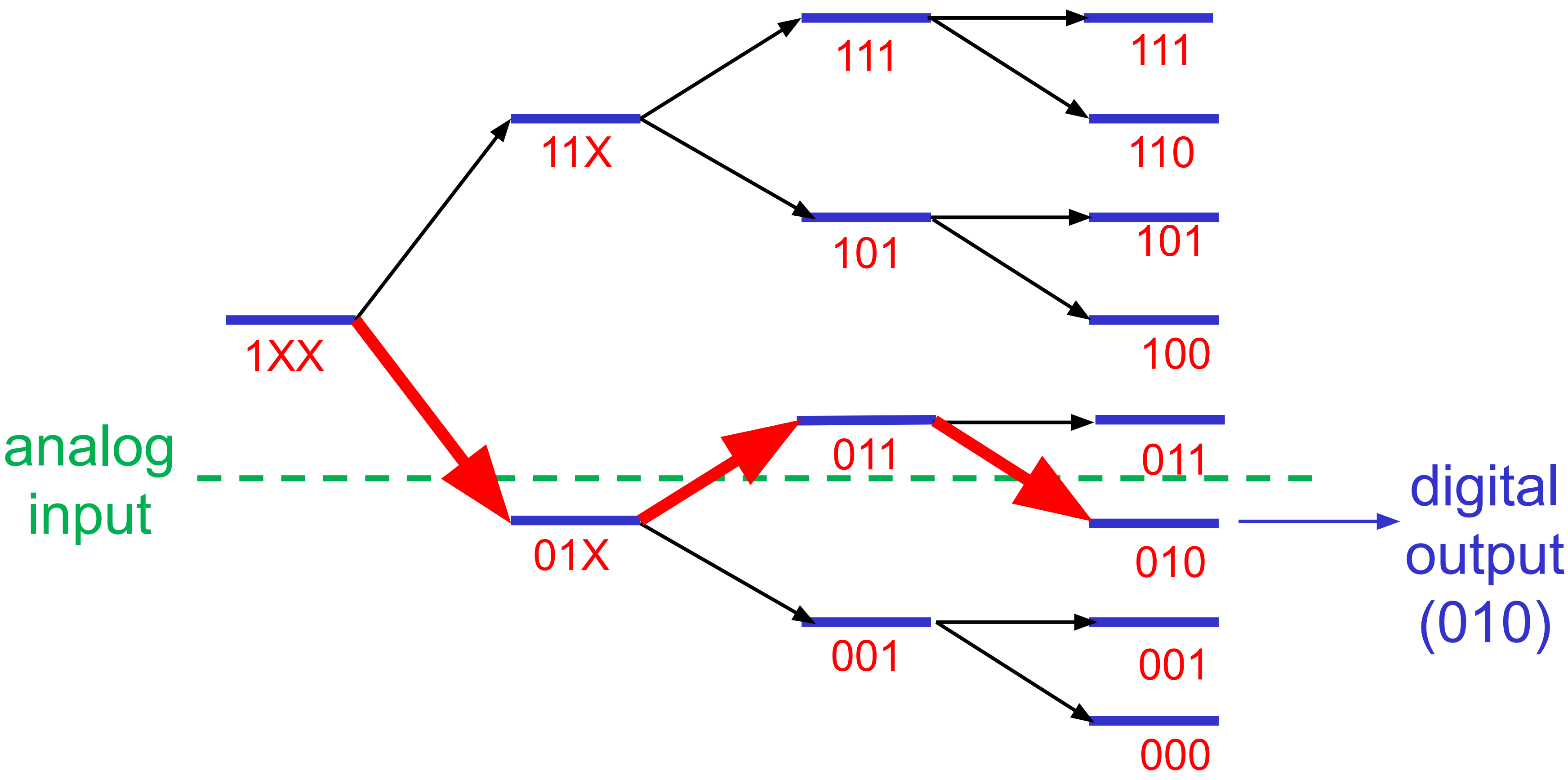
Successive Approximation A/D Converter

- Guesses and then corrects digital code in SAR one bit at a time



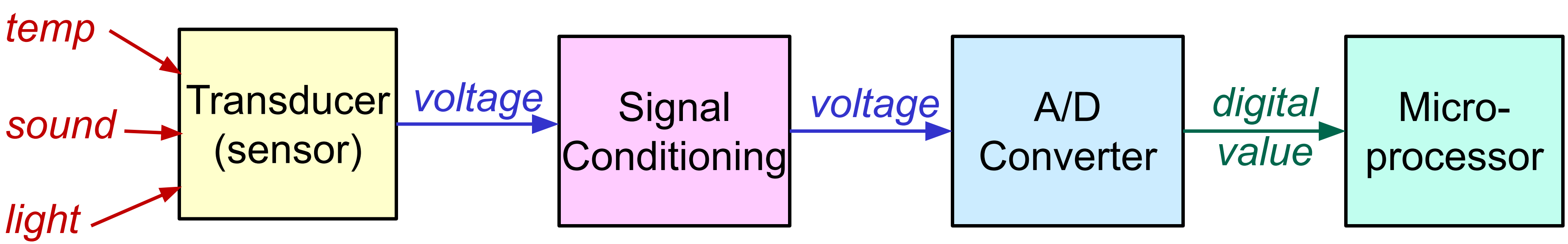
- Initially sets all bits in SAR to '0'
- Then starting with MSB, for each bit:
  - set bit to '1' and convert output of SAR to analog value with D/A
  - compare output of D/A to input voltage
  - if D/A is larger, set this bit back to '0' and go on to next (lesser sig.) bit
  - if input is larger, retain '1' for this bit and go on to next bit

Successive Approximation Process



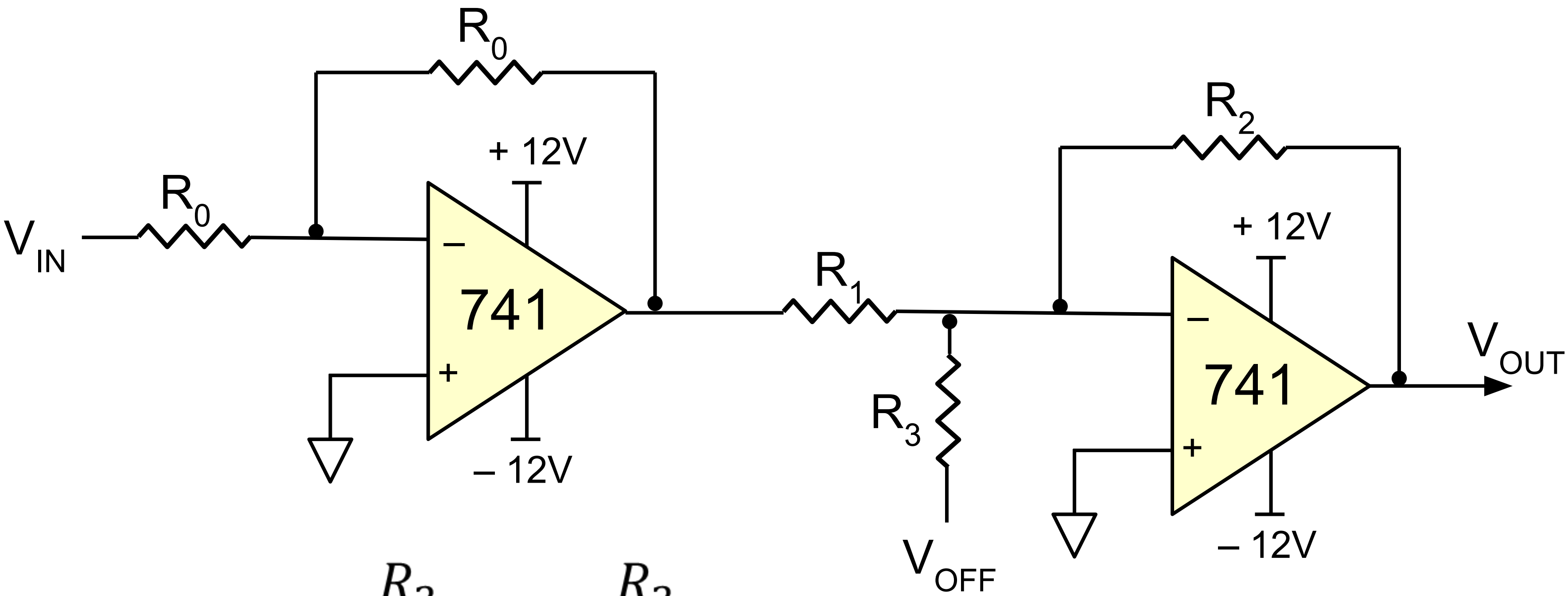
- SAR gives a good tradeoff between speed and precision
- One of most popular A/D techniques in embedded systems
- Used in HCS12

Signal Conditioning



- Signal Conditioning is process of matching transducer output to input characteristics of A/D
  - Need to match in voltage and time (frequency)

Shift & Scale Circuit



$$V_{OUT} = \frac{R_2}{R_1}.V_{IN} - \frac{R_2}{R_3}.V_{OFF}$$

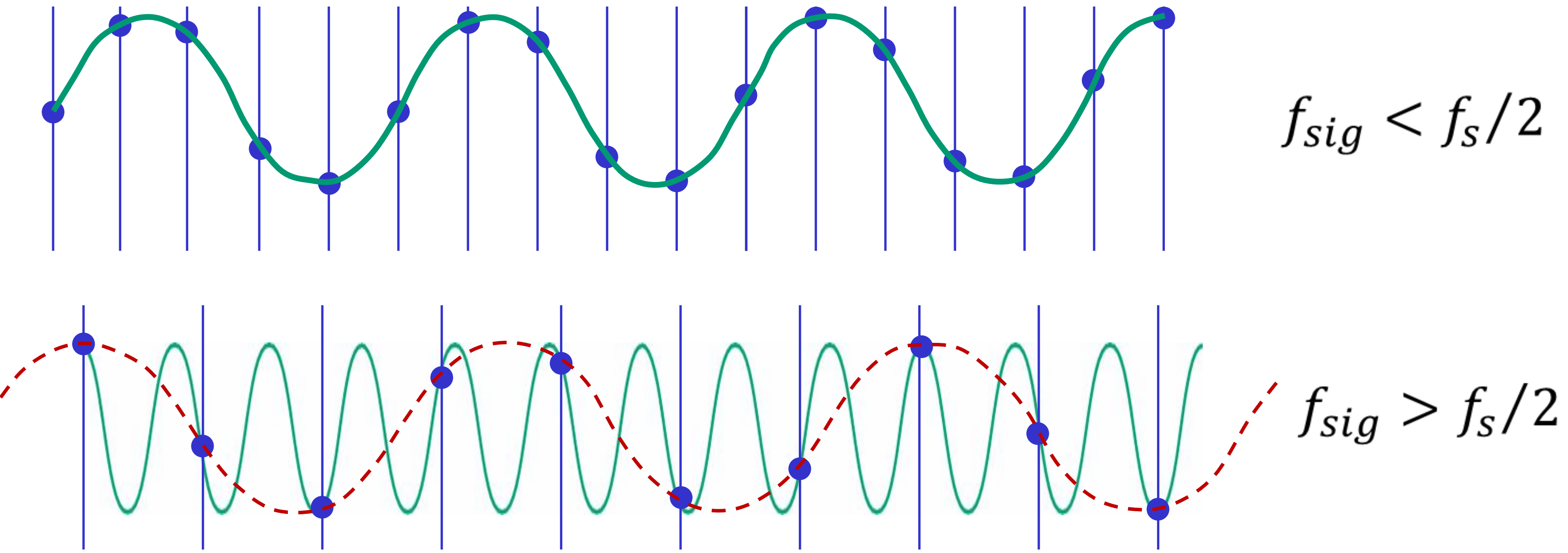
- From previous example, if $R_1 = R_3 = 10k\Omega$, $R_2 = 20k\Omega$, $V_{OFF} = -1V$:

$$V_{OUT} = (2 \times V_{IN}) + 2$$

Nyquist Frequency

- If f_s is the sampling frequency, $f_s/2$ is known as Nyquist frequency

Aliasing



- Even if desired signal does not contain components > Nyquist, there may be high frequency noise components which must be removed
- Signal conditioning circuits frequently include a sharp low-pass filter to take out any signal components > Nyquist

A/D Conversion on Arduino Due

- Basic Arduino has 6 A/D channels, 10-bit about 7700hz
- The Due has
  - 12 bit accuracy (1 part in 4096)
  - 1MHz sample rate
  - 16 input channels
  - The basic Arduino can be run faster than rated A/D conversion less accurately.

How do Instruments Work?

How does a thermometer work?
How would a computer “Read” this?

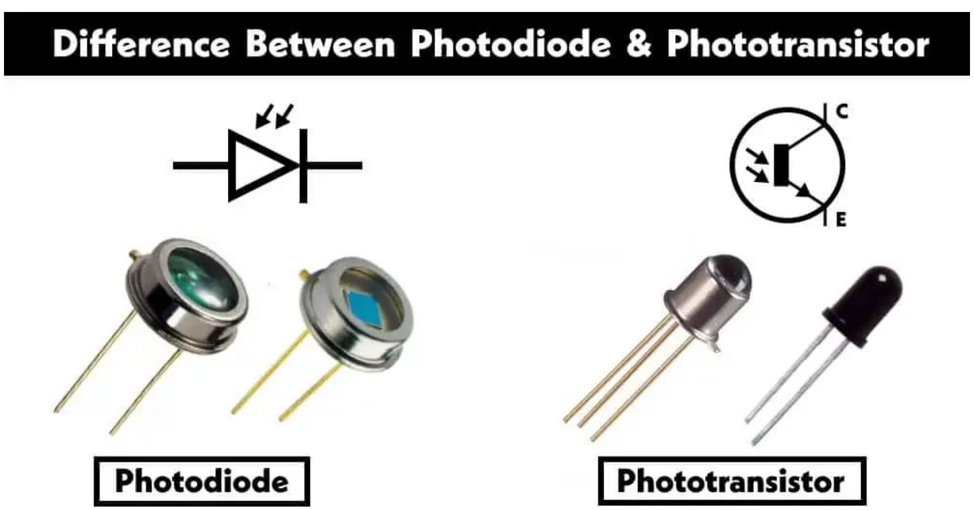
Designing Circuits to Measure

Since A/D typically measures voltage

Turn any physical quantity into voltage

Typical devices change resistance not voltage

- Photoresistor
- Photodiode
- Phototransistor
- Thermistor



Typical Semiconductor Sensor

Increased energy (heat/light) moves electrons into the conduction band

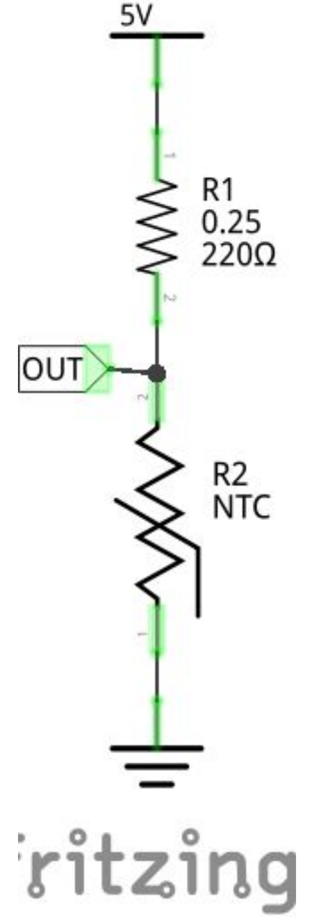
Decreases Resistance

Therefore, negative coefficient for resistance

Example: Thermistor NTC (Negative Thermal Coefficient)

How to Convert Variable Resistance to Voltage

- The variable resistance is not measurable by A/D converter
- Create a voltage divider with one fixed and one variable resistor
- The variable resistor is the sensor



Example: NTC Thermistor

Let's look at a spec sheet:
https://github.com/RU-ECE/ECE231-DigitalLogicDesign/blob/main/specsheets/NTCM-10K-B3380.pdf

What is the resistance at room temp?
What is the resistance at 100°C?
What is the resistance at -50°C?

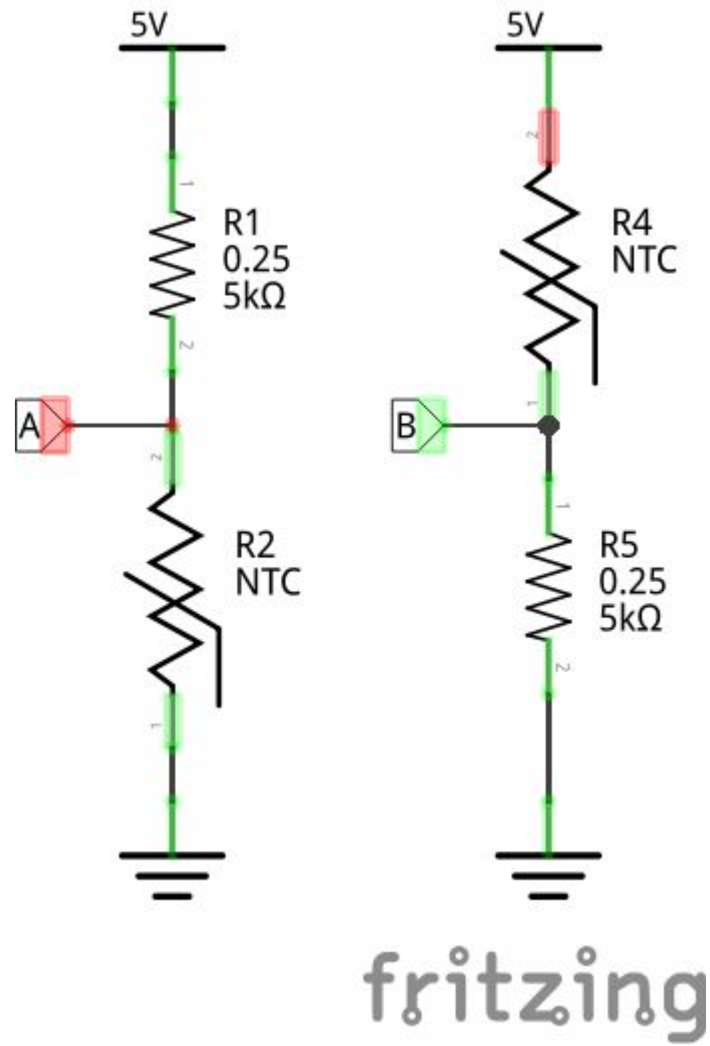
What is the relationship between temp and resistance?

Relationship of Voltage to Resistance

When designing a voltage divider, the fixed resistor can be on top or bottom

Ex. Thermistor
@25°C R=5kΩ
@100°C R = 500Ω

@25°C A =
@100°C A =
@25°C B =
@100°C B =



What is the Range of Numbers A/D?

Suppose we have a 10-bit A/D Converter (Arduino)

V_{ref} = 5V

For 0V ⇒ 0000000000 = 0

for 5V ⇒ 1111111111 = 1023

Resolution = 5V / 1024 = 4.88mV

What number will we get for

@25°C A = 2.5V A/D reads: ~511

@100°C A = .454V A/D reads: ~93

- We are only using from 93 .. 511
- More than half the range (and accuracy) is wasted

Sensitivity of Voltage Dividers

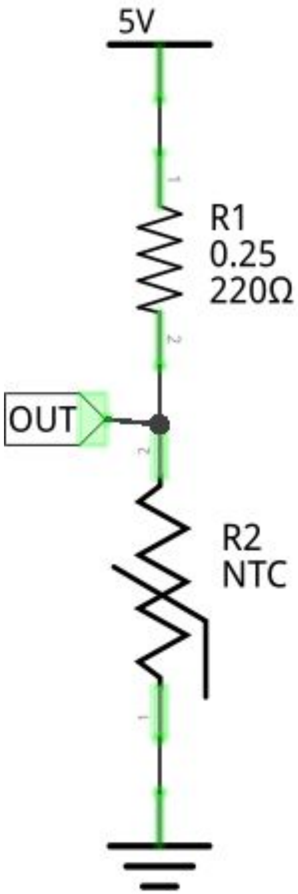
If the fixed resistor is too big or small the sensor is less sensitive

Optimally, the two resistors are equal

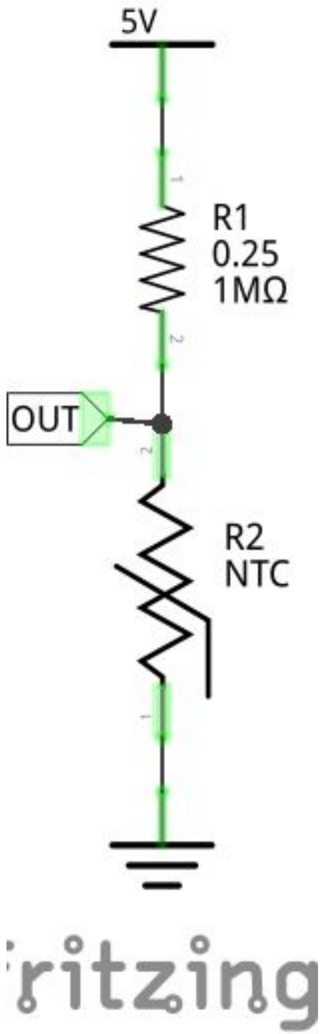
Unfortunately, if one resistance varies, they cannot be equal all the time

Pick the fixed resistor to have a value in the middle of the varying one

Example: Fixed Resistor too Small



Example: Fixed Resistor too Big



Solving the Range Problem?

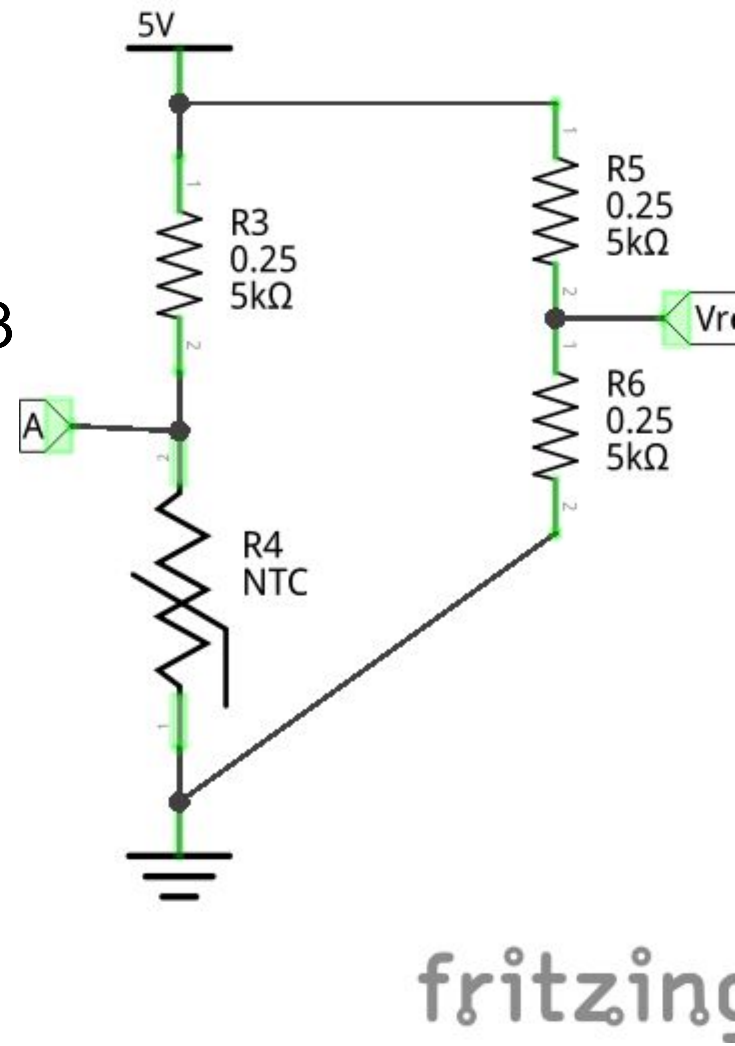
Can we use the whole range of the A/D converter?
We need to be able to define V_{ref}

Now:

$V_{ref} = 2.5V$

@25°C A = 2.5V A/D reads: 1023

@100°C A = .454V A/D reads: ~93



Calibration

Designing a circuit to measure something is relatively easy

What’s hard is making it accurate

Problems

1. Nonlinear nature of electronics
2. The usual environmental effects
   a. What affects the performance of the resistors, thermistor, op-amps in the A/D converter?
3. Tolerance of the components
4. Stability of the components over time
5. Measuring reality
   a. This is called metrology
   b. In order to create an instrument, we need to calibrate with a known value

How would you Calibrate a Thermometer?

Thermistor

Resistors

Arduino (with 10-bit A/D converter)

Display? (you can just use your laptop)

Other Types of Sensors

Not all sensors are voltage dividers!

Example: Thermocouple

A thermocouple is two dissimilar metals connected at two points

If one point is at temperature T_1 and the other at T_2 a voltage difference is generated

Voltage is small (μV) not a good generator of electricity!

Using waste heat to generate electricity would be awesome

ThermoelectricGenerator (TEG) currently 7% efficient

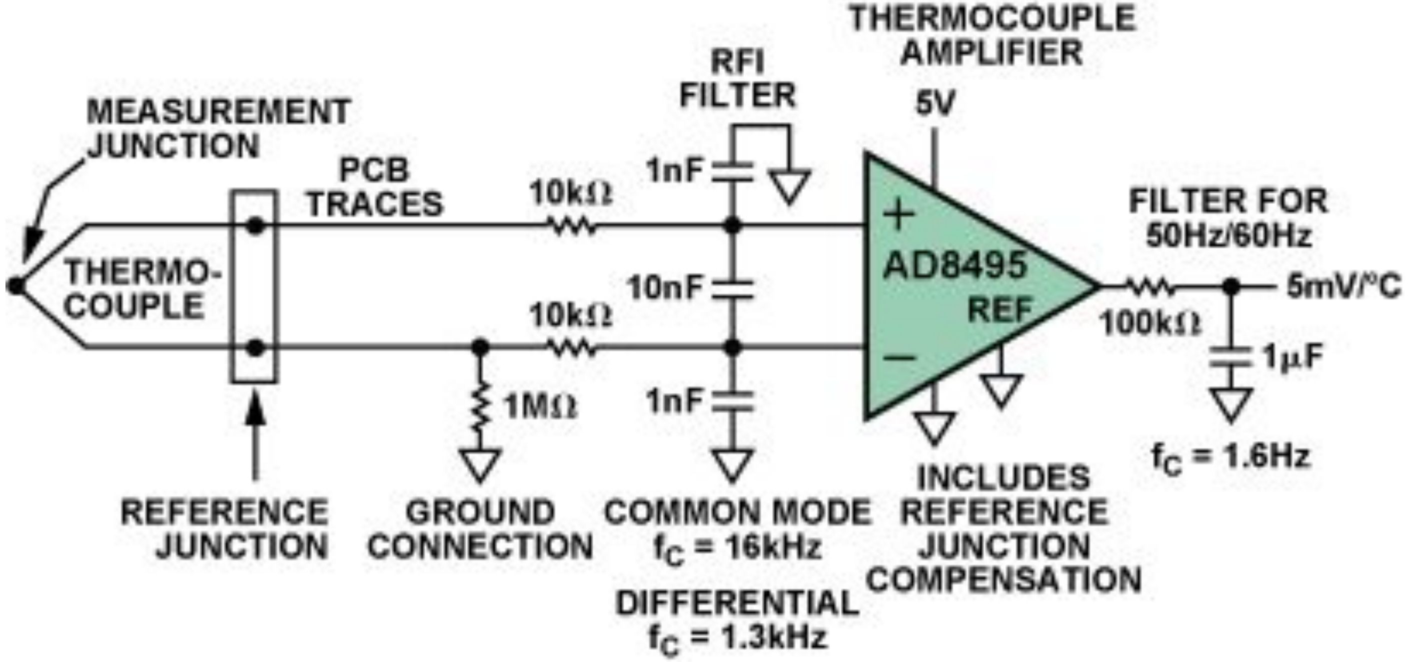
Thermocouple Circuit

To create a sensor for a thermocouple we need

Amplifier (because voltage is tiny)

Capacitors (to absorb noise)

https://www.analog.com/en/resources/analog-dialogue/articles/measuring-temp-using-thermocouples.html



Thermocouple Doesn’t Measure Temperature!

Take a look at the previous slide. The thermocouple ISN’T MEASURING THE TEMPERATURE

What is it measuring?

Calibration is Hard!

Establish ground truth

Build a thermistor probe you can dunk into liquid

What temperatures do we know?

0°C = freezing point of water – or is it?

100°C = boiling point of water – or is it?

How could you design a test rig to calibrate your thermistor circuit?