We've been considering the case of Analog meets Digital: The universe is analog (pressure, temperature, voltage, mass etc are real numbers) but the sort of circuits we've been doing only know about 0 & 1. Certainly we can use 0s & 1s to represent real numbers ("floating point numbers") or use integers to approximate real numbers. How do we get these analog quantities into our digital circuits? How do we get our digital circuits to produce such numbers? So far we've looked at comparators which make simple above/below cut on real number inputs, now lets make integer approximations of real numbers: Voltage in → integer out

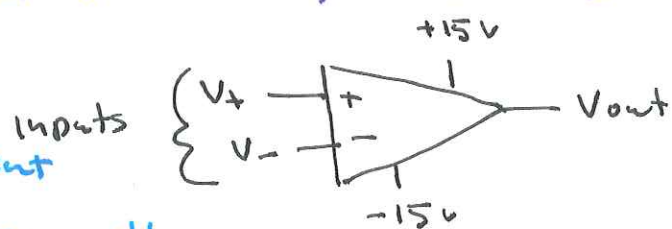
Analog to Digital Converter
ADC

integer in → Voltage out

Digital to analog Converter
DAC

Digital to Analog Converters (DAC)

→ Begin with an "Op Amp" (operational amplifier) which will be the star of analog electronics



Op Amp Rules:

1) V_+ & V_- do not eat current

2) $V_+ \simeq V_-$ if operating correctly
[$V_{out} = 10^7 (V_+ - V_-)$ but with ±15v supplies $V_+ - V_-$ is limited to $\leq 1.5\,\mu V$]

Basic Circuit: $I = \frac{V_{in}}{R_1}$ as no where to go but continue

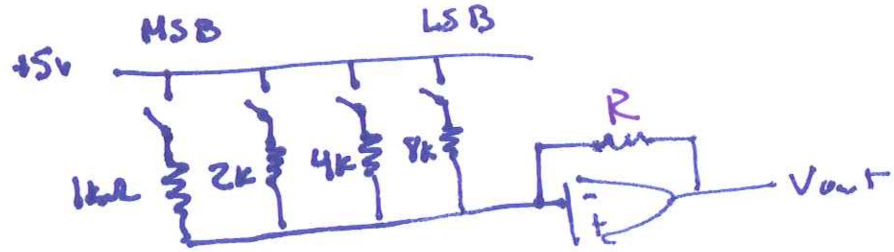
$V_{out} = -I R_2 = -\frac{R_2}{R_1} V_{in}$

$I = \frac{V_{in}}{R_1}$ virtual ground

Inverting amplifier

Q: what go from 10^7 amp to $\frac{R_2}{R_1}$?
A: wait for analog course.

Basic DAC circuit:



the (in this case) 4 bit binary number closes or opens switches to +5V. If closed the current $\frac{5V}{R}$ flows towards virtual ground and then around thru R producing $V_{out} = -R I_{total}$

$$I_{total} = \frac{5V}{1k\Omega}\left(D + \frac{1}{2}C + \frac{1}{4}B + \frac{1}{8}A\right)$$

Note: TTL controlled "switches" = CMOS transmission gate aka analog switch

Note2: Not perfect switch - few Ω resistance; may not be bipolar

Note3: This circuit has problems as precision resistors are expensive

Note: Example: CD audio is stereo (2 channels) of 16 bits @ 44.1 kHz
ie 64K → 15 ppm accurate resistor required

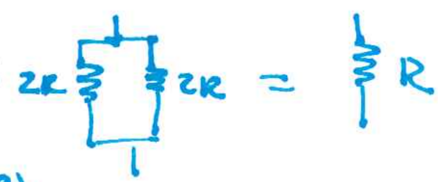
Tricky solution - use lots of resistors that are identical but not of any precise value.

R-2R ladder:

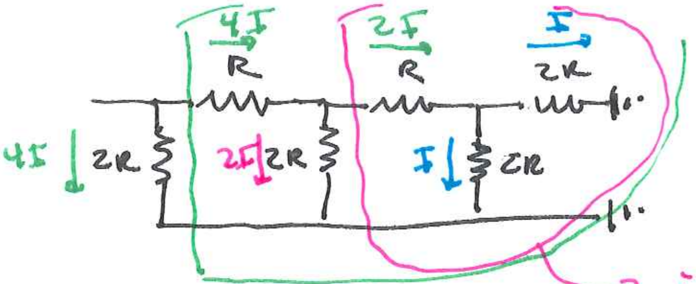
use:

2 1R resistors in series

starting point:



as $\frac{(2R)(2R)}{(2R)+(2R)} = R$



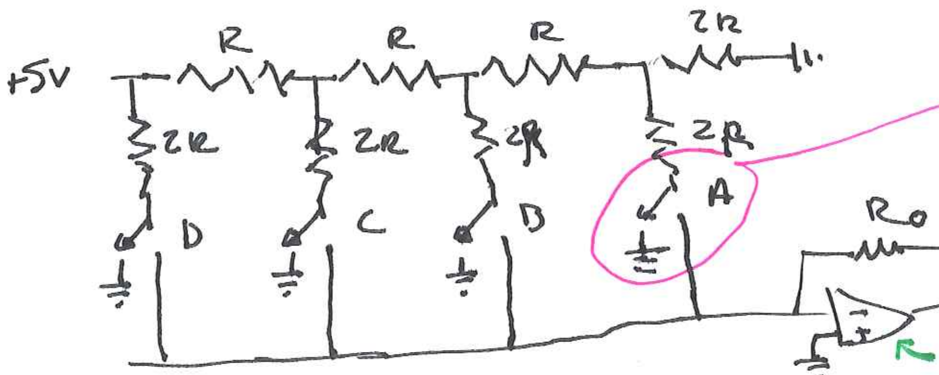
I: same volts same 2R ⇒ same current

2I: current in = current out

(pink loop) → is equivalent to 2R so 2I going right must mean 2I goes down

(green loop) → is equivalent to 2R so 4I going right must mean 4I goes down

Result: A system that produces currents exactly $2^N I$ from identical but not precise Rs. (Note: exact value of I will dependent on R, thus the proportional constant between (digital in) & (voltage out) is not accurately known, but the proportionality between (digital in) & (voltage out) should be accurate — ie Fit between (voltage out) & (digital in) should be accurately linear but the slope is only approximately set.

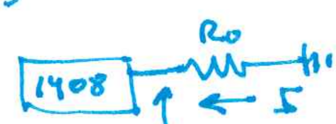


Analog switch direct current to ground or opAmp according to value of digit

← speed limited only by OpAmp

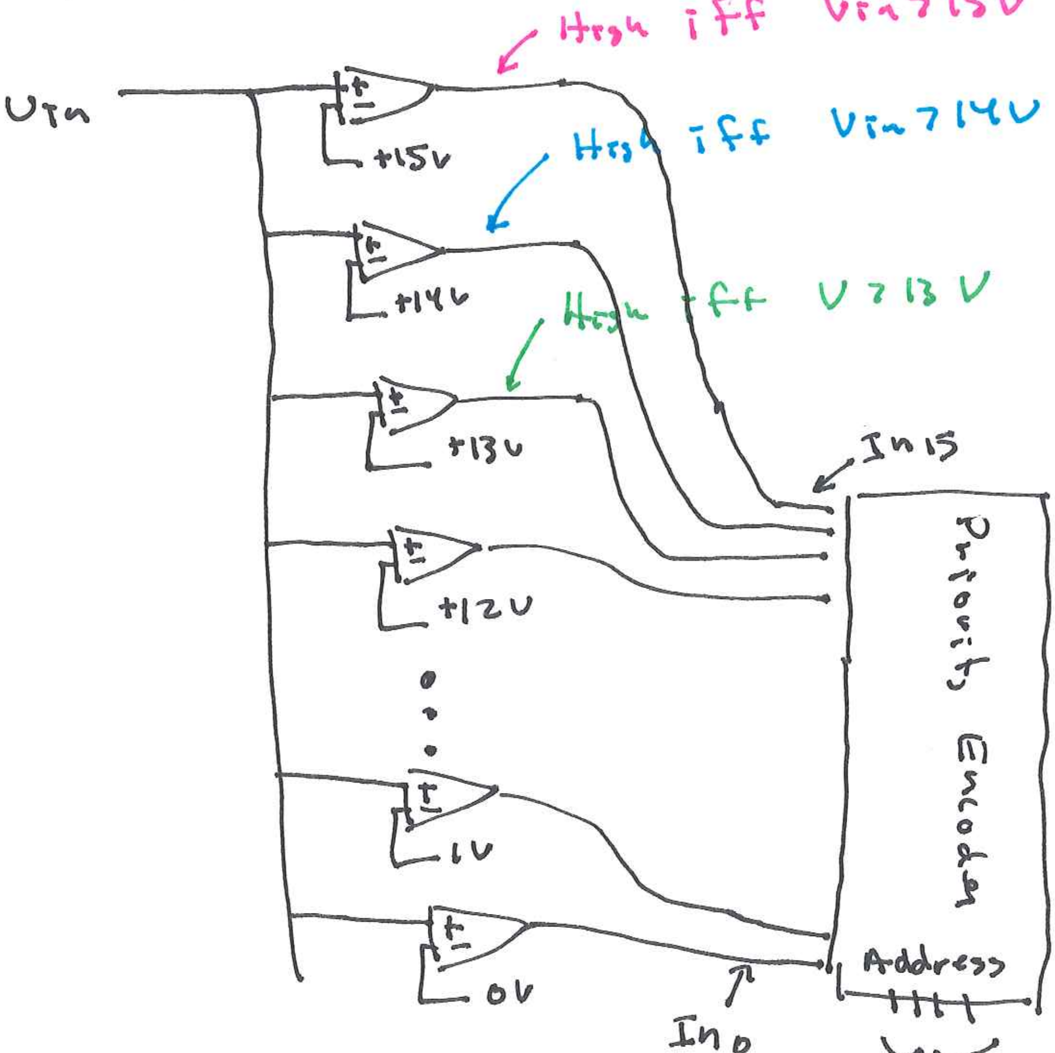
Note: Ro sets the overall scale of the output voltage and it is often an external component.

"Multiplying DAC" — 1408



$V_o = -IR_o$

Analog to Digital Conversion (ADC)

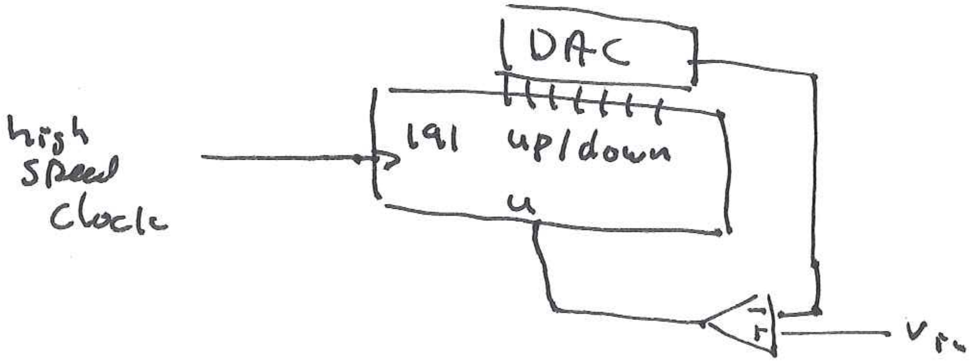


"Flash ADC" in Digital Scopes

→ another bit doubles the price.

output # of highest number In that is High

Slower but less expensive: use feedback & control



if the DACs output is below Vin, count up
if DACs output above Vin; count down
The value in the counter is the binary value of Vin

Successive Approximation ADC: Play 20 questions with Vin ... Is Vin more than $\frac{5V}{2}$? if yes MSB is 1, otherwise 0.

↳ is Vin more than $\frac{3}{4}$ 5V? if yes next bit also 1 otherwise

↳ is Vin more than $\frac{7}{8}$ 5V?

↳ is Vin more than $\frac{1}{4}$ 5V? if yes next bit is 1.

↳ is Vin more than $\frac{5}{8}$ 5V?

answer to each question gives next bit of approx digital value

Note: in below A is MSB; H is LSB

this controls clears & makes 1 bit in shift

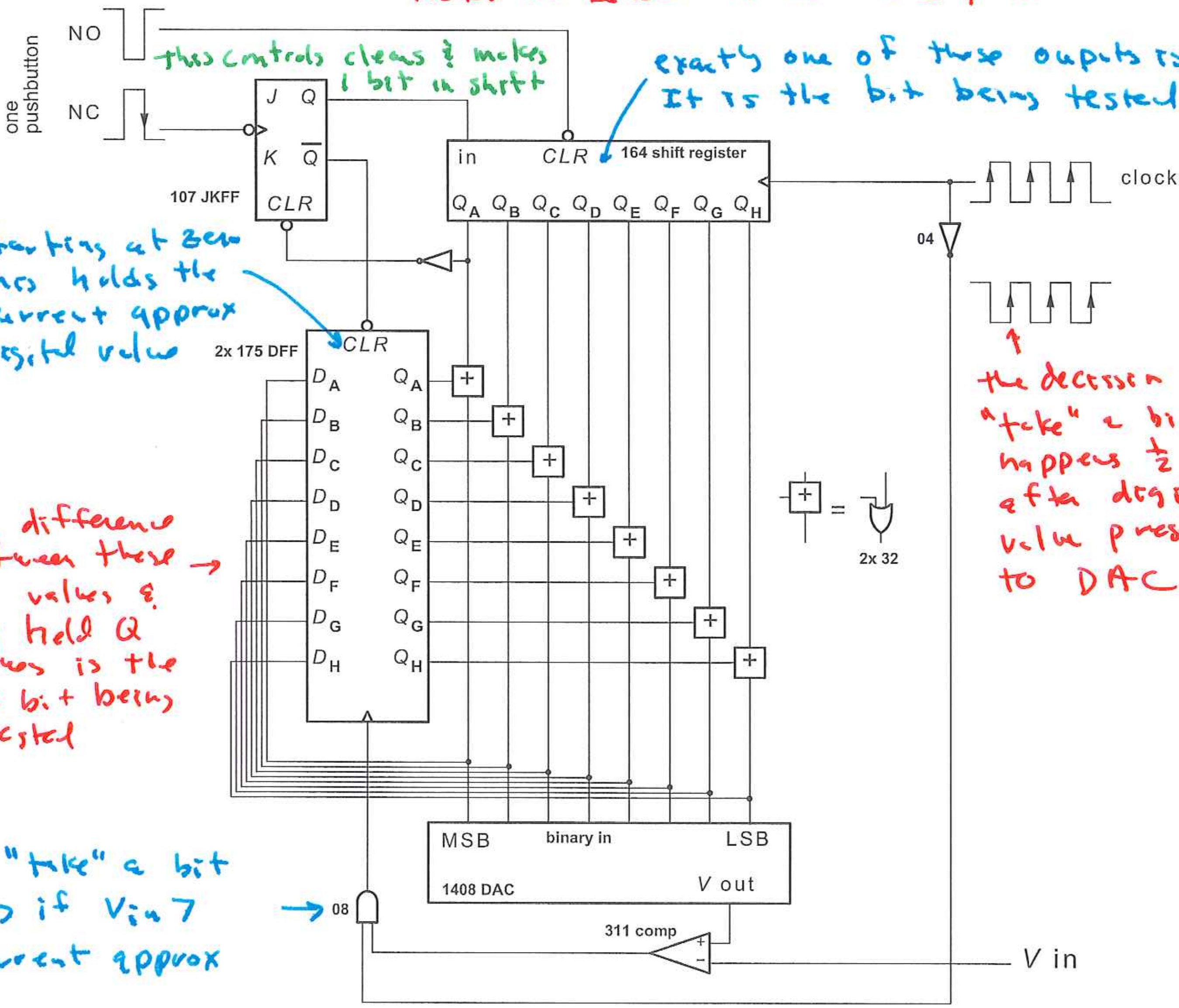
exactly one of these outputs is High. It is the bit being tested

starting at zero this holds the current approx digital value

the difference between these D values & the held Q values is the one bit being tested

the decision to "take" a bit happens ½ cycle after digital value presented to DAC

we "take" a bit only if Vin > current approx



Note: in actual circuit 1408 DAC produces a negative voltage output. If thinking of positive DAC outputs reverse +− on comparator