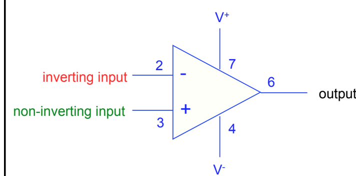
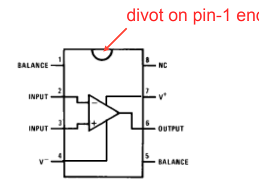
Operational Amplifiers

Magic Rules
Application Examples

Op-Amp Introduction

- Op-amps (amplifiers/buffers in general) are drawn as a triangle in a circuit schematic
- There are two inputs
  - inverting and non-inverting
- And one output
- Also power connections (note no explicit ground)





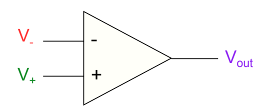
The ideal op-amp

- Infinite voltage gain
  - a voltage difference at the two inputs is magnified infinitely
  - in truth, something like 200,000
  - means difference between + terminal and - terminal is amplified by 200,000!
- Infinite input impedance
  - no current flows into inputs
  - in truth, about 10^{12} Ω for FET input op-amps
- Zero output impedance
  - rock-solid independent of load
  - roughly true up to current maximum (usually 5–25 mA)
- Infinitely fast (infinite bandwidth)
  - in truth, limited to few MHz range
  - slew rate limited to 0.5–20 V/μs

Op-amp without feedback

- The internal op-amp formula is:

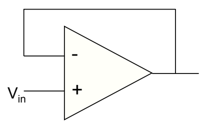
  $V_{out} = \text{gain} \times (V_+ - V_-)$
- So if V_+ is greater than V_-, the output goes positive
- If V_- is greater than V_+, the output goes negative



- A gain of 200,000 makes this device (as illustrated here) practically useless

Infinite Gain in negative feedback

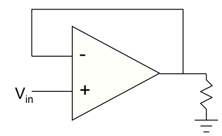
- Infinite gain would be useless except in the self-regulated negative feedback regime
  - negative feedback seems bad, and positive good—but in electronics positive feedback means runaway or oscillation, and negative feedback leads to stability
- Imagine hooking the output to the inverting terminal:
- If the output is less than V_{in}, it shoots positive
- If the output is greater than V_{in}, it shoots negative
  - result is that output quickly forces itself to be exactly V_{in}



negative feedback loop

Even under load

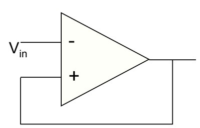
- Even if we load the output (which as pictured wants to drag the output to ground)…
  - the op-amp will do everything it can within its current limitations to drive the output until the inverting input reaches V_{in}
  - negative feedback makes it self-correcting
  - in this case, the op-amp drives (or pulls, if V_{in} is negative) a current through the load until the output equals V_{in}
  - so what we have here is a buffer: can apply V_{in} to a load without burdening the source of V_{in} with *any* current!



Important note: op-amp output terminal sources/sinks current at will: not like inputs that have no current flow

Positive feedback pathology

- In the configuration below, if the + input is even a smidge higher than V_{in}, the output goes way positive
- This makes the + terminal even *more* positive than V_{in}, making the situation worse
- This system will immediately “rail” at the supply voltage
  - could rail either direction, depending on initial offset

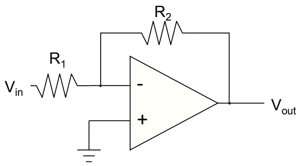


positive feedback: BAD

Op-Amp “Golden Rules”

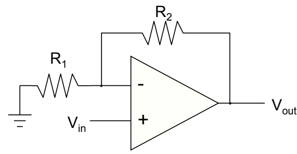
- When an op-amp is configured in *any* negative-feedback arrangement, it will obey the following two rules:
  - The inputs to the op-amp draw or source no current (true whether negative feedback or not)
  - The op-amp output will do whatever it can (within its limitations) to make the voltage difference between the two inputs zero

Inverting amplifier example



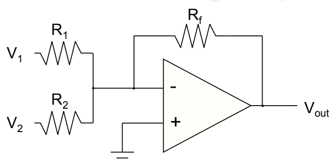
- Applying the rules: - terminal at "virtual ground"
  - so current through R_1 is $I_f = V_{in}/R_1$
- Current does not flow into op-amp (one of our rules)
  - so the current through R_1 must go through R_2
  - voltage drop across R_2 is then $I_f R_2 = V_{in} \times (R_2/R_1)$
- So $V_{out} = 0 - V_{in} \times (R_2/R_1) = -V_{in} \times (R_2/R_1)$
- Thus we amplify V_{in} by factor $-R_2/R_1$
  - negative sign earns title "inverting" amplifier
- Current is *drawn into* op-amp output terminal

Non-inverting Amplifier



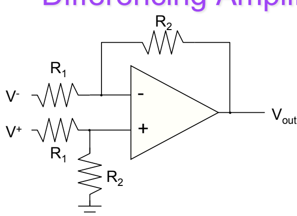
- Now neg. terminal held at V_{in}
  - so current through R_1 is $I_f = V_{in}/R_1$ (to left, into ground)
- This current cannot come from op-amp input
  - so comes through R_2 (delivered from op-amp output)
  - voltage drop across R_2 is $I_f R_2 = V_{in} \times (R_2/R_1)$
  - so that output is higher than neg. input terminal by $V_{in} \times (R_2/R_1)$
  - $V_{out} = V_{in} + V_{in} \times (R_2/R_1) = V_{in} \times (1 + R_2/R_1)$
  - thus gain is $(1 + R_2/R_1)$, and is positive
- Current is sourced from op-amp output in this example

Summing Amplifier



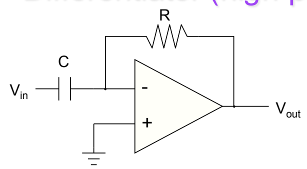
- Much like the inverting amplifier, but with two input voltages
  - inverting input still held at virtual ground
  - I_1 and I_2 are added together to run through R_f
  - so we get the (inverted) sum: $V_{out} = -R_f \times (V_1/R_1 + V_2/R_2)$
    - if $R_2 = R_1$, we get a sum proportional to $(V_1 + V_2)$
- Can have any number of summing inputs
  - we'll make our D/A converter this way

Differencing Amplifier



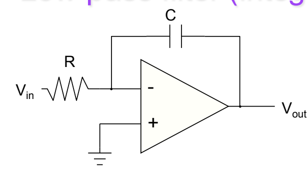
- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^+ R_2/(R_1 + R_2)$
- So $I_f = (V^- - V_{node})/R_1$
  - $V_{out} = V_{node} - I_f R_2 = V^+(1 + R_2/R_1)(R_2/(R_1 + R_2)) - V^-(R_2/R_1)$
  - so $V_{out} = (R_2/R_1)(V^+ - V^-)$
  - therefore we difference V^+ and V^-

Differentiator (high-pass)



- For a capacitor, $Q = CV$, so $I_{cap} = dQ/dt = C \cdot dV/dt$
  - Thus $V_{out} = -I_{cap}R = -RC \cdot dV/dt$
- So we have a differentiator, or high-pass filter
  - if signal is $V_0 \sin\omega t$, $V_{out} = -V_0 RC\omega \cos\omega t$
  - the ω-dependence means higher frequencies amplified more

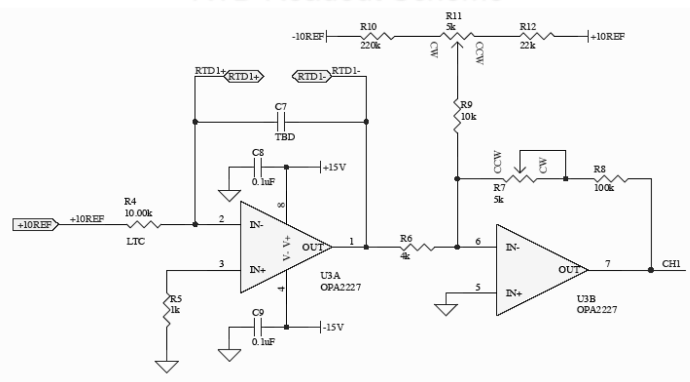
Low-pass filter (integrator)



- $I_f = V_{in}/R$, so $C \cdot dV_{cap}/dt = V_{in}/R$
  - and since left side of capacitor is at virtual ground:

    $-dV_{out}/dt = V_{in}/RC$
  - so $V_{out} = -\frac{1}{RC}\int V_{in}dt$
  - and therefore we have an integrator (low pass)

RTD Readout Scheme

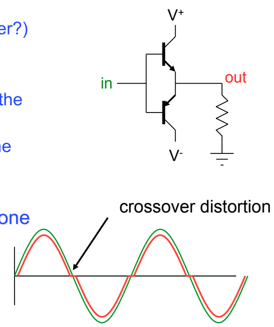


Notes on RTD readout

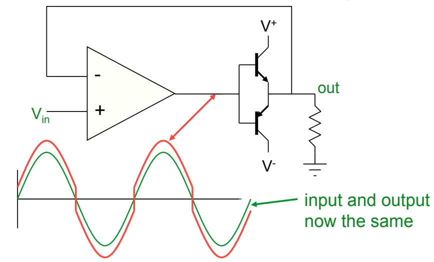
- RTD has resistance R = 1000 + 3.85×T(°C)
- Goal: put 1.00 mA across RTD and present output voltage proportional to temperature: $V_{out} = V_0 + \alpha T$
- First stage:
  - put precision 10.00 V reference across precision 10kΩ resistor to make 1.00 mA, sending across RTD
  - output is -1 V at 0°C; -1.385 V at 100°C
- Second stage:
  - resistor network produces 0.25 mA of source through R9
  - R6 slurps 0.25 mA when stage 1 output is -1 V
    - so no current through feedback → output is zero volts
  - At 100°C, R6 slurps 0.346 mA, leaving net 0.096 that must come through feedback
  - If R7 + R8 = 10389 ohms, output is 1.0 V at 100°C
- Tuning resistors R11, R7 allows control over offset and gain, respectively: this config set up for $V_{out} = 0.01T$

Hiding Distortion

- Consider the "push-pull" transistor arrangement to the right
  - an npn transistor (top) and a pnp (bot)
  - wimpy input can drive big load (speaker?)
  - base-emitter voltage differs by 0.6V in each transistor (emitter has arrow)
  - input has to be higher than ~0.6 V for the npn to become active
  - input has to be lower than -0.6 V for the pnp to be active
- There is a no-man's land in between where neither transistor conducts, so one would get "crossover distortion"
  - output is zero while input signal is between -0.6 and 0.6 V

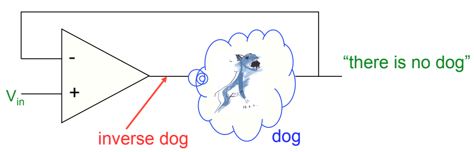


Stick it in the feedback loop!



- By sticking the push-pull into an op-amp's feedback loop, we guarantee that the output faithfully follows the input!
  - after all, the golden rule demands that + input = - input
- Op-amp jerks up to 0.6 and down to -0.6 at the crossover
  - it's almost magic: it figures out the vagaries/nonlinearities of the thing in the loop
- Now get advantages of push-pull drive capability, without the mess

Dogs in the Feedback



- The op-amp is obligated to contrive the inverse dog so that the ultimate output may be as tidy as the input.
- Lesson: you can hide nasty nonlinearities in the feedback loop and the op-amp will "do the right thing"

We owe thanks to Hayes & Horowitz, p. 173 of the student manual companion to the *Art of Electronics* for this priceless metaphor.

Reading

- Read 6.4.2, 6.4.3
- Pay special attention to Figure 6.66 (6.59 in 3rd ed.)