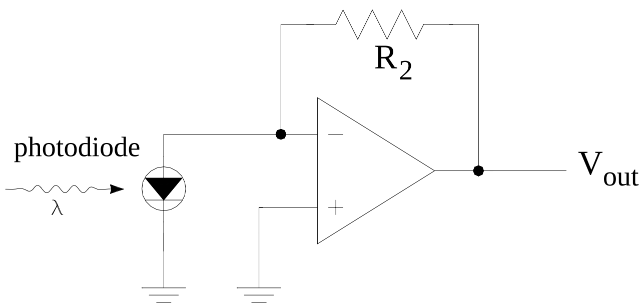
TRANSIMPEDANCE AMPLIFIER

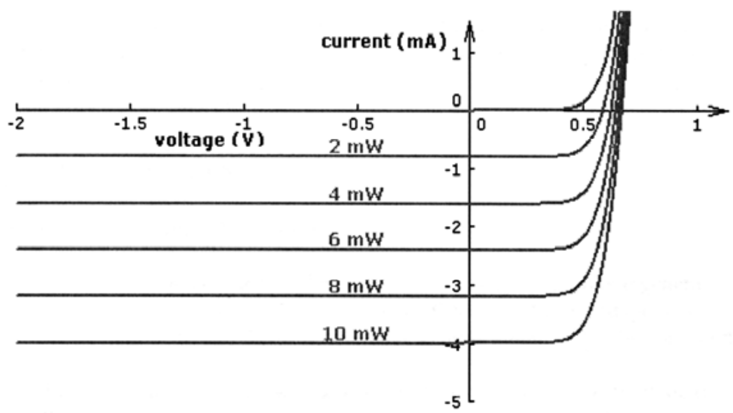
Optical photodiode detectors and optical photoconductive detectors are current sources, with the current produced being proportional to the light intensity illuminating them.

As a result, they are ideally suited to a transimpedance amplifier (TIA) configuration. In particular, we simply let the photodetector replace the input resistor R_1:



In this configuration, the photodiode generates the input current directly. Since the – input is at ground potential here ($V_{-} = 0$), the TIA's input impedance is nearly zero, which is exactly what is needed if we want to capture the maximum current from the photodiode.

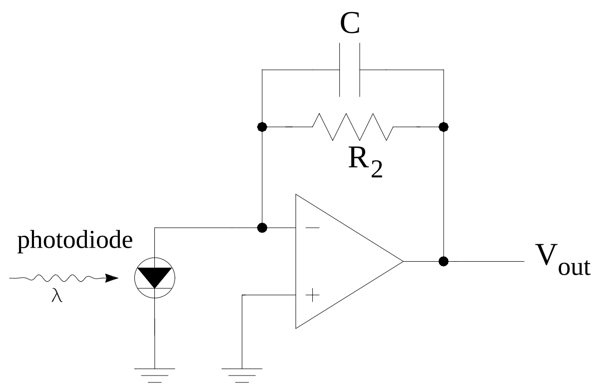
Notice also that we are operating the photodiode at points along the $V_D = 0$ axis of the photodiode's I-V curve, which means that the photodiode is operating in its linear region, just as it does when operating with a reverse bias.



In fact, instead of connecting the photodiode cathode to ground, it is often connected to a positive voltage, which reverse biases the diode and provides higher speed response by lowering the photodiode's capacitance.

Transimpedance amplifiers are given their name because they translate the output from a very high impedance current source (note the slope of the I-V curve above) to a low impedance op amp output.

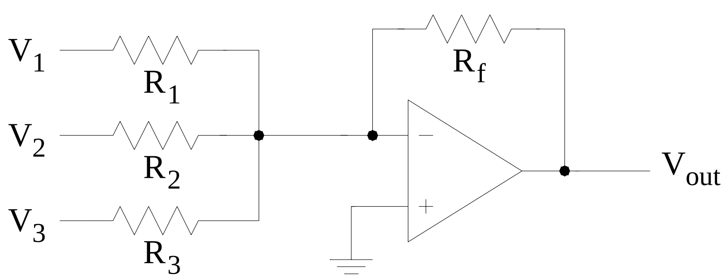
Transimpedance amplifiers are usually operated at very high gain. This produces a strong tendency for the amplifier to go into oscillation at some high frequency above the gain bandwidth cutoff. This problem can be eliminated by adding a small capacitor in the feedback loop, which lowers the gain at very high frequencies.



The drawback of operating any op amp with very high gain is that its frequency response is greatly reduced because an op amps gain and bandwidth are inversely proportional to each other, a characteristic that will be discussed in detail later.

SUMMING AMPLIFIER

If we have two or more input signals that we want to add together, we can make good use of the fact that the V_- input is a virtual ground. We just tie the signals together at the V_- input.

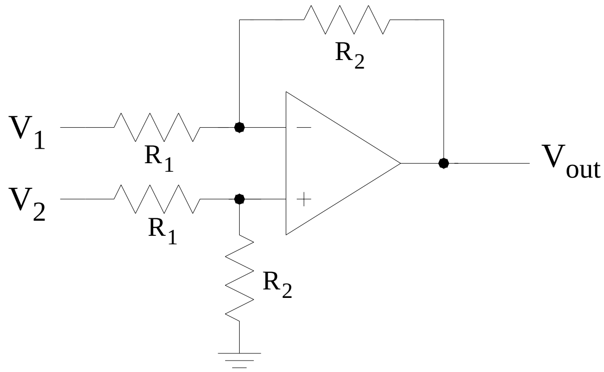


In this arrangement, each signal thinks it's looking at a grounded input, and the other signals have no effect on it. However, the currents from the inputs all add together and flow through the feedback resistor to produce an output voltage that is just

$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

DIFFERENTIAL AMPLIFIER

If we need to amplify a differential voltage, it can easily be done by using both the V_+ and V_- inputs.



Because the input-output relationships for signals at the two terminals are linear, we can analyze this circuit by superposition.

First, turn off V_2 (i.e., short V_2 to ground). Then the V_+ input will be at ground, and the circuit looks just like the standard inverting op-amp with a output signal

$$V_{out}(V_2 \text{ off}) = -\frac{R_2}{R_1} V_1$$

Next, turn off V_1 by shorting it to ground. The feedback circuit at the V_- input then becomes that for a noninverting op-amp, whose output signal is given by

$$V_{out}(V_1 \text{ off}) = \left(\frac{R_1 + R_2}{R_1}\right) V_+$$

But the signal at V_+ is just V_2 reduced by the $R_1 : R_2$ voltage divider,

$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

so

$$V_{out}(V_1 \text{ off}) = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_2}{R_1 + R_2}\right) V_2 = \frac{R_2}{R_1} V_2$$

Adding the two results for V_{out} with V_1 turned off and for V_{out} with V_2 turned off, we obtain the simple result

$$V_{out} = V_{out}(V_1 \text{ off}) + V_{out}(V_2 \text{ off}) = \frac{R_2}{R_1}(V_2 - V_1)$$

which is just the output one would like from a differential amplifier.

The primary reason for using a differential amplifier is to have an amplifier that is immune from the effects of common-mode signals or noise, i.e., voltages that appear at both the V_1 and the V_2 signals. One common source of common-mode noise is pick-up of a 60 Hz power line radiation by the wire leads coming from some sensor.

The common mode voltage is defined to be ½ ($V_1 + V_2$). When a common mode voltage is present, the actual output voltage of a differential amplifier is given by

$$V_{out} = A_{diff}(V_2 - V_1) + \frac{1}{2}A_{com}(V_2 + V_1)$$

where A_{diff} is the differential mode gain, and A_{com} is the common mode gain. To remove the unwanted common-mode signals we want the amplifier to amplify only the *difference* between the voltages V_1 and V_2 and nothing else. The key parameter for a differential amplifier that quantifies how well an amplifier does this is its *common mode rejection ratio* (CMRR), which is defined to be the ratio of the differential-mode gain to the common-mode gain, expressed in decibels. Thus we have

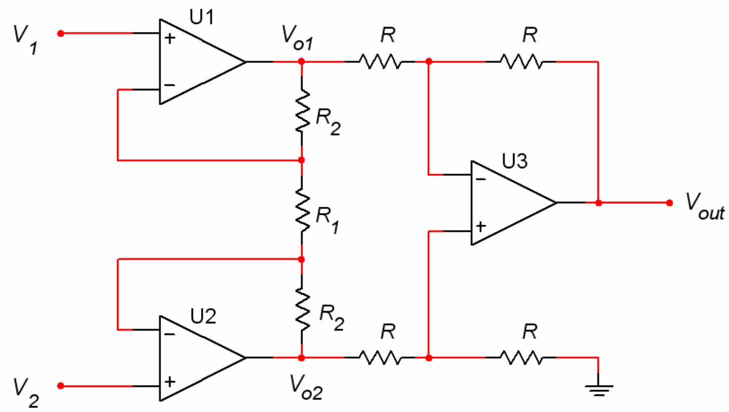
$$CMRR = 20\log\left(\frac{A_{diff}}{A_{com}}\right) = 20\log\left(\frac{\frac{1}{2}(V_2 + V_1)}{V_2 - V_1}\right)$$

This differential amplifier is less than ideal because it relies on having a perfectly matched pair of resistors R_1 and a matched pair of resistors R_2. Any mismatch will create an amplifier that has both common mode gain and differential mode gain, greatly reducing the common-mode rejection ratio. When a precision differential amplifier is needed, a better choice is to turn to a device called an instrumentation amplifier.

INSTRUMENTATION AMPLIFIER

An *instrumentation amplifier* is an op-amp circuit that has a high gain differential input and a high common mode rejection ration (CMRR), along with high input impedance and a single-ended output. A single garden variety op-amp can't provide all of these features at once, but it can be done by using more than one op-amp and the appropriate circuit.

Here is the classic three op-amp instrumentation amplifier design:



To see how this circuit works, note that the two input op-amps are each wired up as noninverting op-amps, except that the resistor R_1 is shared between them.

If we imagine that resistor R_1 is divided into two equal pieces and input signals V_1 and V_2 are applied to the inputs, the circuit's symmetry tells us that the center point of R_1 will be at ground, and we can then treat the U1 and U2 op-amp circuits separately.

Both op-amps have a voltage divider feedback circuit consisting of R_2 and ½ R_1, so their output voltages are given by

$$V_{o1} = \frac{\frac{1}{2}R_1 + R_2}{\frac{1}{2}R_1}V_1 \qquad\qquad V_{o2} = \frac{\frac{1}{2}R_1 + R_2}{\frac{1}{2}R_1}V_2$$

The third op-amp, U3, is wired up as a standard differential op-amp circuit with unity gain, and hence the output signal from op-amp U3 is

$$V_{out} = V_{o2} - V_{o1} = \left(1 + \frac{2R_2}{R_1}\right)(V_2 - V_1)$$

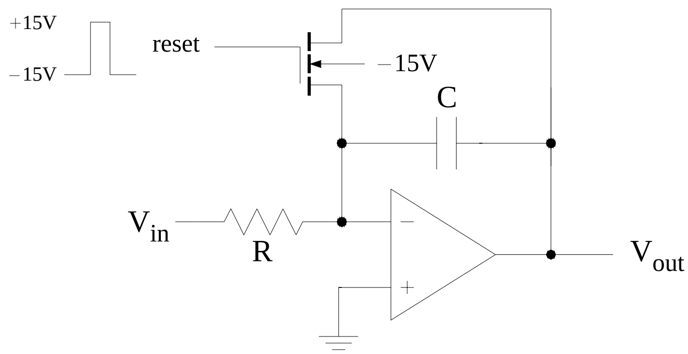
On the other hand, the circuit symmetry will cause a common mode signal to experience zero gain if the resistors R and the resistors R_2 are perfectly matched.

The advantage of an instrumentation amplifier over a single differential op-amp circuit is that the overall CMRR is the product of the CMRR of the U1 + U2 first stage and the CMRR of the final op-amp, U3. A high input impedance can also be provided by using FET op-amps for U1 and U2. In addition, the overall gain of the circuit can easily be changed by simply changing the value of the resistor R_1.

In practice, when an instrumentation op-amp is needed, you can buy specialized op-amp circuits that put this design (or something similar) into a single integrated circuit. Laser trimming then allows very good matching of the resistors to be obtained.

INTEGRATOR

Replacing the resistor in an inverting op-amp circuit with a capacitor results in a circuit that will integrate the total charge entering the circuit from V_{in}.



For the moment, ignore the MOSFET transistor, which in normal operation will be turned off and behaves like an open circuit.

Since the V_{-} input is a virtual ground, we must have $I_R = I_C$, and hence, using the I–V relationship for a capacitor, we have

$$\frac{V_{in}}{R} = C\frac{dV_{out}}{dt}$$

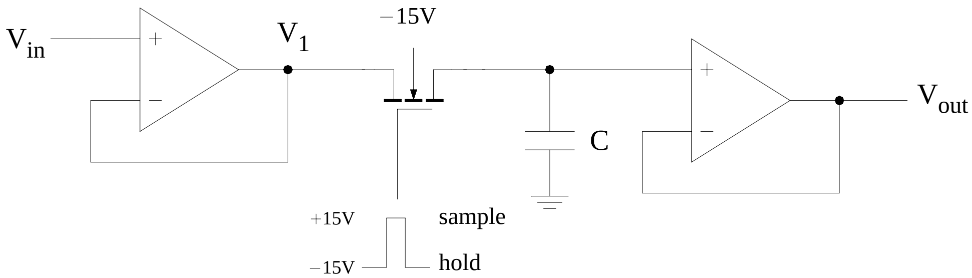
If $V_{\text{out}} = 0$ at $t = 0$, we can integrate this to obtain $V_{out} = \dfrac{1}{RC}\int_0^T V_{in}\,dt$

So, as advertised, the output is the integral of the input.

A positive pulse applied to the MOSFET will turn it on and short out the capacitor, thus setting $V_{\text{out}} = 0$. Note that we need to have a body lead that can be set to the negative power supply rail to ensure that the MOSFET remains turned off regardless of the voltage at V_{out} .

SAMPLE AND HOLD

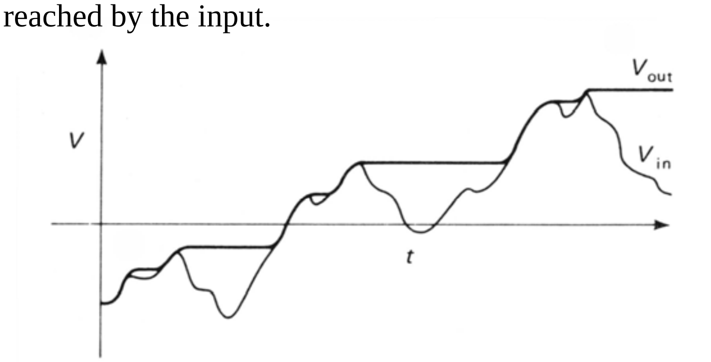
Another very useful device is a *sample and hold* (S/H) *amplifier*. The purpose of a S/H amplifier is to sample the voltage of a time-varying input waveform and hold that voltage value as a constant output voltage for use by some other circuit (an analog-to-digital converter, for example).



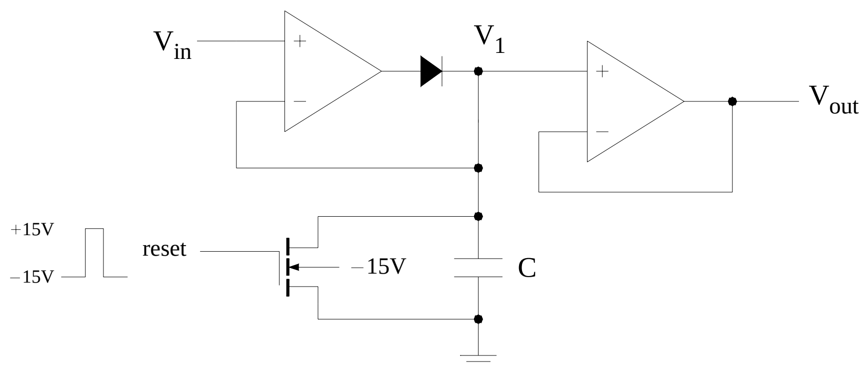
The first source follower provides a low impedance output that provide a substantial output current while still maintaining $V_1 = V_{in}$. When a +15V pulse is applied to the MOSFET, it acts like a short circuit, allowing the op-amp output to charge the capacitor to the voltage V_{in} while the pulse is on. The second source follower needs to have an FET input so that it can sense the voltage on the capacitor without discharging it by drawing current from it.

PEAK DETECTOR

Another circuit that is often useful is a peak detector that provides an output voltage equal to the highest voltage reached by the input.



An op-amp circuit that does this is shown below:



The second op-amp here is a source follower that simply reproduces the output voltage V_1 from the first op-amp (which is just the voltage appearing on the capacitor), without drawing an appreciable current from it.

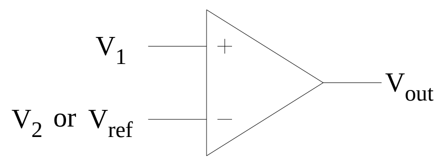
Immediately after a reset pulse the capacitor will be uncharged. The feedback loop tries to force $V_1 = V_{in}$, and, as long as the voltage is rising, it will succeed in doing this.

However, if the input voltage falls, the voltage at the op-amp's output terminal falls also. But the diode blocks the feedback loop voltage from following the output terminal, so the op-amp then behaves as if the feedback loop has been broken. The result is that for falling voltages, the op-amp's ouput terminal swings as far negative as it can go (to the negative power supply rail), but V_1 remains constant.

COMPARATOR

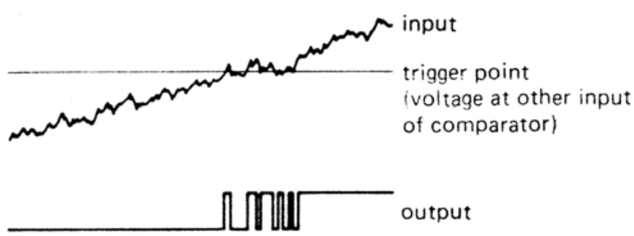
The function of a *comparator* is to generate a high voltage (typically near the positive power supply rail) if the voltage at its V_+ input is greater than at its V_- input, or a low voltage (typically near the negative power supply rail) if $V_+ < V_-$.

Clearly, an op-amp with no feedback will do just that since it's a very high gain differential amplifier. If its gain is 10^4, a voltage difference of about 1.5 mV between its inputs will produce a full scale output.

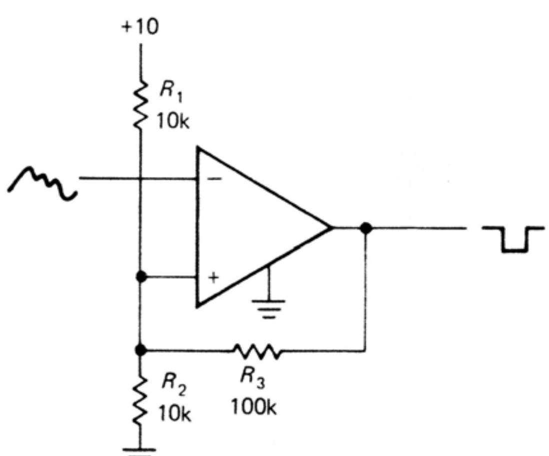


The comparator can be used to compare either two input signal voltages or to compare a single input with respect to a reference voltage connected to the other output.

A noisy and/or very slowly varying input signal can cause problems when the two input voltages are almost exactly equal. Specifically, the output can switch back and forth between the two output states, and this is usually very undesirable.



This problem can be cured by adding *positive feedback* as illustrated in the circuit below.



The op-amp here uses a single +10V power supply and R_1 and R_2 bias the V_+ input so that the nominal threshold for a transition from one output state to the other is +5V. However, positive feedback via R_3 changes this threshold by sending a portion of the inverted output back to the V_+ input.

Quantitatively, if $V_- > V_+$ the output voltage is low (0V), so the voltage at the V_+ input is

$$V_+ = \left(\frac{R_2 \parallel R_3}{R_1 + R_2 \parallel R_3} \right) V_{CC} = 4.76V$$

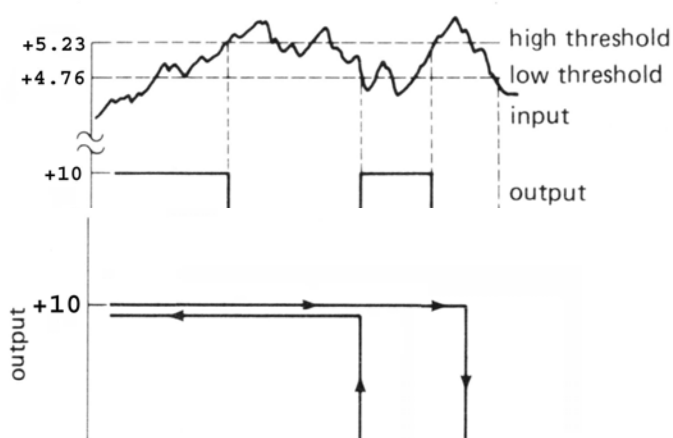
This means that, if initially $V_- > V_+$, and the V_- input then falls to 4.76 V, the output will flip from low to high.

On the other hand, if $V_- < V_+$ the output voltage is high (+10V), so the voltage at the V_+ input is

$$V_+ = \left(\frac{R_2}{R_2 + R_1 \parallel R_3} \right) V_{CC} = 5.23V$$

This means that, if initially $V_- < V_+$, and the V_- input then rises to 5.23 V, the output will flip from high to low.

What the positive feedback has done is to introduce *hysteresis* into the comparator's threshold voltage. The threshold is 5.23 V for rising input voltages and 4.76 V for falling input voltages:



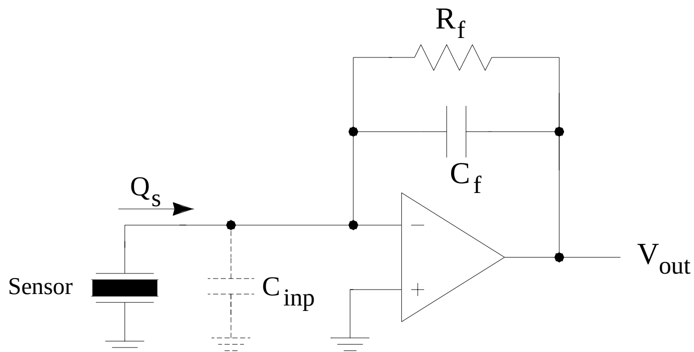
This type of input circuit is called a *Schmitt trigger* input.

In practice, general purpose op-amps are not often used as comparators. Instead, special purpose op-amps designed and sold as comparators are available which offer a number of useful built-in features such as very fast switching times, controllable hysteresis, a selectable internal voltage reference, and adjustable high and low output voltage levels.

CHARGE AMPLIFIER

Sensors (or transducers) such as microphones, piezoelectric pressure, force, and acceleration sensors, semiconductor gamma ray detectors, and pyroelectric infrared detectors, all behave like capacitors whose charge varies when they receive a time varying signal.

For these types of devices we need an amplifier that converts small changes in the charge on a capacitor into a voltage. A circuit that does this is called a *charge amplifier*.



The sensor generates a tiny charge Q_S in response to a change in pressure (for a piezoelectric sensor) or in temperature (for a ferroelectric sensor). Because this charge is so small, we need to take into account the stray capacitance C_{inp} of the op-amp's input transistor and of the cable or wiring connecting the sensor to the op-amp when analyzing the circuit.

This is just a transimpedance amplifier configuration, but here the feedback capacitor is larger and determines the impedance of the feedback loop rather than the (large) resistor.

To do the analysis, we use the charge analog of KCL, i.e., the sum of all charges entering and leaving a circuit node must be zero. Since no current enters or leaves the op-amp V_- input, we have

$$Q_S - Q_{inp} - Q_f = 0$$

and since, by definition, $Q = CV$,

$$Q_S = C_{inp} V_{inp} + C_f (V_{inp} - V_{out})$$

But $V_{inp} = V_- = 0$ because V_+ is grounded, so

$$Q_S = -C_f V_{out}$$

or

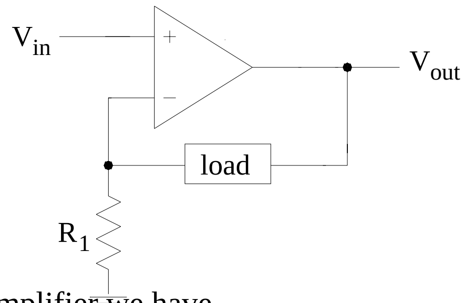
$$V_{out} = -\frac{Q_S}{C_f}$$

Thus we have a circuit that converts a charge into a voltage, and, importantly, the op-amp feedback eliminates any effect of the stray cable and input capacitance from the output signal.

VOLTAGE-TO-CURRENT AMPLIFIERS

So far, we've only discussed op-amp circuits that produce output voltages from either an input voltage or an input current, but sometimes we want to produce an output current from an input voltage.

This can be accomplished quite simply by putting the load into the feedback loop. For example, if the load is put into the feedback loop of a noninverting op-amp circuit, we have



For a noninverting amplifier we have

$$V_{out} = \left(\frac{R_1 + R_L}{R_1} \right) V_{in}$$

and the current through the load is

$$I_{load} = \frac{V_{out}}{R_1 + R_L}$$

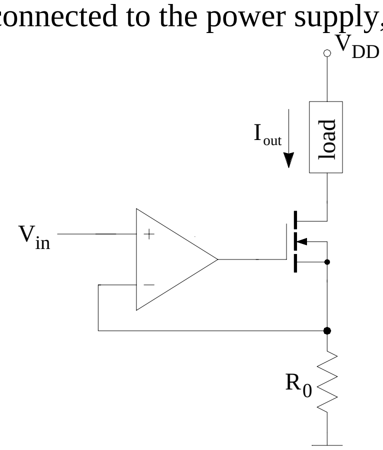
Hence

$$I_{load} = \frac{1}{R_1} V_{in}$$

The major drawback of this circuit is the fact that the load is floating with respect to ground (one side is at V_{in}, the other side is at V_{out}), but this is seldom what is needed.

Typically one side of the load must either be grounded or be connected to the power supply voltage, and the best circuit solution in this case is to add some external circuitry.

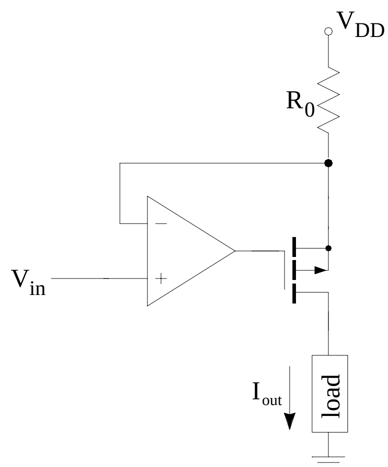
If one side of the load is connected to the power supply, one possible circuit is



The n-channel MOSFET is turned on when the gate voltage is positive with respect to the source, and the feedback circuit forces the voltage at V_- to be $I_{\text{load}} R_0$. Since $V_{\text{in}} = V_+ = V_-$, we must also have

$$I_{load} = \frac{1}{R_0} V_{in}$$

If one side of the load must be connected to ground, we could use:



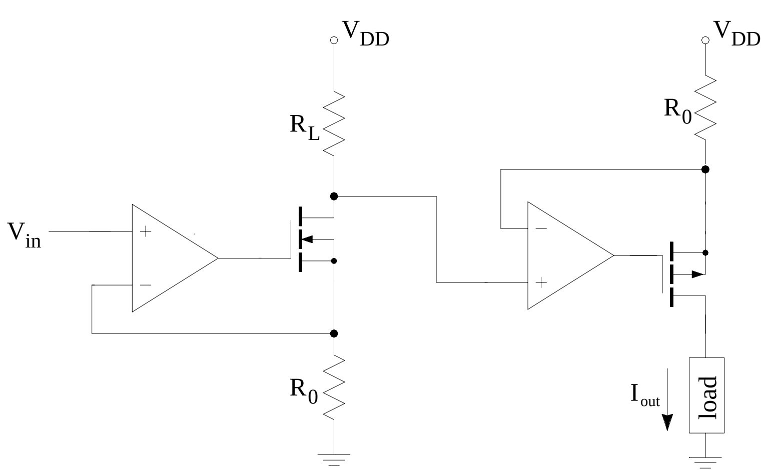
Here we have the op-amp output drive a p-channel MOSFET, which turns on when the gate voltage is set to be more negative than the source. The feedback circuit forces the voltage at V_- to be $V_{\text{DD}} - I_{\text{load}} R_0$ and since $V_+ = V_-$, we must also have

$$V_{in} = V_{DD} - I_{load} R_0$$

or

$$I_{load} = \frac{1}{R_0}(V_{DD} - V_{in})$$

This circuit has the drawback that the input voltage is referenced to V_{DD} rather than ground (the input signal is $V_{\text{DD}} - V_{\text{in}}$), but this can be remedied by adding the op-amp circuit on the previous slide to the circuit above so that the first op-amp circuit drives the second one.



The voltage at the low side of R_L is $V_{DD} - [(1/R_0)V_{in}]R_L$. This is the input signal V_{in} for the second op-amp. Putting this expression into the input voltage–output current relationship we found for the second circuit, we have

$$I_{load} = \frac{1}{R_0}(V_{DD} - V_{DD} + [(1/R_0)V_{in}]R_L)$$

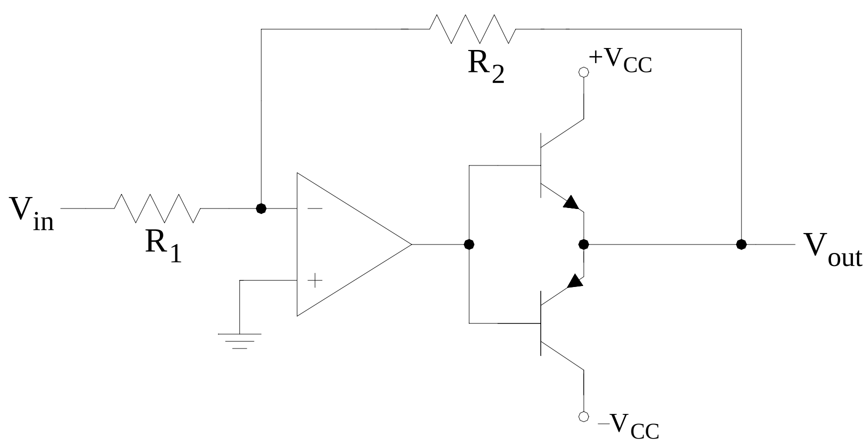
which reduces to

$$I_{load} = \frac{R_L}{R_0^2}V_{in}$$

giving us the input–output relationship we want.

Because op-amps are so cheap and readily available, it's common practice to add one or more op-amps to a circuit when a single op-amp can't give us what we need.

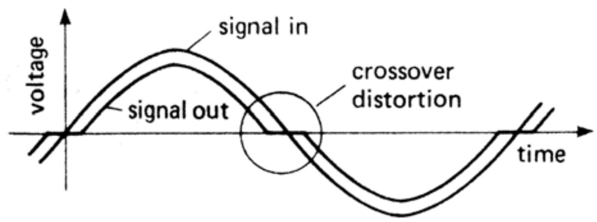
Using external transistors in the feedback loop is also useful when we need more output power than a given op-amp can provide.



Here we've added a push-pull amplifier stage to the output. Here neither transistor conducts when no input signal is present, but the upper transistor amplifies positive-going signals, while the lower transistor amplifies negative-going signals**.**

When used as a stand-alone power amplifier, this simple stacked transistor arrangement doesn't perform very well when the output voltage is less than ±0.7 V, because in that signal range, neither transistor conducts, and the output signal will be nearly zero.

With a sinusoidal input signal, the resulting amplifier output will exhibit *crossover distortion*.



However, putting the transistors in the feedback loop causes the op-amp to largely remove this distortion and maintain the relationship

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

for all input signal voltages.

Op-amps can also be used to make a huge variety of other circuits, including active rectifiers, signal clippers, logarithmic amplifiers, square root amplifiers, differentiators, and many others.