

The operational amplifier

Up to now, we have been primarily concerned with digital devices — devices having two states only.

Now we will talk about some ways in which a (continuous) electrical signal can be modified, or operated upon.

We will primarily consider a single device, called an operational amplifier, or *op amp*.

We will discuss mainly *ideal* op amps, occasionally noting where the fact that a circuit must be implemented with non-ideal devices may cause some problems.

An operational amplifier is a device with 2 input terminals and one output terminal (of course, it also has terminals for power, usually requiring both a positive and negative power supply, and ground), in which the voltage V_0 between the output terminal and ground is related to the voltage difference between the two input terminals, designated as $+$ and $-$, whose voltages are V_+ and V_- respectively, relative to ground, by the equation

$$V_0 = A(V_+ - V_-)$$

where A is the amplification (often called the open loop amplification) for the op amp. For an ideal op amp, A is infinite.

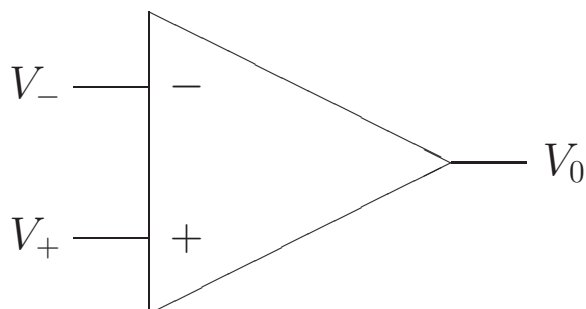
The $+$ input is usually called the non-inverting input, and the $-$ input is called the inverting input.

(Note that when $V_+ = 0$, then $V_0 = -AV_-$).

The op amp is called a *linear* device, because the output voltage is linearly related to the input voltage.

Ideal op amps require zero input current for V_+ and V_- .

The circuit symbol for an op amp is shown here:



Op amps are currently available as a single integrated circuit (abbreviated IC) package, with up to 4 op amps to a single IC, and cost approximately the same as simple digital logic devices.

In practice, the output of an op amp cannot exceed the voltage of its power supply; typically 5–30V.

Since the difference between the inputs can be either positive or negative, op amps typically have both positive and negative power supplies.

In special cases, we can use certain op amps with a single (positive) voltage supply.

Clearly, an op amp is seldom used as an amplifier, directly, because of its nearly infinite gain. About the only direct application would be as an analog comparator.

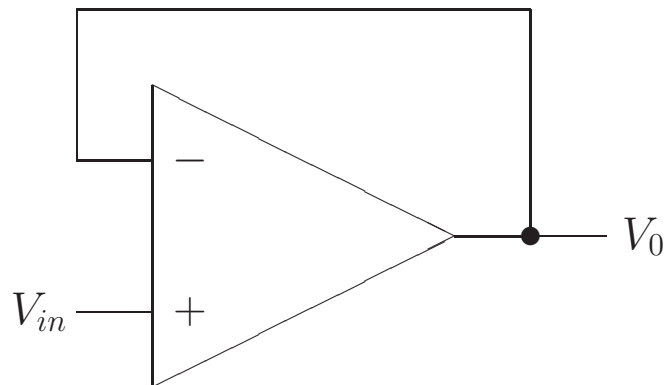
Feedback in an op amp

Typically, “feedback” is used to accurately control (reduce) the amplification, called the gain, of the op amp, and to give it other desirable features as well.

Perhaps the simplest example of feedback is shown in the following circuit, called a “voltage follower.”

Here, if $A \rightarrow \infty$, $V_{out} = V_+$.

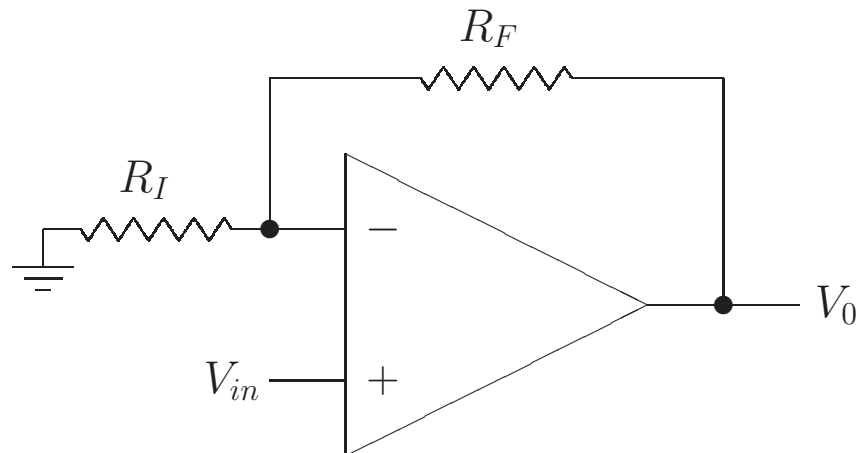
This is an example of a “non-inverting amplifier” — the output has the same sign as the input.



$$\begin{aligned} V_0 &= A(V_+ - V_-) \\ \text{but } V_- &= V_0, \text{ so } V_0 &= A(V_+ - V_0) \\ V_0 &= \frac{A}{1 + A} V_+ \\ &= V_+ \quad \text{if } A \rightarrow \infty \end{aligned}$$

This is really a specific example of the more general “non-inverting amplifier” shown in the next figure.

The non-inverting amplifier



here $V_0 = A(V_+ - V_-)$

and $V_- = \frac{R_I}{R_I + R_F} V_0$

so $V_0 = \frac{A}{1 + A(R_I/(R_I + R_F))} V_{in}$

if $A \rightarrow \infty$, $V_0 = \frac{R_I + R_F}{R_I} V_{in}$

$$= (1 + R_F/R_I) V_{in}$$

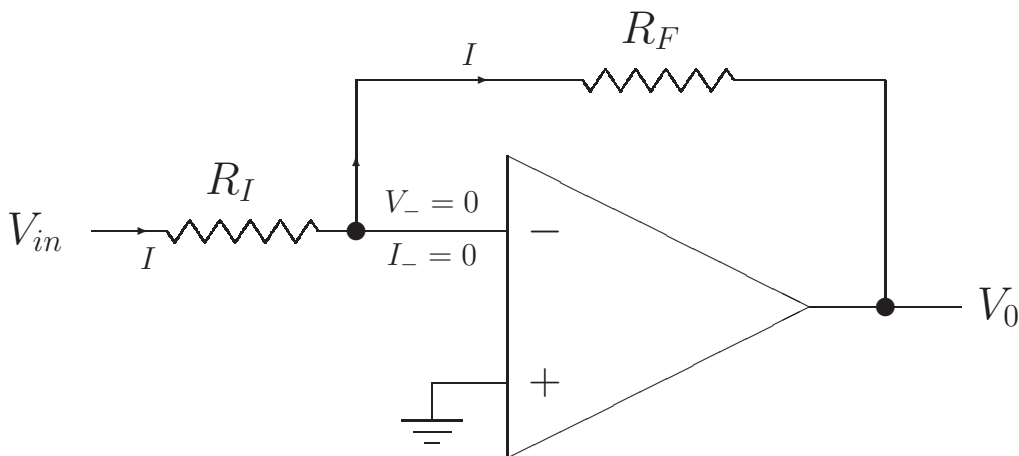
which is independent of A — the resistors in the feedback path determine the gain of the amplifier circuit.

We can have any gain we wish, simply by choosing appropriate values of R_F and R_I .

The inverting amplifier

The following diagram shows a second feedback configuration for an op amp called the “inverting amplifier.”

[Note that in this amplifier the non-inverting (+) input is grounded. This is for convenience in discussion only, and is not required.]



Here, since no current flows into the inverting input; i.e., $I_- = 0$, then the same current, I , must flow through both R_I and R_F . Therefore:

$$I = \frac{V_{in} - V_-}{R_I} = \frac{V_- - V_0}{R_F} \quad (\text{by Ohm's law})$$

$$V_- - V_0 = \frac{R_F}{R_I}(V_{in} - V_-)$$

$$\text{but} \quad V_0 = A(V_+ - V_-) = -AV_- \quad (\text{since } V_+ = 0)$$

$$\text{so} \quad V_- = -V_0/A$$

$$\text{and} \quad V_0 = -\frac{V_0}{A} - \frac{R_F}{R_I}(V_{in} + V_0/A)$$

$$\text{as } A \rightarrow \infty, \quad V_0 = -\frac{R_F}{R_I}V_{in}$$

Note that the amplification, or gain, is again determined only by the characteristics of the feedback loop, not the amplifier, provided that A is sufficiently large (and the ratio R_F/R_I is not chosen to be too large).

Note also, that in this example, V_- is 0. In this case, the inverting input is said to be a “virtual ground”. This, of course, is what one would expect of any differential amplifier with *negative* feedback — the output V_0 is proportional to the difference between the two inputs, and has the opposite sign. Since this output forms part of the input as well, it would always tend to *decrease* the difference between the two inputs.

One difference between the non-inverting and inverting configurations is rather important.

The non-inverting amplifier has an infinite input impedance. (The input is connected to V_+ directly, which has infinite resistance.)

The inverting amplifier has an input impedance R_I .

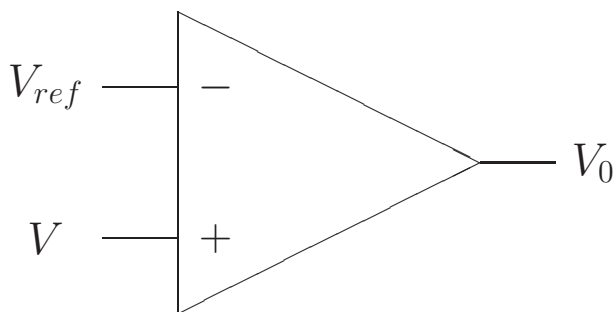
In this sense, the inverting amplifier produces an output voltage proportional to the input current, with R as the constant of proportionality.

The inverting amplifier configuration is used much more often than the non-inverting configuration, but for single voltage supply applications the non-inverting configuration is very useful.

OP-amp circuits

There are several op amp circuits which, although quite simple, are extremely useful. The simplest of these is the comparator circuit, shown following.

Here, an unknown voltage, V , is compared to a reference voltage, V_{ref} . If $V > V_{ref}$, then the output is $+\infty$ (the actual output will be the maximum voltage the op amp can produce). If $V < V_{ref}$, then the output is $-\infty$ (the actual output will be the minimum voltage the op amp can produce).

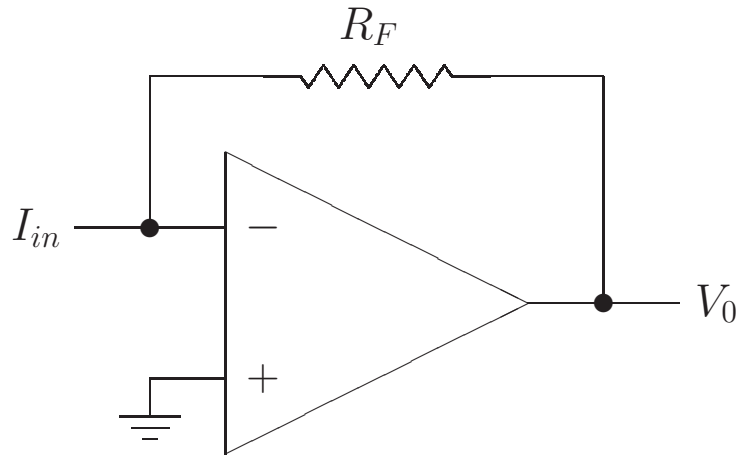


In these cases, the output from the op amp *saturates* — it is set firmly to its maximum value.

In practice, an op-amp may take a long time to recover from a saturated output, so if response time is important, using a device designed specifically as a comparator is best.

Such devices are available commercially, and are characterized by their response time.

A current-to-voltage converter can be constructed as follows:



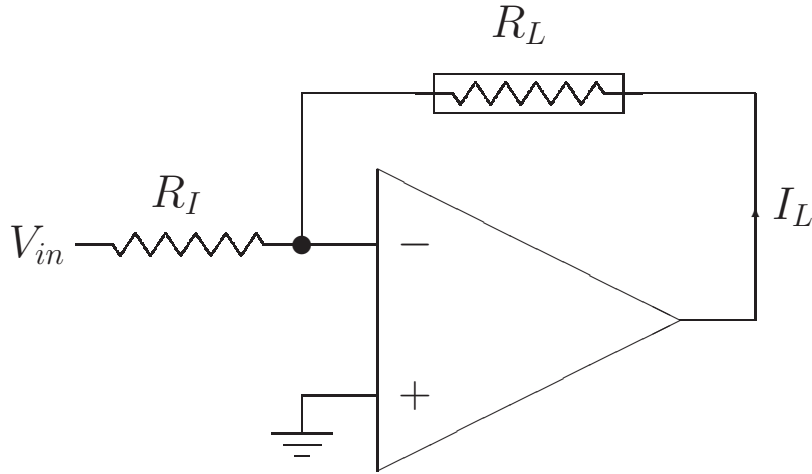
This is essentially an inverting amplifier, but with no input resistor; the input current I_{in} is applied directly to the inverting ($-$) input of the op amp. The input voltage is then given by

$$V_0 = -I_{in}R_F$$

This circuit is often used to convert current output from devices like photodiodes or photomultipliers to a voltage to be measured using, say, an analog-to-digital converter.

Of course, a simple resistor has the same property ($V = IR$), but the output of the op amp can be used to power another device.

A voltage-to-current converter can be constructed as follows:



where R_L is the resistance of the load, or device which receives the constant current.

This device, called a “transconductance amplifier” is again a simple inverting amplifier configuration.

Here, since no current flows into the inverting input of the op amp,

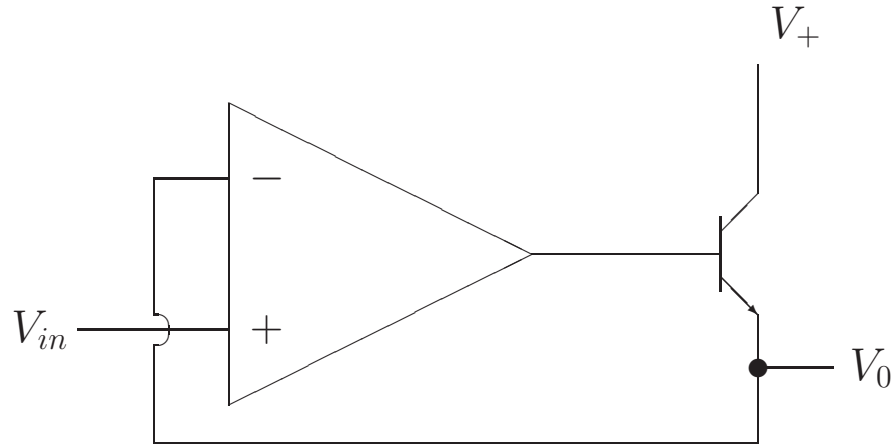
$$V_I = I_L R_I$$
$$I_L = V_I / R_I$$

independent of the value of the load resistance, R_L .

This circuit is often used with a *fixed* input voltage, V_{in} , to provide a constant current source.

In fact, constant current sources are available commercially, so it is not common to construct one using an op amp circuit.

Virtually any circuit can be used in the feedback loop of an op amp. In fact, a simple way to provide a high power output from an op amp circuit is to have a power transistor in the feedback loop, as follows:



This example shows a unity gain (voltage follower) op amp configuration, but any of the amplifier configurations will also work. (V_+ is the voltage supply for the transistor; it need not be the same as for the op amp, but they must share a common ground reference.)

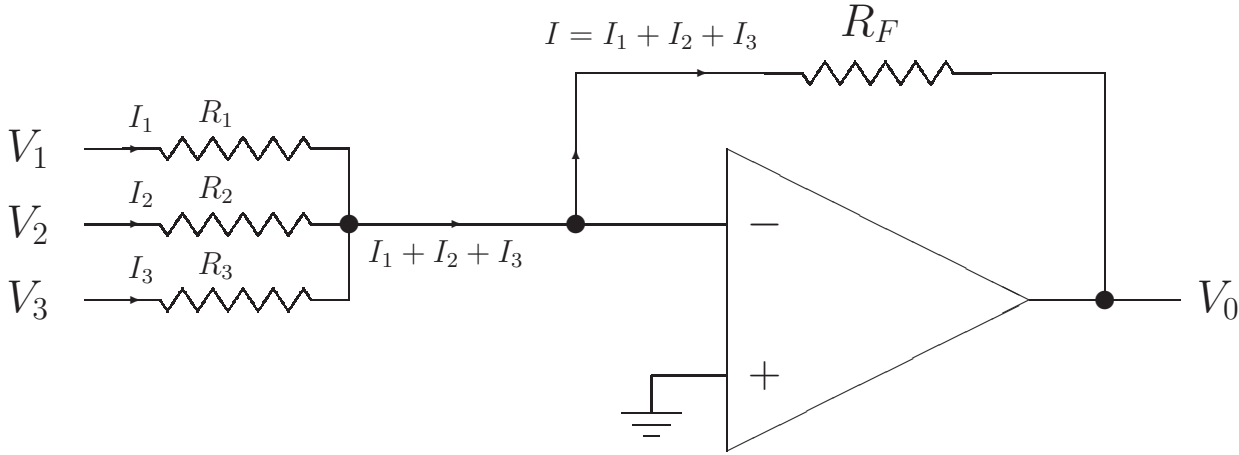
Mathematical operations using operational amplifiers

The operational amplifier can be used to perform arithmetic operations on the input voltage waveforms. In fact, this is what gives the device its name.

It is immediately obvious from the preceding equations that an inverter (i.e., a sign changer), or a scale changer, (i. e. a constant multiplier) can be easily constructed.

Also, a level shifter (i.e., addition of a constant) can be performed, and if complex impedances are used for R_I and R_F , a phase shifter can be constructed.

A circuit which adds together several input voltages can be constructed quite easily, for either of the op amp configurations. The case of the inverting amplifier is easiest:



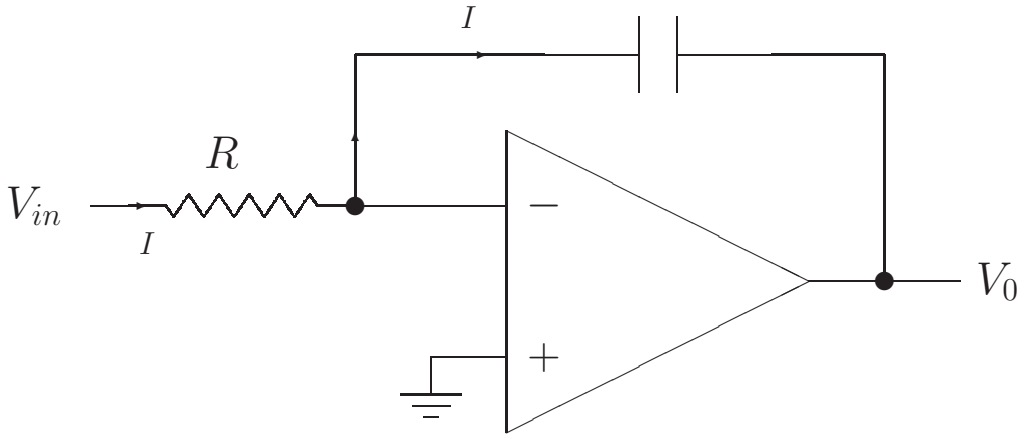
$$\begin{aligned}
 I &= I_1 + I_2 + I_3 \\
 &= V_1/R_1 + V_2/R_2 + V_3/R_3 \\
 &= -V_0/R_F
 \end{aligned}$$

$$\begin{aligned}
 &\text{if } R_1 = R_2 = R_3 = R_F, \\
 &\text{then } V_0 = -(V_1 + V_2 + V_3)
 \end{aligned}$$

In general, the output V_0 is the weighted sum of V_1, V_2, V_3, \dots where the weights are $R_F/R_1, R_F/R_2$, etc. Subtraction can be performed by inverting the required input. Any desired phase shift can be accomplished by adding reactive components to R_1, R_2 , etc. Note that the input signals V_1, V_2 , etc. can be time varying signals. They must only satisfy the (non-ideal) criteria that they are within the (frequency) bandwidth of the op amp, and that the rate of change of output voltage not exceed the slew rate of the op amp.

Other operations can be performed as well, including integration and differentiation. In fact, it is in the solution of differential equations that operational amplifiers found their greatest traditional use, in analog computers.

The following circuit can perform integration; $V_0 = -1/RC \int V_{in} dt$



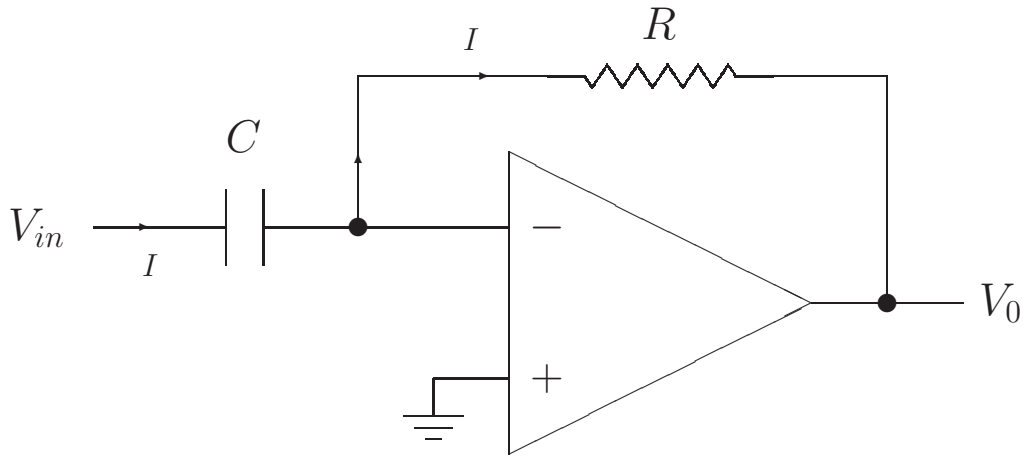
For a capacitor, $Q = CV$ where C = capacitance, Q = charge, V = voltage across capacitor. The current $I = dQ/dt$ = rate of flow of charge. As before,

$$\begin{aligned}
 I &= V_{in}/R = dQ/dt = \frac{d}{dt}(-CV_0) = -C \frac{dV_0}{dt} \\
 dV_0/dt &= -1/C \times V_{in}/R \\
 V_0 &= -1/RC \int V_{in} dt
 \end{aligned}$$

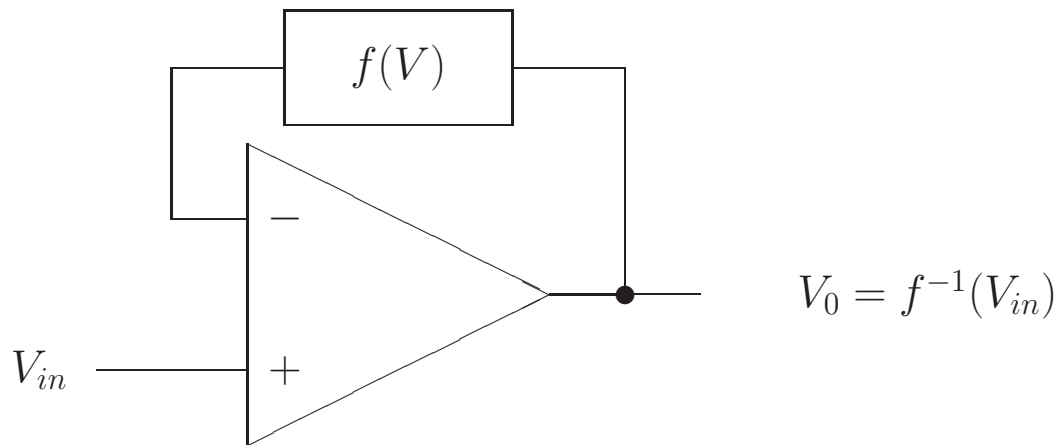
If we interchange R and C in the previous circuit, we have a device which can perform differentiation, as follows:

$$I = dQ/dt = \frac{d}{dt}(-CV_{in}) = -V_0/R$$

$$V_0 = -RC \frac{dV_{in}}{dt}$$



A most useful function of op amps is that if a device is available to perform any mathematical function on an input signal, then the inverse of this operation can be performed by placing the device which performs this operation in the feedback loop of a non-inverting op amp as follows:



$$V_0 = A[V_{in} - f(V_0)]$$

$$AV_{in} = V_0 + Af(V_0)$$

$$\text{if } A \rightarrow \infty, \text{ then } f(V_0) = V_{in}$$

$$\text{or } V_0 = f^{-1}(V_{in})$$

Analog circuits are readily available, at reasonable prices, which can perform the following functions:

multiplication	division
exponentiation	logarithm extraction
square	square root
ideal diode	ideal comparator
RMS extraction	

Other functions can be derived from these, or at least closely approximated. The IC's are available at reasonable cost (from a few cents to a few dollars, in single quantities), with accuracy of from about 1% to better than 0.1%, and bandwidth of 1 - 100 MHz. This corresponds to, in the digital world, accuracy of from 7 to 10 bits, and function evaluation times of about 0.1 μ s; comparing this to a typical microprocessor, a single add operation is performed in less than 1 ns.

In general, it is possible to solve mathematical problems, with limited accuracy, in very short times using analog techniques.

One problem with analog computers, however, is that in order to program them, the functional blocks must be physically connected together.

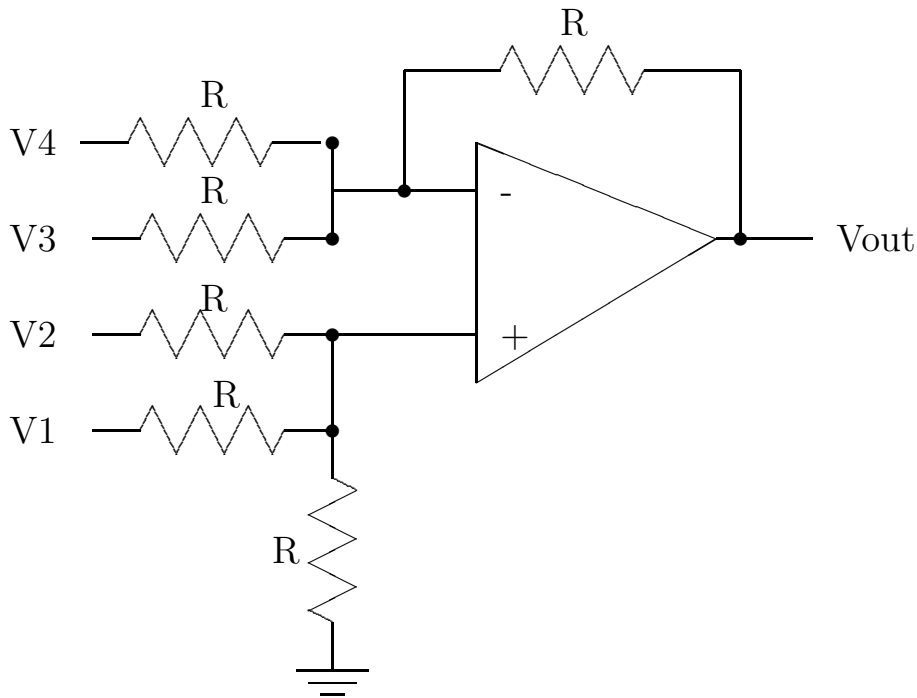
Today, it is possible to assemble an array of analog “building blocks”, and use digitally controlled analog switches, multiplexors, etc. to, in a sense, “program” an analog computer. (Generally, though, these are used only for very specific types of functions. Analog computation, *per se*, is long obsolete.)

Single supply op amp circuits

For single supply op amps, typically the non-inverting configuration is preferred.

In any case, the differential input between the $+$ and $-$ terminals should never be negative.

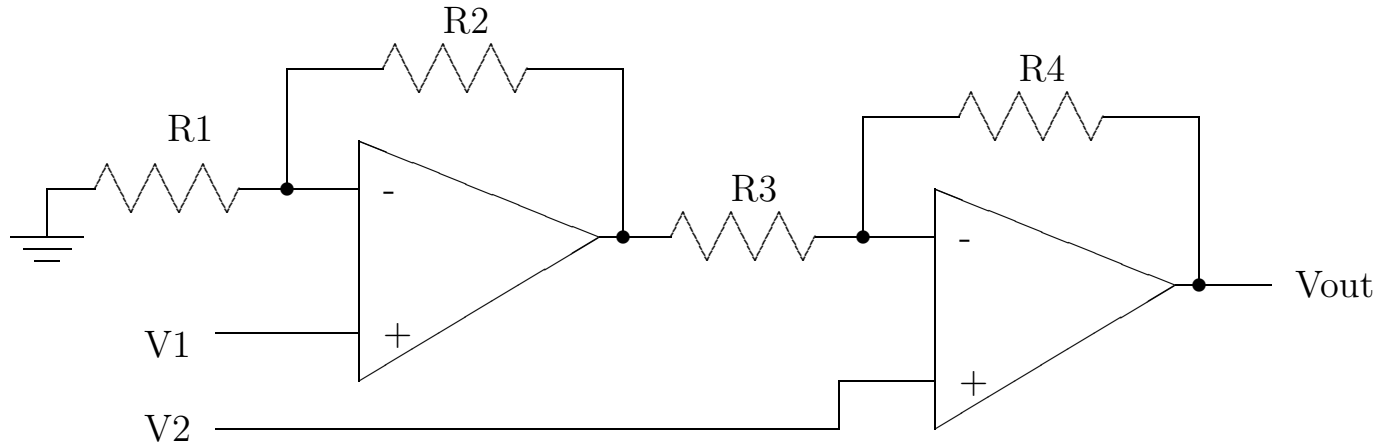
The following is a summing amplifier:



$$V_{out} = V_1 + V_2 - (V_3 + V_4)$$

Typically, R is chosen to be fairly large, say about 100K ohms.

The following is a high input impedance differential amplifier:

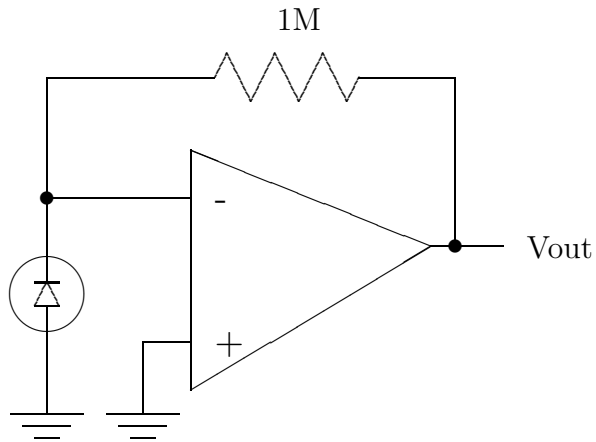


Here, $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ in order to maintain the “common mode rejection ratio.” (Basically, it should not preferentially amplify the noise in one stage.)

In this case, $V_{out} = (1 + R_4/R_3)(V_2 - V_1)$
 (We assume $V_2 \geq V_1$).

Again, the resistor values are typically chosen to be reasonably large; in the range of 100K ohms.

The following is an interesting circuit used as an amplifier for a light sensor (photovoltaic device — outputs a voltage when light shines on it):



An interesting thing here is that the photocell has 0V across it.

This would be typical of our kind of use for an op amp — conditioning a signal so that an ADC or comparator would have a reasonable dynamic range for an input.

This typically means scaling (amplifying) a signal, and/or adding or subtracting some value from it.

Design example

Design a circuit to enable accurate digitization of temperature (to within 0.2 degree) in the range 0 to 40 Celsius.

Use the LM335 temperature sensor, and the ADC on the ATmega644.

The LM335 produces an output of 10 mV/K, so at 0C the output would ideally be 2.73 V (corresponding to a temperature of 273K).

At 40C the temperature would be 313K, and the output 3.13V. The difference is 0.4V, which must be measured in steps of at least 0.2C, or 2mV. The ADC can digitize to 10 bits, so its minimum resolution is $\approx 0.1\%$ of V_{ref} . If V_{ref} is 5V, then this corresponds to 5mV.

In order to get this accuracy, we need to amplify the output of the sensor (by a factor of at least 2.5). If we do this, the output will be over 5V, which is beyond the input range of the ADC.

Since we do not need to consider temperatures below 0C (273K) we can subtract 2.73V from the output, and amplify only the difference. Therefore, we need to

- set up the temperature sensor
- subtract a fixed voltage (2.73V) from the output
- amplify the new value by at least 2.5 (say, 10)
- digitize the amplified value

We also assume that we can calibrate the whole system after it is assembled.

We will use a single supply op amp (the MCP6241/4) to do this “signal conditioning.” (There are many more that would be effective, as well; e.g., the TLC2254, or even the LM324.)

We choose this op amp because

- it is a low power single supply device
- it has rail-to-rail output
- it uses the same power supply range as the AVR processors
- it is low cost, and I have some on hand
- it comes with 4 op amps in one 14 pin chip

Although it can all be done using one op amp, we will use three, in one package.

The first will be a unity gain configuration, to isolate the sensor from the rest of the circuitry.

The second will be a single supply summer (actually a subtracter.)

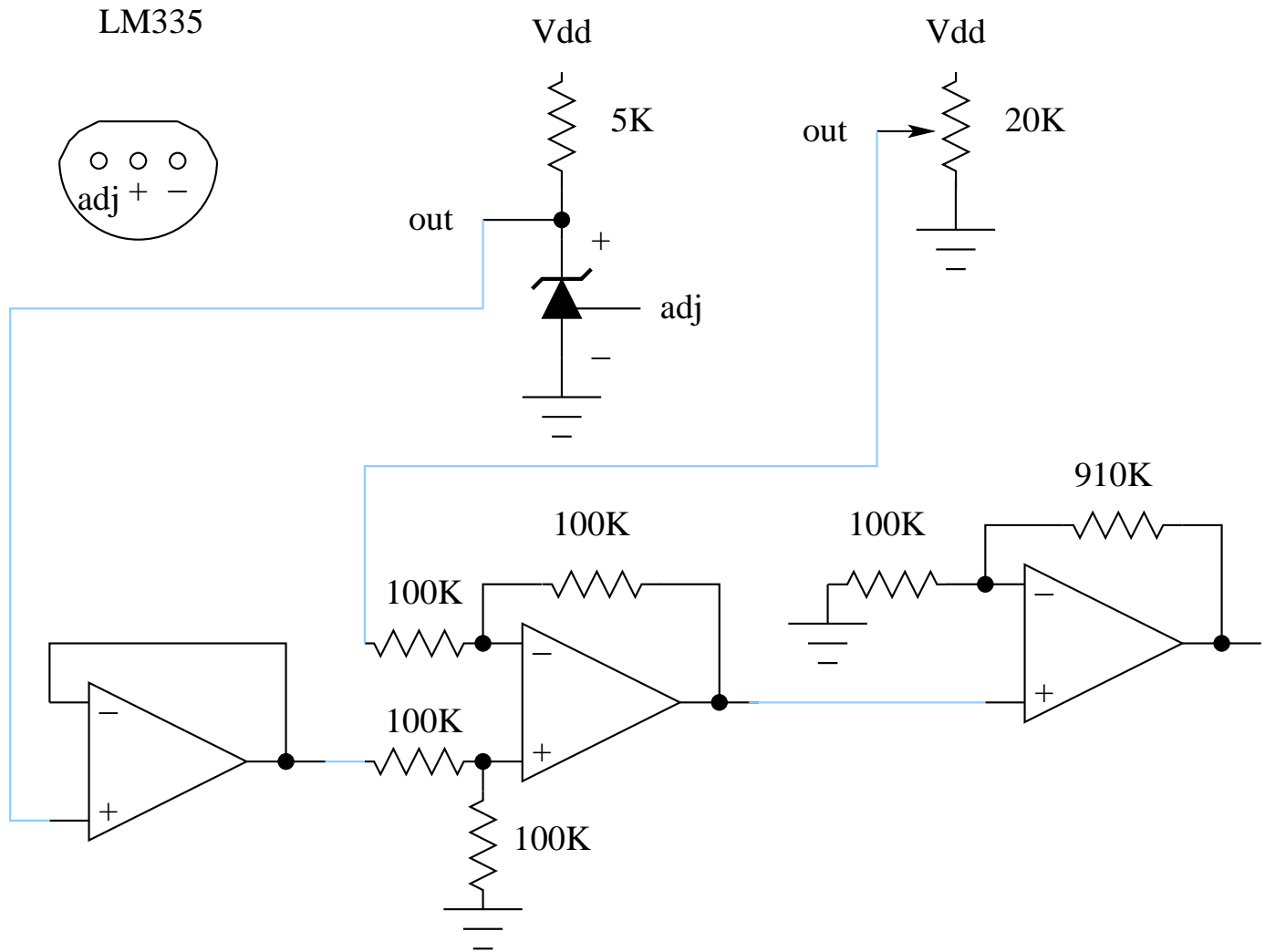
The third will be a non-inverting amplifier configuration.

One requirement is a source for the 2.73 V to be subtracted.

We can use a (resistive) voltage divider (but the voltage will then depend on the supply voltage, or a constant current source supplying a fixed resistor, or a “voltage reference” where we amplify the voltage with an op amp.

We will use the voltage divider, but the other methods are preferable.

Circuit diagram for example:



How long will this design run if powered by battery?

We can calculate the approximate current used by the various components, assuming a 4.5 – 6 V battery, and high resistance output:

LM335	$\approx 1 \text{ ma}$	$I = V/R = (6V - 2.73V)/5K = 0.65 \text{ ma}$
20K pot	$\approx 0.3 \text{ ma}$	$I = 6V/20K = 0.3 \text{ ma}$
op amp	$\approx 1 \text{ ma}$	input resistance 100K ($< 0.1 \text{ ma/stage}$)
total	$< 3 \text{ ma}$	

The capacity of some common batteries is tabulated below:

Type	voltage	capacity (ma-H)
Alkaline		
AAA	1.5	1250
AA	1.5	2850
C	1.5	8350
D	1.5	20500
9V	9	625
Lantern	6	26000
Lithium		
CR123	3	1500
CR2032	3	220
CR2477	3	1000

How can the battery life be extended?

Another design example

Given a 40 KHz. ultrasonic transmitter and receiver, Design a circuit to detect when a sensor is “close” to a solid object. (I.e., when a return signal of a certain amplitude can be detected.)

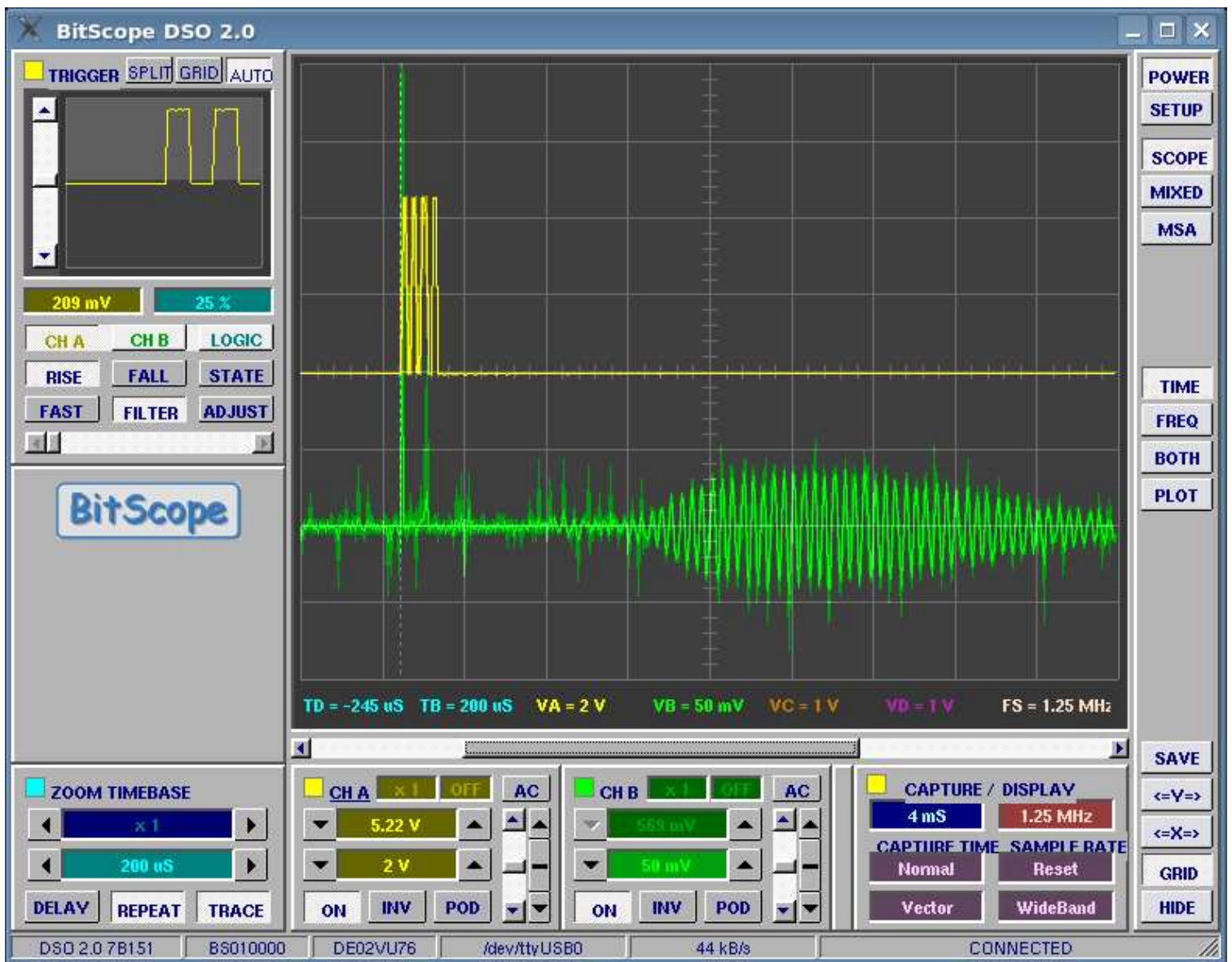
The same idea can be used to measure the distance from a transducer to a solid object.

Following is an oscilloscope trace of the output and received signal from a transmitter/receiver pair.

The yellow trace is the 40 KHz. input applied to the ultrasonic transmitter. The green trace is what is picked up by the receiver, with a reflector about 8 cm. away from the transducers.

Note the difference in the scales — about a factor of 100.

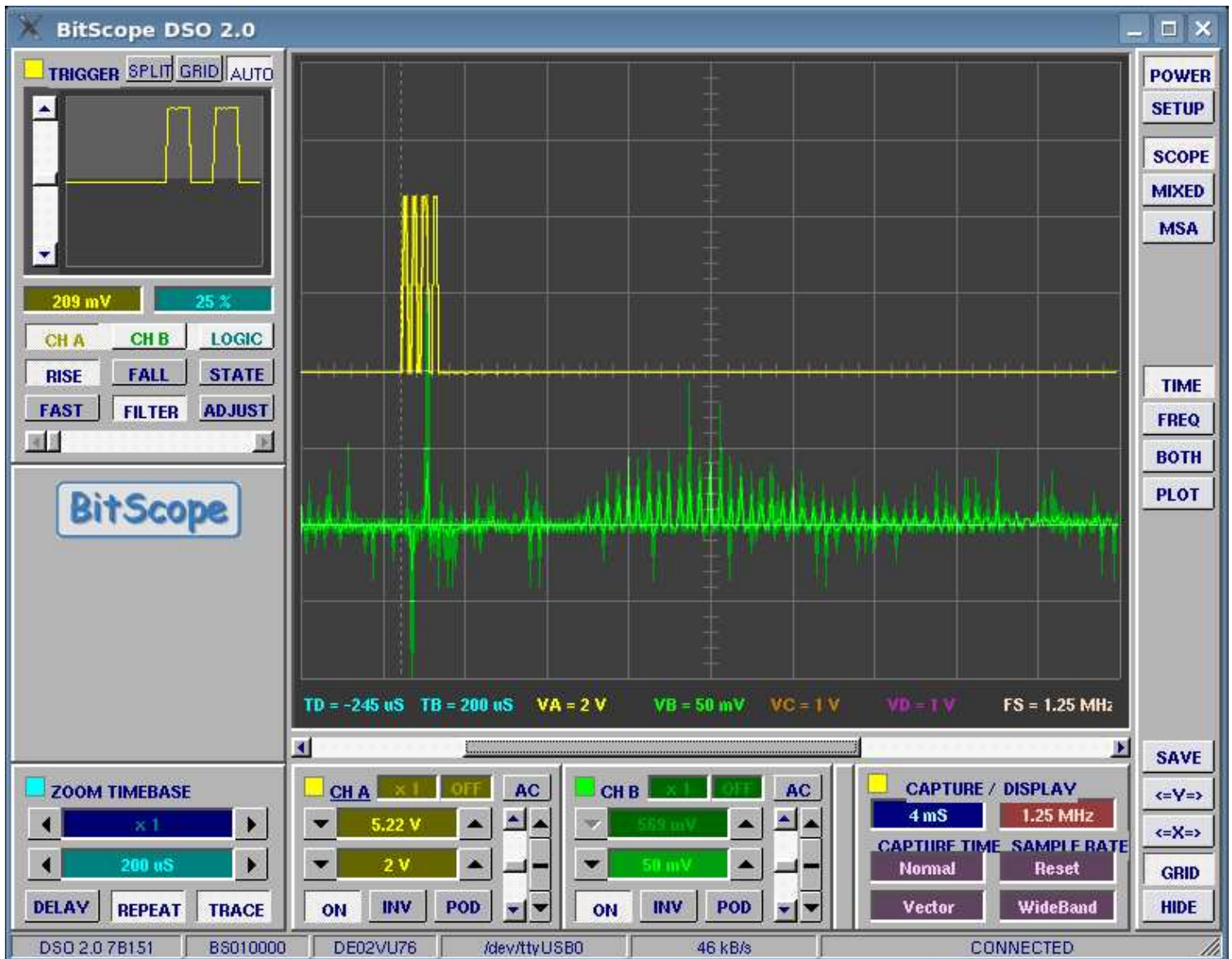
We therefore need to amplify the returned signal by a factor of about 100.



Again, we will use a unity gain op amp configuration as the first stage.

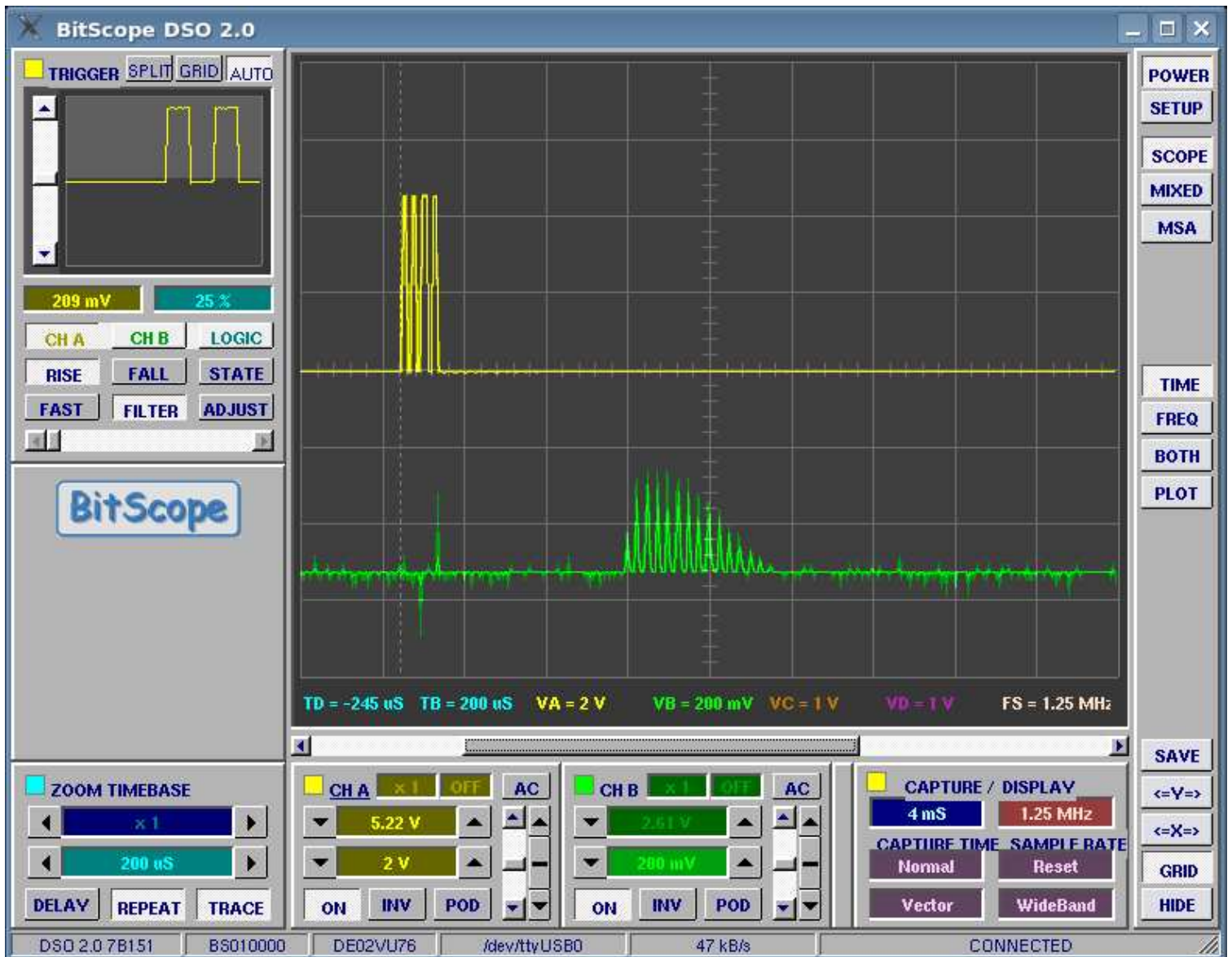
An added benefit this time is that, since we are using a single supply op amp, the negative portion of the returned signal will be eliminated.

Following is the output from this stage:



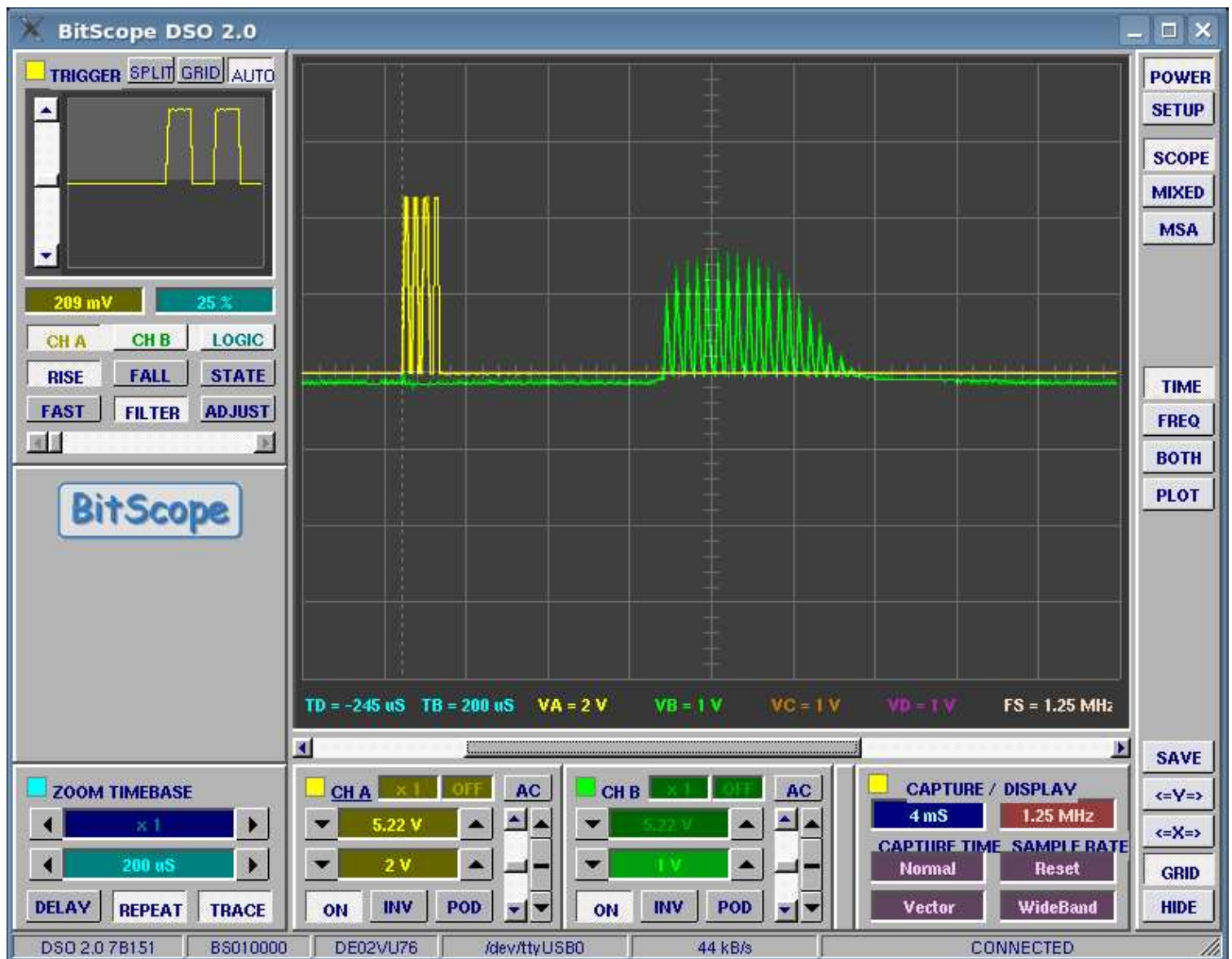
We now need to amplify this signal by a factor of approximately 100. Since the gain-bandwidth product for this amplifier is about 550 KHz, and we are amplifying a 40 KHz signal, we can achieve a gain of about 10 in one stage. Therefore, we need at least two such stages.

Following is the output from the first amplifier stage:

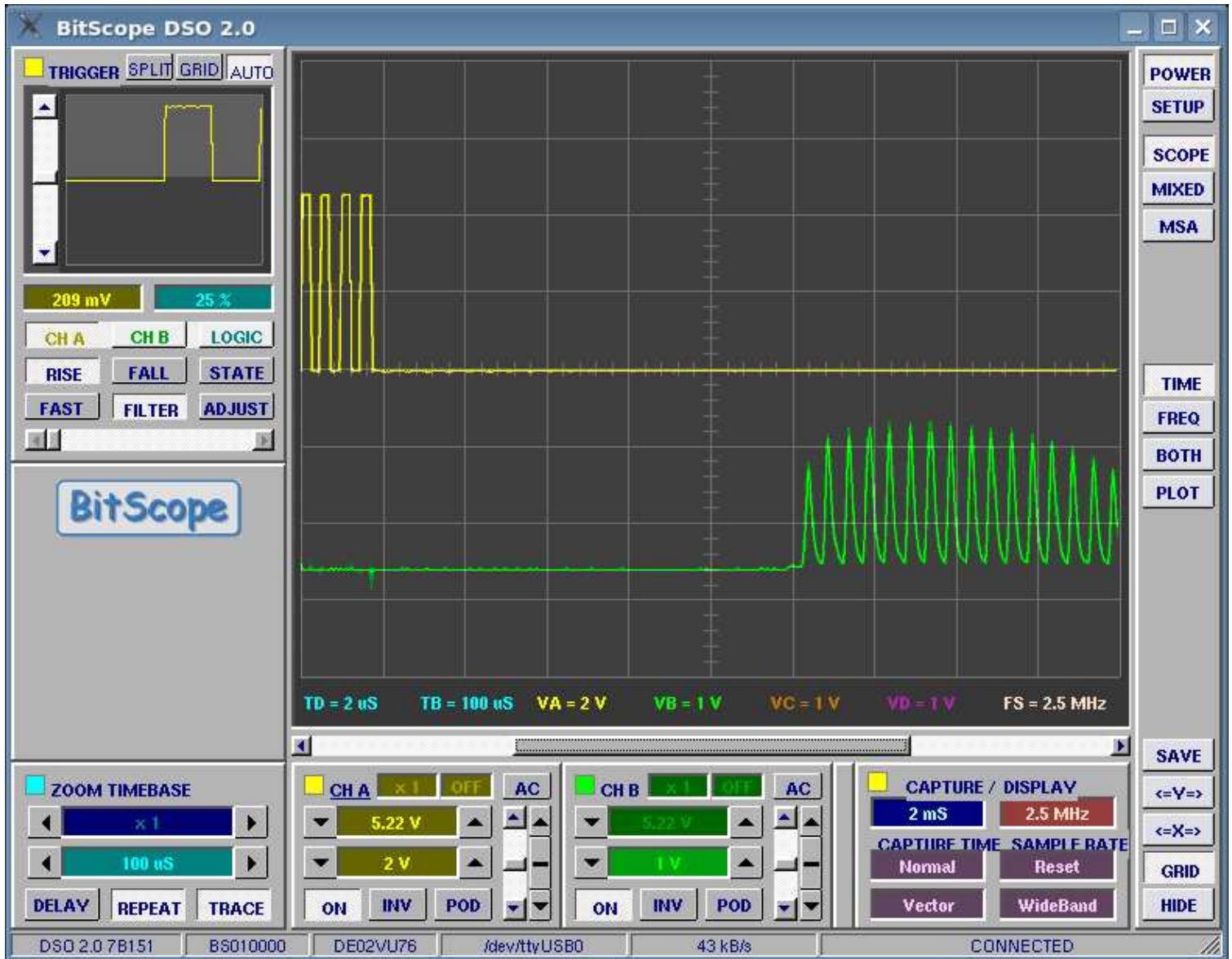


Note the oscilloscope gain settings — the signal is amplified by a factor of about 10.

Following is the output from the second amplifier stage:



Following is the output from the second amplifier stage, again, with the time scale expanded. Note the structure in the returned signal:



The position of the returned signal (time between the output and return pulse) varies with the distance to the reflector. A more powerful ultrasonic burst can be used to measure distances up to several meters with these transducers.

Sensors and transducers

A *transducer* is a device that converts one type of energy to another. For example, a speaker converts electrical energy to sound.

The term transducer is also used for a device that converts one type of signal to another.

A *sensor* is transducer that allows some effect to be measured or sensed.

For example, a mercury thermometer is a sensor, where the output is easily read by a human. Such sensors — litmus paper for measuring pH is another example, are said to be *direct reading*.)

More typically, though, when we call something a sensor, it is a device that converts something into a form that can be measured automatically, by electronic instruments, such as a voltage or current, or by direct digital methods (e.g., counting).

Many things can be sensed in different ways. For example, the speed of a bicycle can be obtained by measuring the time required for a revolution of the wheel. Knowing the circumference of the wheel, and the time for a full revolution, the speed can easily be calculated. The wheel could also be connected to a small electrical generator, and the output current measured, also giving an output related to the speed of revolution of the wheel.

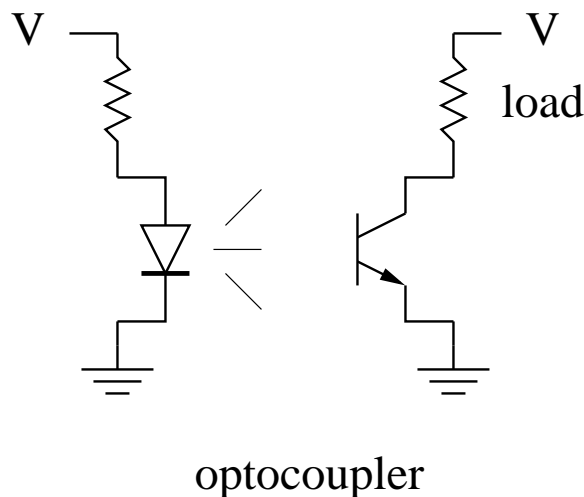
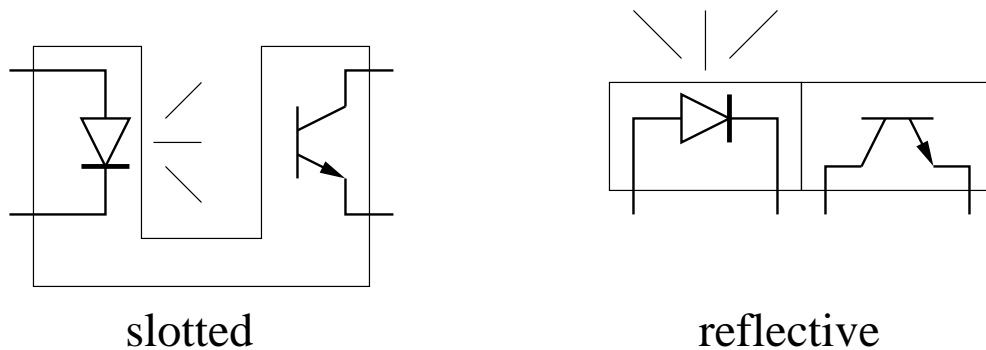
Typically, we would call the first type of sensor — counting revolutions per unit time— a digital sensor, and the second — generating a voltage or current proportional to the speed – an analog sensor.

Digital sensors

Digital sensors typically produce discrete outputs that can be counted (e.g., revolutions of a bicycle wheel) or outputs that can be timed, using a digital counter.

Often digital sensors include analog components. For example, a counter can have a photosensor that generates an electrical pulse whenever a reflecting surface is near the sensor. If the time between those pulses is related to the parameter to be measured, then the pulses can be used to build a digital sensor.

Typical optosensors use LEDs and phototransistors:



Often the analog component of a digital sensor is more elaborate than a simple switch. In the optical sensors, the emitter is usually an infrared (IR) LED, and the sensor is a phototransistor. The phototransistor can be used as a simple switch, turning a logic gate on or off, or as part of an amplifier circuit.

Other electrical parameters can also be used in digital sensors. Consider a capacitor that is allowed to charge to some voltage, through a fixed resistor. The time to charge the capacitor (up to some fixed voltage, say) is related to the voltage applied to the capacitor. An analog comparator could be used to generate an output when the target voltage was reached, and the charging time (measured with a digital clock) is a measure of the applied voltage.

If either the resistance or the capacitance changes, then the charging time also changes. This technique (or a variant of it, where the resistor and capacitor are in the feedback loop of an oscillator) is often used to measure changes in resistance or capacitance.

Devices which vary resistance and/or capacitance can be constructed which measure many physical parameters — pressure, temperature, sound, humidity, force, light intensity, radiation, and many others.

The 555 timer

This “timer” is one of the first commercially popular analog integrated circuits, first produced by Signetics Corp. in 1971. It is still used today — in 2003, over 1 billion 555 timers were produced.

It is a simple circuit, basically consisting of two voltage comparators set to $1/3$ and $2/3$ of the supply voltage, a control flip-flop, and a power output stage.

The basic device has 8 pins, as follows:

555 timer			
Gnd	1	8	Vcc
Trigger	2	7	Discharge
Output	3	6	Threshold
Reset	4	5	Control

The Trigger and Threshold inputs (2 and 6) are inputs to the upper and lower comparators, respectively.

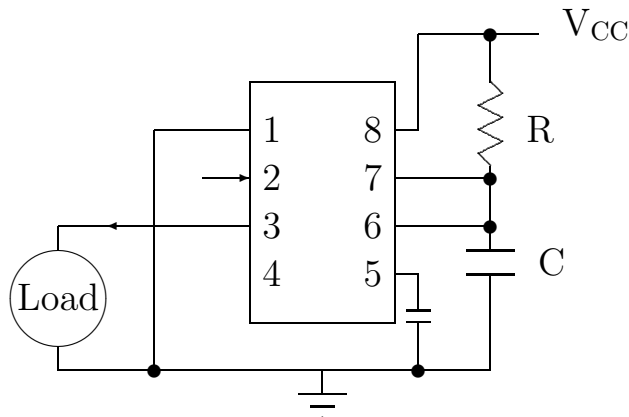
The Discharge output is used to discharge the timing capacitor.

The Reset input brings the output low.

In typical operation, a pulse starts when the Trigger input is brought low, and its duration is controlled by a RC network.

When configured to generate a single pulse, the configuration is called “monostable” or a “one-shot.”

A typical “one-shot” configuration is the following:



The duration of the output pulse is $1.1 \times RC$.

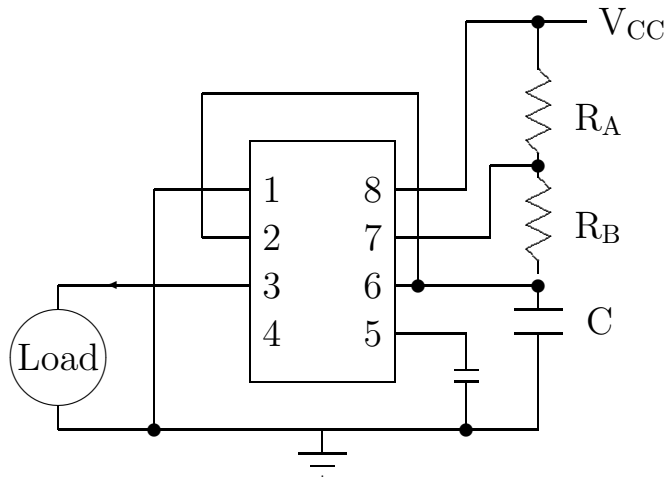
(The small capacitor is a decoupling capacitor, typically $0.01\mu F$.)

This device is capable of producing quite a range of pulses; e.g. if R is 1 M ohm and C is $1\mu F$, the pulse has a duration of about 1.1 seconds.

If R is 1K ohms, and C is 1 nF, then the pulse has a duration of 1 μs .

The device can also be set to trigger itself, by connecting pins 2 and 6, and adding another resistor. In this configuration, it is said to be “free running” or “astable.”

Perhaps the most common configuration is the free running configuration:



In this mode, the capacitor charges and discharges between $1/3$ and $2/3$ of V_{CC} .

The charge time is $t_c = 0.693(R_A + R_B)C$

The discharge time is $t_d = 0.693(R_B)C$

The total period is $t_d = 0.693(R_A + 2R_B)C$

The frequency is $\frac{1.44}{(R_A + 2R_B)C}$

The “duty cycle” D is $R_B / (R_A + 2R_B)$

Because of the linear relationship between the period and the resistance and capacitance, this kind of circuit (producing an output which can easily be counted) is a common component of a digital sensor.

Consider the following types of devices, all of which vary depending on some physical effect:

thermistor — resistance varies with temperature

photoresistor — resistance varies with light intensity

capacitive diaphragm — varies with pressure (sound as well)

capacitive channel — varies with flowing material

Analog sensors

Not all of the things we might wish to sense have a convenient way to be converted to the digital domain. In other cases, it may be possible to increase the accuracy in the analog domain.

Consider two common parameters — temperature and pressure.

We can use a thermistor in the RC feedback of a timer to get a digital value, but there are other devices with strong temperature effects as well. For example, the current flowing through a transistor junction is a function of temperature (this is what is used in the LM335, in fact).

The thermocouple effect, which produces a small voltage difference between the “hot” and cold” ends of a connection between two wires is often used to measure high temperatures (1000 C or so).

A fixed container of gaseous material could be used, and the pressure inside the container could be measured, also giving a measure of temperature.

Pressure can be measured digitally using capacitance — changing the separation of two conducting plates.

It can also be measured by other effects, including the piezoelectric effect, where a small voltage is generated due to forces acting on a crystal.

This effect can be used to measure large forces or pressures, and is commonly used in high pressure sensors.

Generally, analog sensors are devices in which the interaction between the sensor and the sensors energy domain produce an output directly in the electrical domain.

For example, piezoelectric sensors — output is voltage
photovoltaic sensors — output is current.

Sometimes, sensors are constructed by adding a material which interacts with a particular entity to be sensed. For example, some gas sensors have thin layers of material which interact (reversibly) with the entity being sensed, and change some property of the sensing element. (E.g., a gas sensor.)

Other sensors act by their effect on the material to be sensed. Smoke detectors use ionizing radiation from a small radioactive source to preferentially ionize combustion products, causing a small current to flow in the ionization chamber.

INTERFACING TO THE REAL WORLD - DAC's and ADC's

In the past few years, since digital devices have become computationally very fast, many functions previously performed by analog devices are now done digitally. This has allowed the implementation of much more accurate (and more complex) signal processing.

Generally, however, the signal must be digitized from an analog form before it is digitally processed, and then reconverted to analog form after the computation.

Therefore, devices to do these conversions (digital-to analog converters — DACs, and analog-to-digital converters — ADCs) have become important circuit elements.

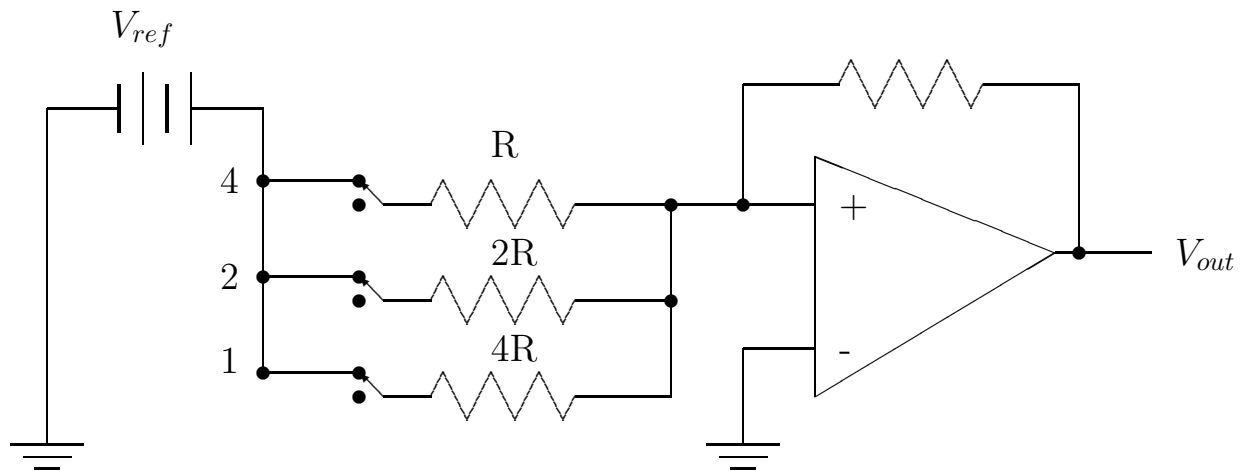
We will look at how these devices are implemented.

Digital to analog converters

D-A converters are generally constructed in one of 3 ways: (all examples will show a 3-bit DAC, having 8 possible outputs, 0-7, with output corresponding to digital input 5 (binary 101)).

Binary weighted summer

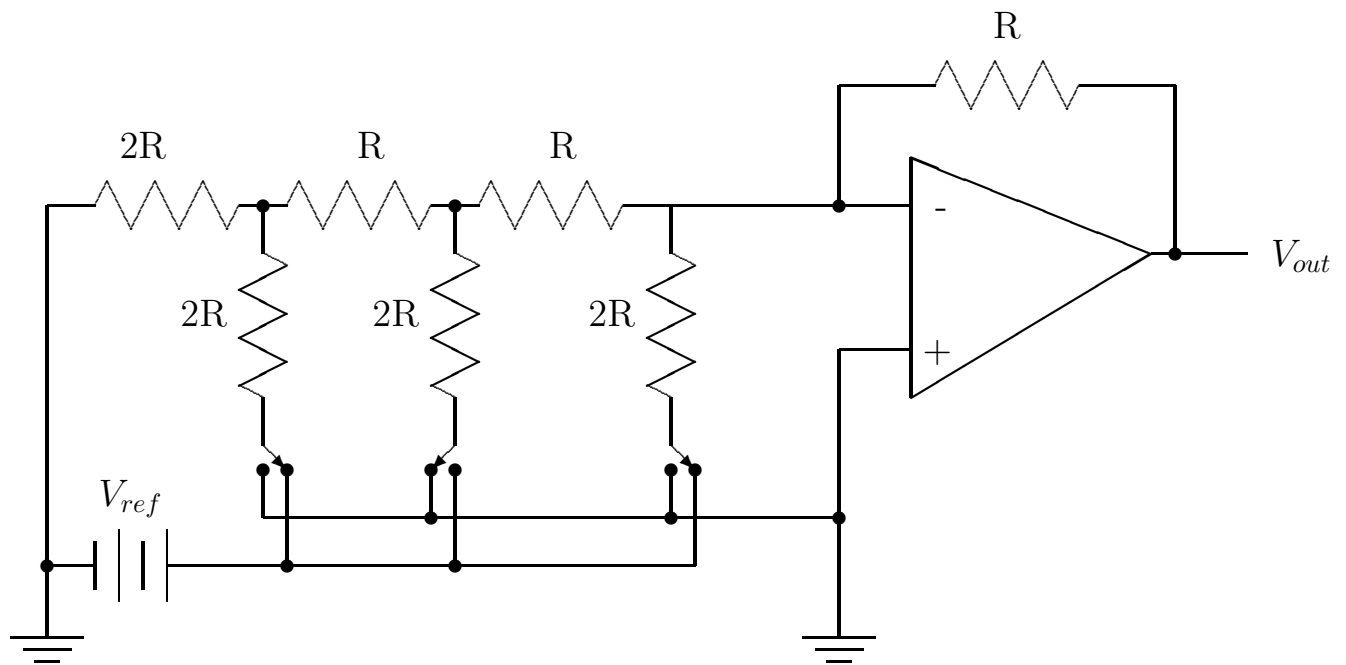
The first method employs a technique we have seen already — binary weighted resistors as input resistors to a summing op amp. In this case, each resistor must be a factor of two greater than the previous. It is rather difficult to make resistors which vary over more than about an order of magnitude with great accuracy on an IC. However, this method requires the least number of resistors, requiring only N resistors for an N bit D-A converter. A circuit diagram for a typical DAC using this technique is shown in the following diagram:



The $R - 2R$ ladder

This circuit requires only two values of resistance, with value R and $2R$, as shown in the following diagram.

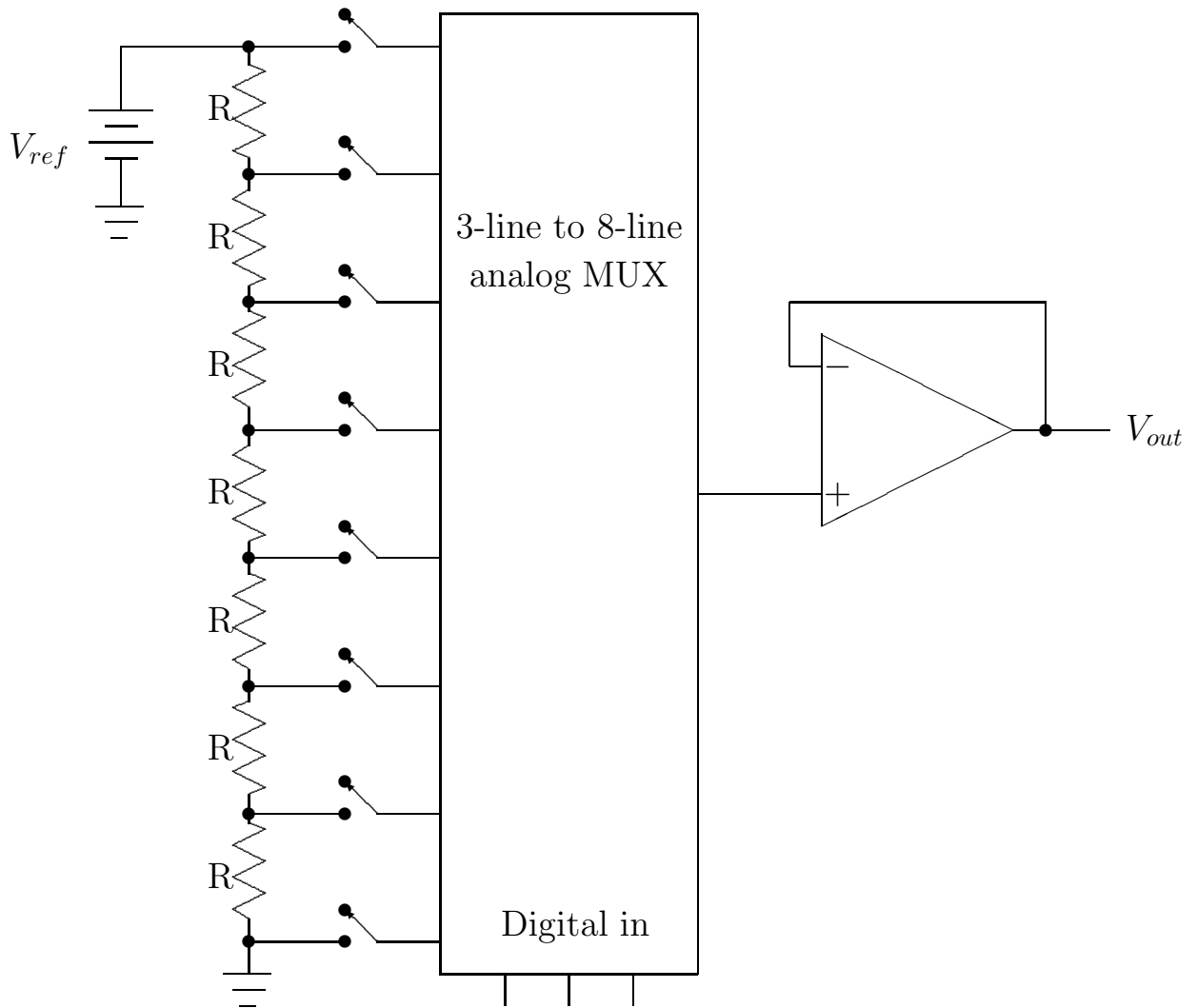
It requires $2N$ resistors, where N is the number of bits in the D–A converter. The resistors must be quite accurate, however. The operation of this D–A converter is more difficult to understand than the previous, but it can be understood readily by noting that at each intersection of 3 resistors the current is divided into two equal parts. This is perhaps most easily seen if the centre leg of the ladder is connected to the reference, and all others are connected to ground; it can then readily be seen that at each junction the current is divided into two.



2^N resistor string

The third method employs a string of 2^N identical resistors, where N is the number of bits in the D to A converter, as shown in the following diagram.

Here the number of resistors is large, but they need not be extremely accurate. This device has the further advantage that the output is certain to be monotonic.



DAC's have either an internal (fixed) reference voltage V_{ref} , or allow an external reference to be used. If an external reference is used, the DAC is called a multiplying DAC, or MDAC. Its output is the product of V_{ref} and the binary code which is input.

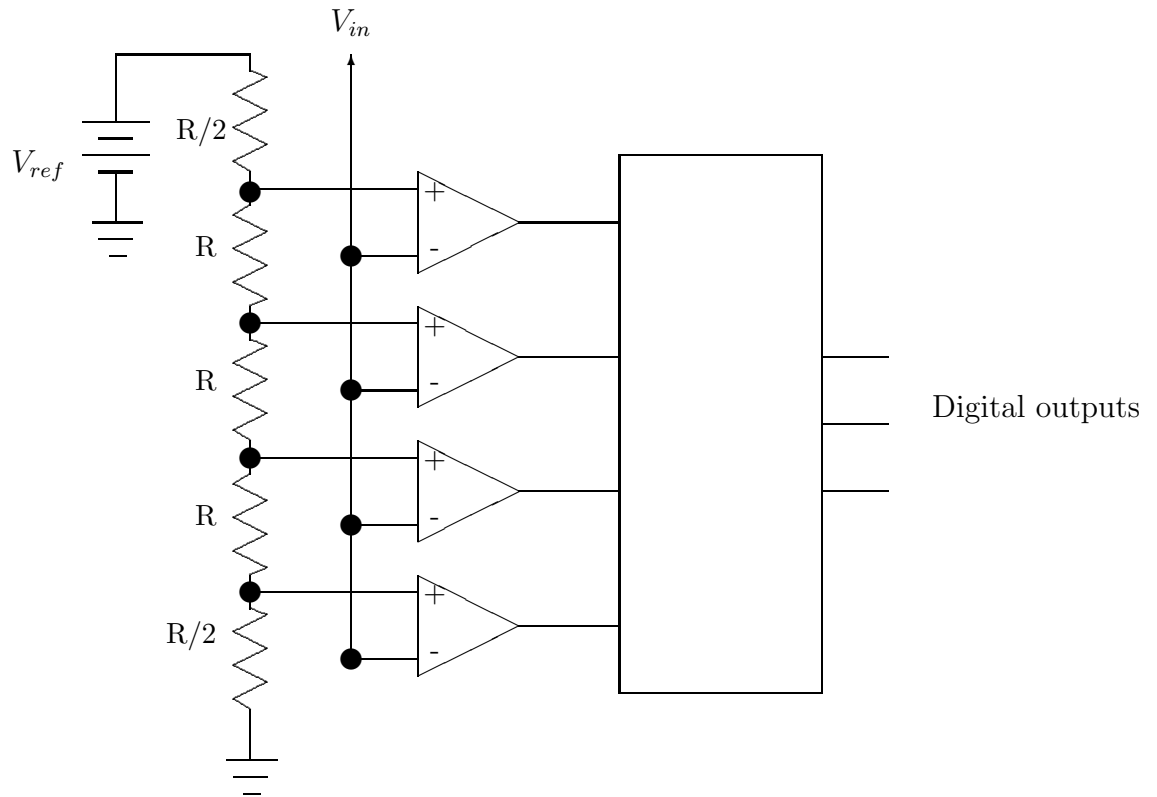
Note that in the last example, if the analog MUX is bi-directional, the MDAC can be used as a programmable resistor.

In fact, this circuit is commercially available. In fact, it is often packaged as a programmable device with a serial input.

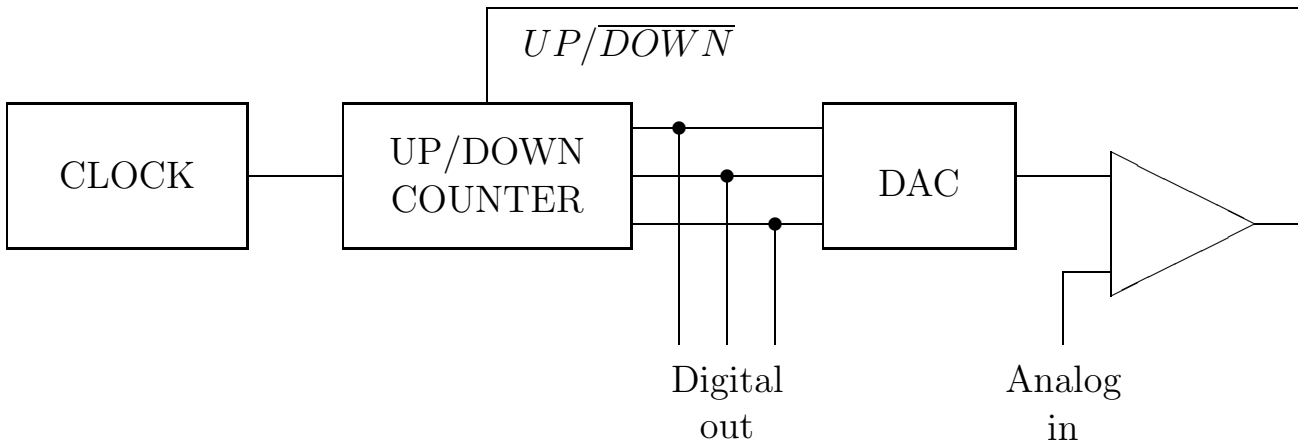
Analog to digital converters

There are 3 main methods.

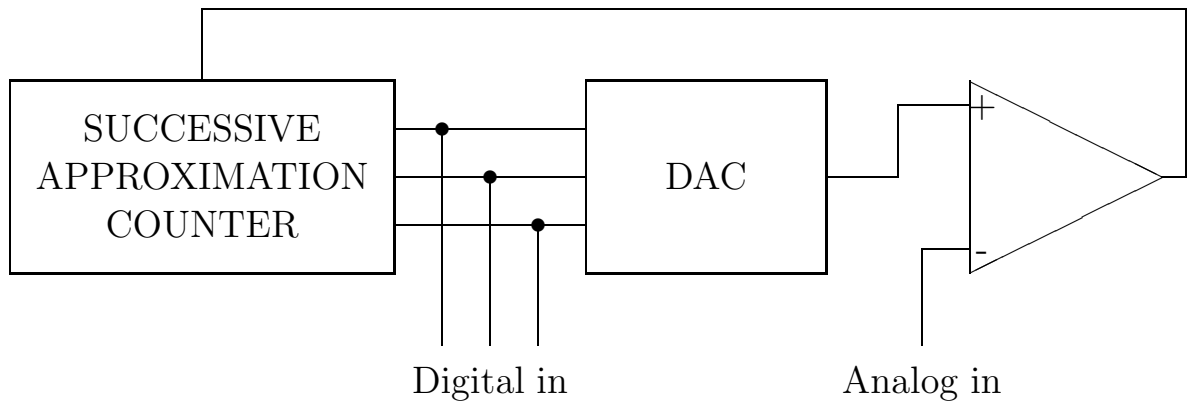
1. Flash conversion — extremely fast. Uses a set of 2^n resistors and 2^n comparators.



2. Using a DAC and a counter, and a single comparator.



3. Using a DAC and a successive approximation counter.

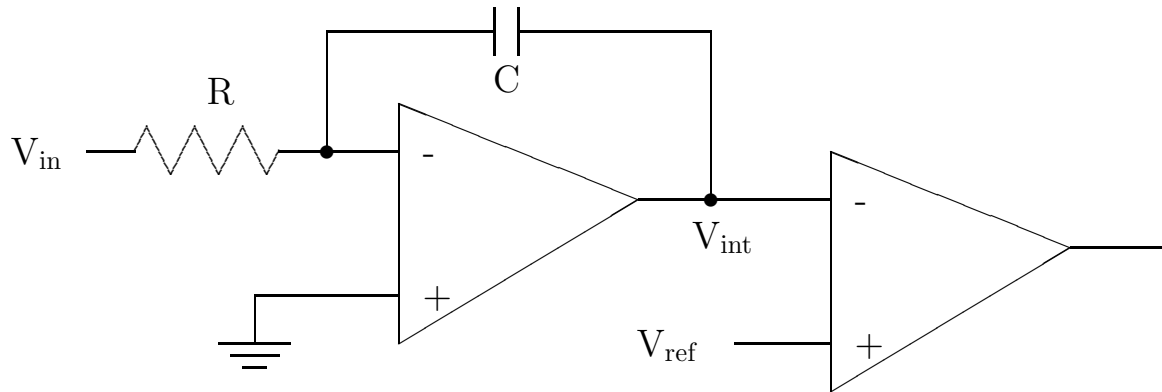


try 100, then either 010 or 100, *etc. i.e.*, perform a binary search for the correct number.

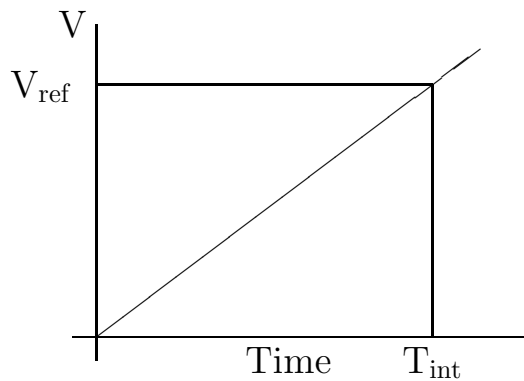
4. Integrating ADCs — again, there are two main methods.

Single slope ADCs

A very simple, accurate, and effective ADC can be constructed using an integrator and timer. Basically, the input is integrated, and the time required to charge the integrating capacitor to a reference voltage is measured.



For a steady input voltage, the voltage from the integrator (V_{int}) increases linearly:

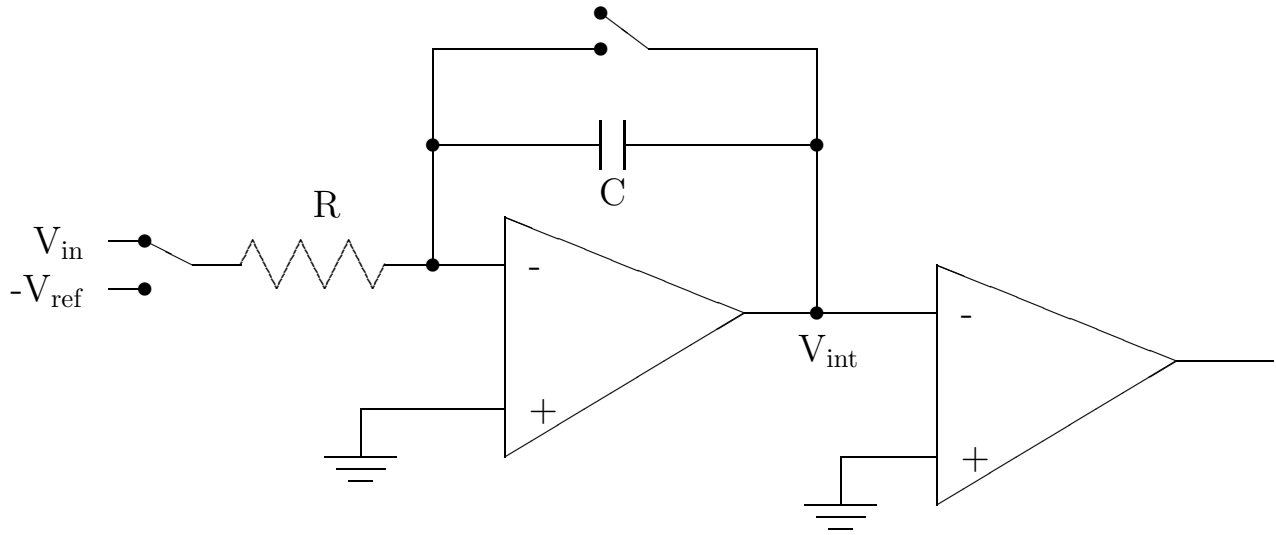


This works reasonably well for slowly varying signals, but its accuracy depends on the tolerances of R and C .

Also, the time for a conversion depends on the input voltage. In particular, for $V_{in} = 0$, the time is infinite.

Dual slope ADCs

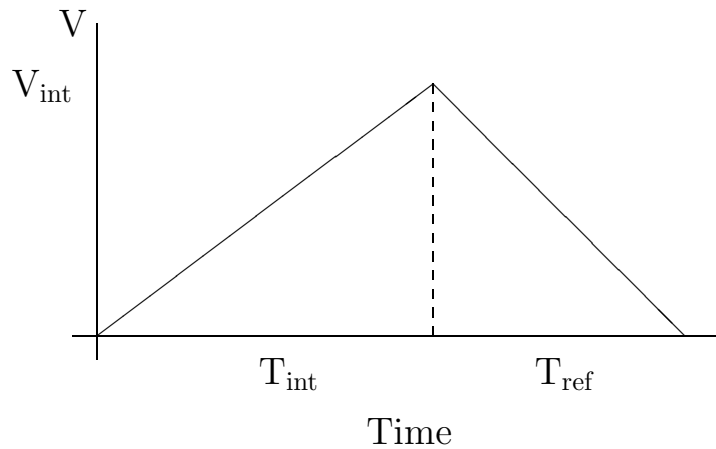
It is possible to eliminate the drawbacks of the previous ADC, by measuring both the charge and discharge time of the integrating capacitor. Effectively, a negative reference voltage is integrated with the positive unknown integral, and the relative times for the positive and negative integration give the required voltage.



This is a three stage process:

1. The capacitor is discharged through switch S.
2. V_{in} is integrated for some fixed time, T_{int} .
3. V_{ref} is integrated until the output is 0, in time T_{ref} .

The ratio $V_{\text{in}}/V_{\text{ref}}$ is the ratio of the integration time T_{int} to T_{ref} .



Here, $V_{\text{in}} = V_{\text{ref}} \times T_{\text{int}}/T_{\text{ref}}$.

Recall that T_{int} is fixed (constant), so the output is a function of T_{ref} only.

This effectively eliminates the effect of variations in R and C , and also solves the problem of a variable integration time.

Integrating ADCs have another interesting property — they tend to average out noise. In particular, periodic noise (e.g., 60 cycle noise from external power) can be averaged out by choosing the T_{int} as some multiple of a 60 cycle period.

Integrating ADCs can have more than 16 bit accuracy. In fact, they are used in many digital voltmeters because of their accuracy and noise reducing properties.

They are not very fast, however.