Lab 6

Amplifiers,
Light Tracking System,
&
Hand-Crank Flashlight

Introduction

In this lab you will build a light tracking system, and a simple hand-crank flashlight.

- You will build a summing amplifier using an Operational Amplifier microchip.
- You will use this summing amplifier, and photoresistor light sensors, to build a light tracking system for a motor.
- You will use a capacitor to store energy from a generator, and power an LED.

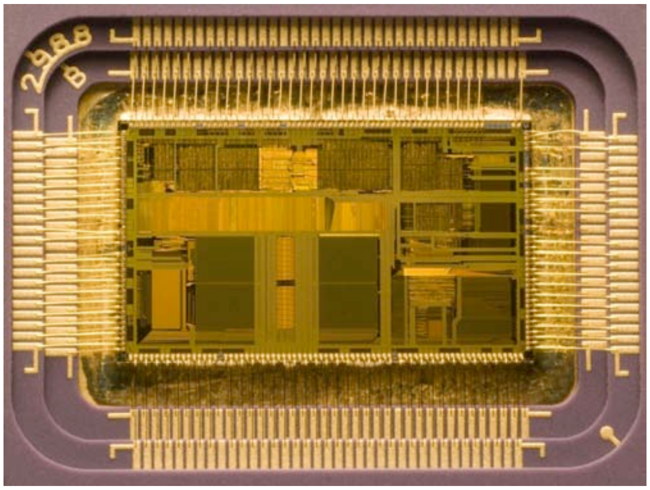
Before we can do these experiments, we need to understand:

- What are microchips.
- What is an Operational Amplifier microchip.
- What is a control system.
- What is a capacitor.

Microchips

Integrated Circuits (ICs)

An IC is simply a very advanced electric circuit. They are made from different electrical components such as resistors, capacitors, diodes, and transistors.



Pictures from Wikipedia

The IC chip inside the 80486 DX2 package has 1.2 million electronic components, and measures 12 mm x 7 mm.

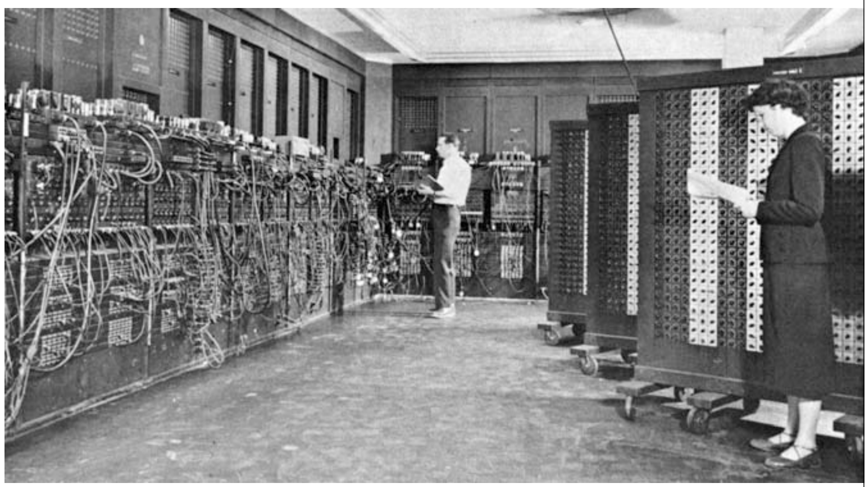
Before IC's

Before the technology to fabricate ICs was developed, assembling complex electronic circuits was time consuming, expensive, and prone to errors.

The first digital computer, ENIAC, was built in 1946.

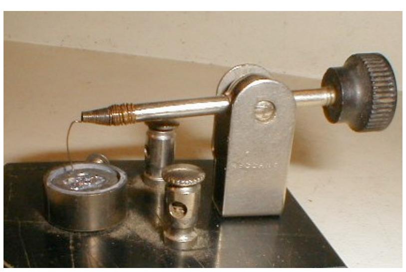
Weight: 27 tons
Power required: 150 kW
Parts included:
- 17,468 vacuum tubes
- 7,200 diodes
- 1,500 relays
- 70,000 resistors
- 10,000 capacitors

It had ~ 5 million hand soldered connections.



Miniaturization Was Needed

In order to build IC's, electronic components had to be miniaturized. Early versions of devices such as diodes and transistors were too large.



In 1906, the "cat's whisker" diode was invented by the American engineer Greenleaf Pickard (1877 - 1956) while working at the AT&T Company.

- It was made from a wire touching a silicon crystal.

In 1947, the first transistor was made at AT&T Bell labs by John Bardeen (1908 - 1991), Walter Brattain (1902 - 1987), and William Shockley (1910 - 1989).

- It was made from germanium.

The first silicon transistor was made in 1954 by Gordon Teal (1907 - 2003) at Texas Instruments.

http://www.rpi.edu/~schubert/Educational-resources/Educational-resources.htm

The First ICs

In 1958, the first IC was fabricated by Jack Kilby (1923 - 2005), an electrical engineer working at Texas Instruments. It was made from germanium.

- In July 1958, as a newly hired engineer, he was not allowed to take a summer vacation. He spent the summer developing the first IC.

In 1959, the first silicon IC was developed at Fairchild Semiconductor by Robert Noyce (1927 - 1990).

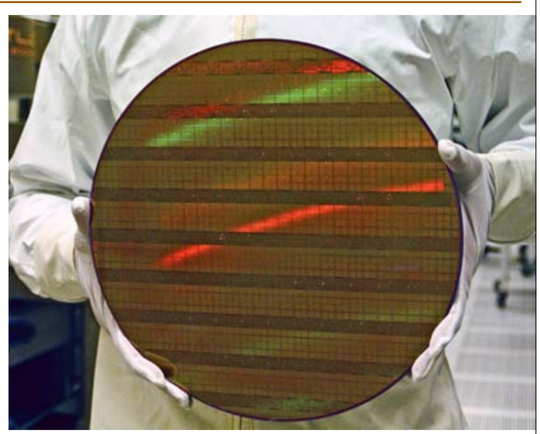
- It contained 4 transistors.

Later, Noyce and Gordon Moore (1929 -) both left Fairchild and founded Intel.

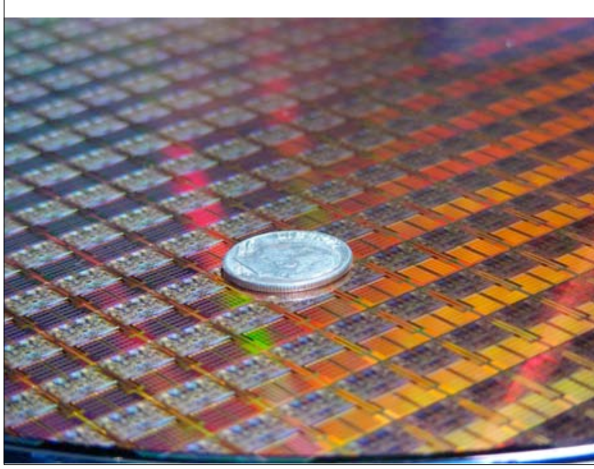
Massive Integration

Most modern ICs devices are fabricated on silicon wafers.

- Many ICs are fabricated at the same time on large wafers to reduce production costs.
- The silicon wafer is then cut apart, and each IC is packaged individually.



Intel



Each of these Intel 5400 microprocessors has 820 million transistors. The smallest features measure only 45 nm in size.

- About 1000x smaller than a human hair.
- This was state of the art in 2007.

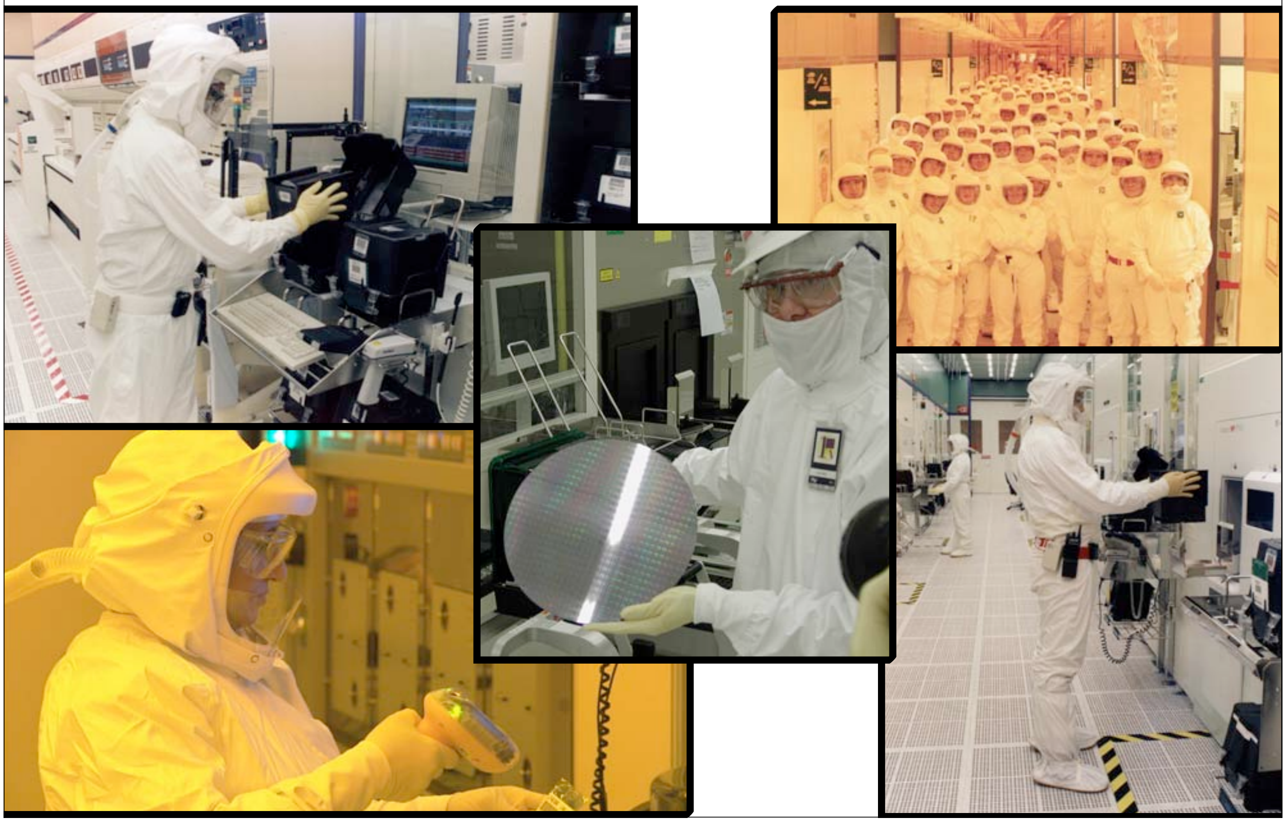
The Need To Be Clean

Making such tiny electronics requires a very clean fabrication environment.

- A modern semiconductor cleanroom fabrication facility can cost $5 billion, and the air is a 1000x cleaner than a hospital operating room.
- People are a source of particle contamination, and they need to wear special clothing. Smokers are also a problem. They exhale 1,000's of contaminants with each breath, even up to 2 weeks after smoking.

Students working in the cleanroom in Electrical and Computer Engineering

Working in a $Billion Intel Cleanroom



The Operational Amplifier (Op Amp)

Amplifiers

You can use a transistor to make an amplifier. However, in order to make amplifiers with specific characteristics, you need combinations of devices such as transistors, resistors, and capacitors.

- The need for inexpensive amplifiers with different characteristics resulted in the development of many IC based amplifiers.
- A common amplifier type is the operational amplifier.

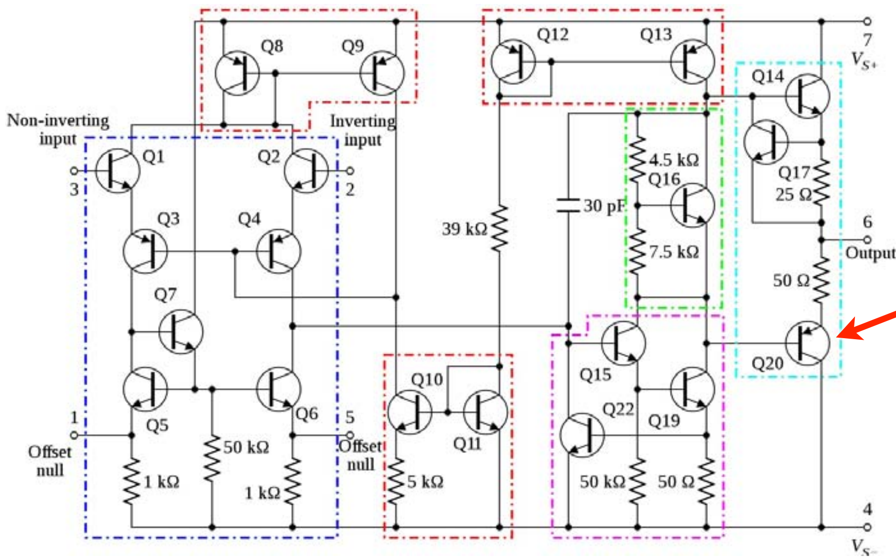
The "741" op amp was designed in 1968 and is still in production today.

- There are 20 transistors on this chip.

Inside the 741 Op Amp

While the IC package of the 741 has convenient connection pins, the internal circuitry is more complex.

Internal circuitry of a 741 op amp.



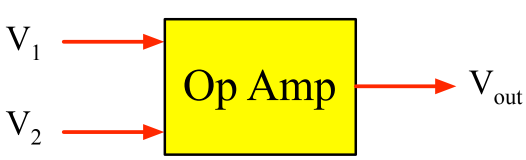
This is a transistor.

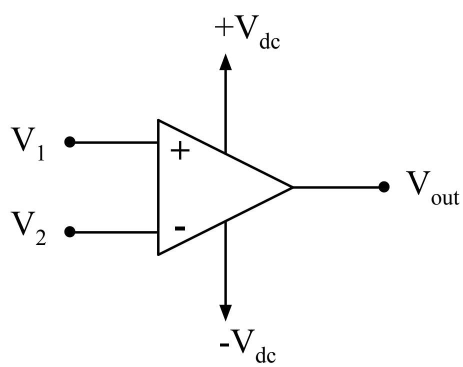
Picture from Wikipedia

What is an Op Amp?

An op amp is a differential amplifier that has two inputs and one output.

- The output voltage is an amplified version of the difference of the input voltages.





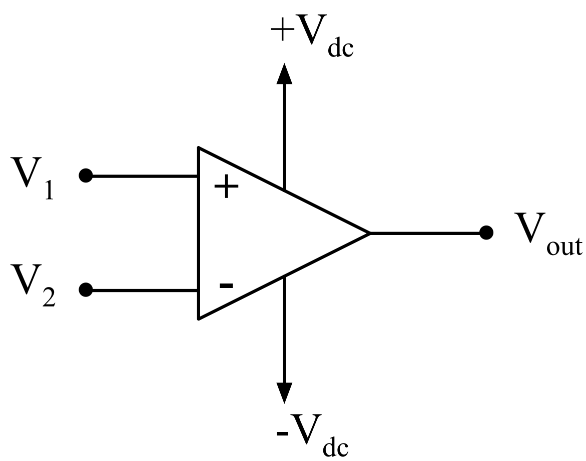
$$V_{out} = A \times (V_1 - V_2)$$

The amplification factor "A" is called the "open loop" gain of the op amp.

- It commonly has a value of 100,000 !

Op Amp Output Voltage Limitation

Even though the gain A is very high, the output of the op amp can't be any higher than the power supply voltages $+V_{dc}$ and $-V_{dc}$ which power the op amp.



$$V_{out} = A \times (V_1 - V_2)$$

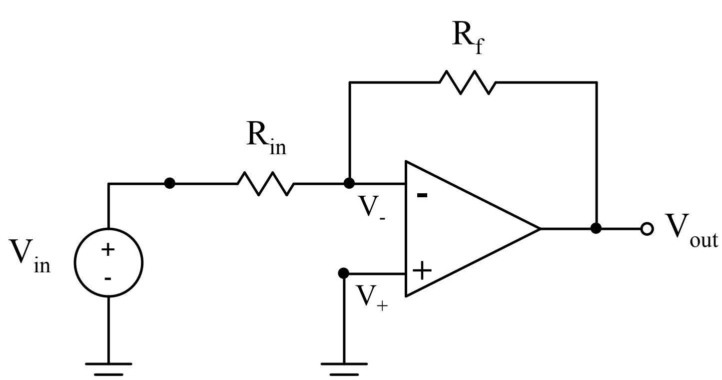
But

$$-V_{dc} < V_{out} < +V_{dc}$$

Controlling the Amplification

By feeding back the output of the op amp to the negative input terminal, we can control the amplification of an input signal.

- Using feedback is called the "closed loop" configuration.



In this "inverting amplifier" circuit, the output of the op amp is:

$$V_{out} = -V_{in} \times \frac{R_f}{R_{in}}$$

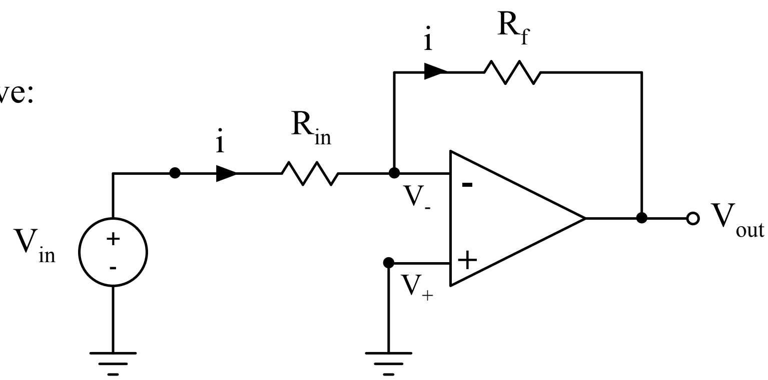
Where does this equation come from?

The Inverting Amplifier: Analysis

The "ideal" op amp has the following characteristics.

- The voltage applied to the V_+ input is mirrored on the V_- input.
- No current can enter the op amp input terminals, and so any current trying to enter V_- must instead travel through the feedback resistor.

Applying these conditions we have:



$$V_+ = 0$$

$$V_- = V_+ = 0$$

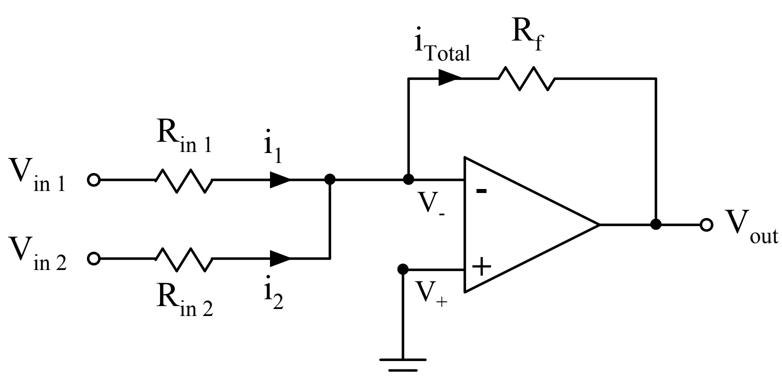
$$i = \frac{V_{in} - V_-}{R_{in}} = \frac{V_{in}}{R_{in}}$$

$$V_{out} = -\left(i \times R_f \right) = -V_{in} \times \frac{R_f}{R_{in}}$$

The Inverting Summing Amplifier

In this closed loop configuration, we have two voltages connected to the V_- input.

- Since $V_- = 0$, the currents i_1 and i_2 combine (i_{Total}), and travel through the feedback resistor. And so the output voltage is the sum of the two inputs treated as separate inverting amplifiers.



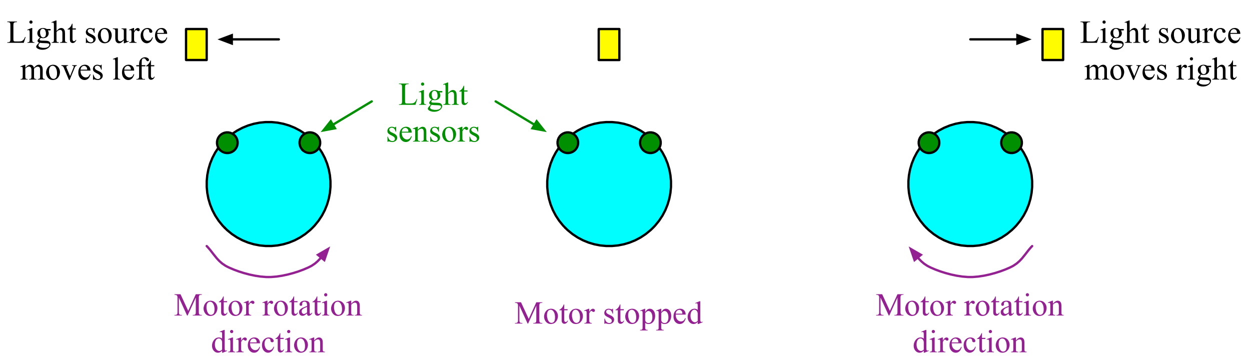
$$V_{out} = -\left(i_{Total} \times R_f \right) = -\left(\frac{R_f}{R_{in\,1}} V_{in\,1} + \frac{R_f}{R_{in\,2}} V_{in\,2} \right)$$

Light Tracking Motor Control System

Light Tracking System

Today you will build a light tracking system.

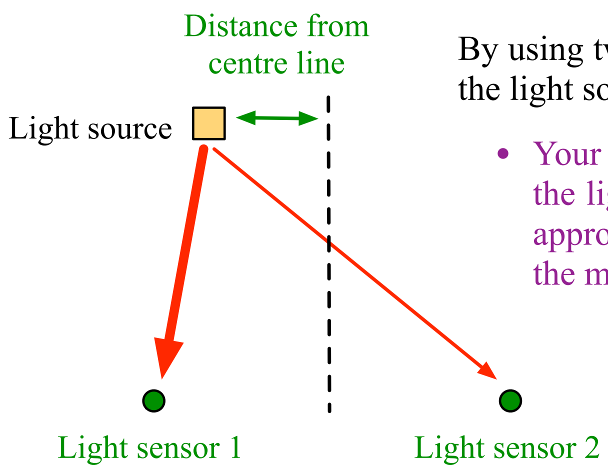
- You will build a circuit to control the rotation of a motor to follow a moving light source. ← Control system
- You will use two photoresistors as light sensors to monitor the position of the moving light. ← Tracking system
- Depending on which direction the light source moves, your control circuit should turn the motor to follow the light source.



DC Motor & Light Sensors

You will use a simple DC motor for your tracking system.

- The motor turns clockwise or counter clockwise, depending on the whether the voltage applied to the motor is positive or negative.



By using two light sensors, you can easily determine if the light source is moving left or right.

- Your control circuit will compare the intensity of the light received by the sensors, and provide the appropriate voltage (positive or negative) to turn the motor to follow the moving light source.

Control Systems

A control system is used to monitor system parameters and then regulate or command the system's behaviour.

Picture from Wikipedia

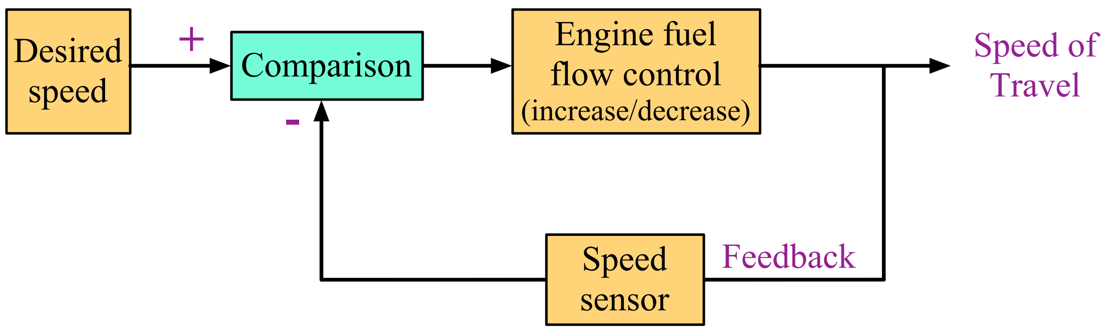
A thermostat is part of the control system that will turn the furnace on in your house if it falls below a set temperature.

The control system in a Segway uses data from the gyroscopic sensors to turn the wheels as needed to balance and move the passenger.

Control System with Feedback

A control loop can be formed using "feedback" of an output condition or sensor data, to try to regulate how something works, or adapt to varying conditions.

- A simple example is the cruise control system in a car. It regulates the fuel supply to the engine, in order to keep the car at a set speed.



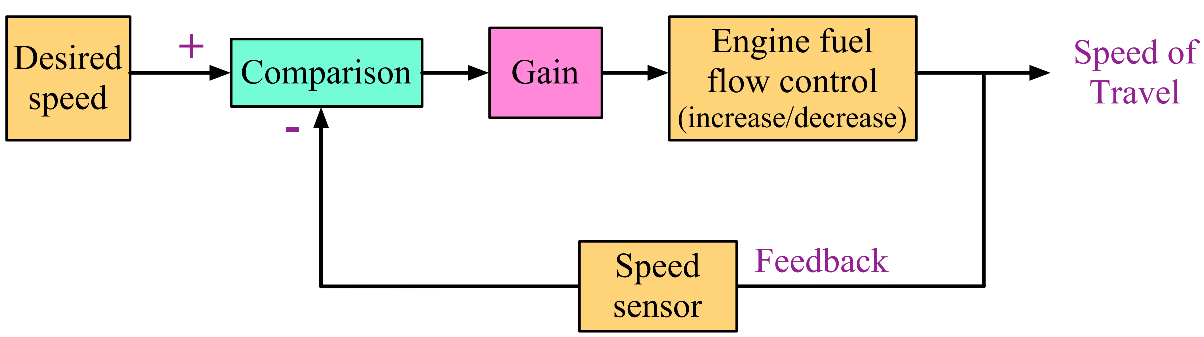
Who invented automotive cruise control?

- It was invented in 1945 by the blind engineer Ralph Teetor (1890 - 1982). His inspiration occurred while being driven in a car by his lawyer, who would slow down while talking and speed up while listening.

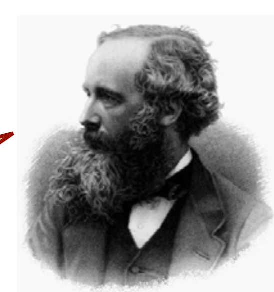
Controlling Reaction Speed

Often the comparison signal is amplified to a higher (or lower) value, in order to vary the speed that a control circuit reacts to a changing output condition.

- This is called Gain.



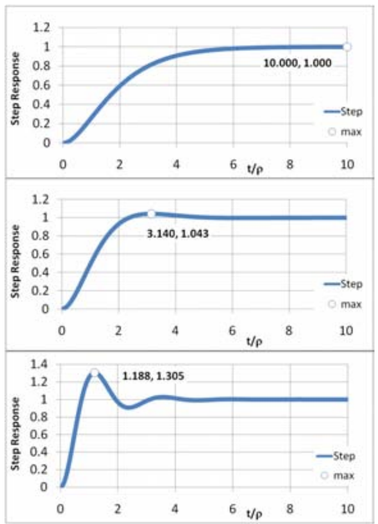
In 1868, the Scottish physicist James Clerk Maxwell published a first formal analysis of a control system, in his paper on the dynamic analysis of a centrifugal governor for steam engines.



Optimizing Control System Gain

Gain control can be critical.

- If the Gain is too low, the system may not be able to respond in time.
- If the Gain is too high, the error correction may be too fast, resulting in significant "overshoot", and the system can even become unstable (or oscillate).



Slow response

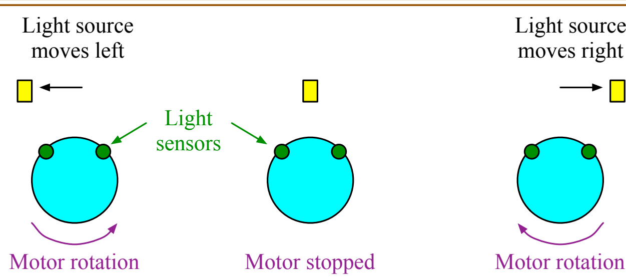
Sufficiently fast response

Very fast response, resulting in overshoot

Picture from Wikipedia

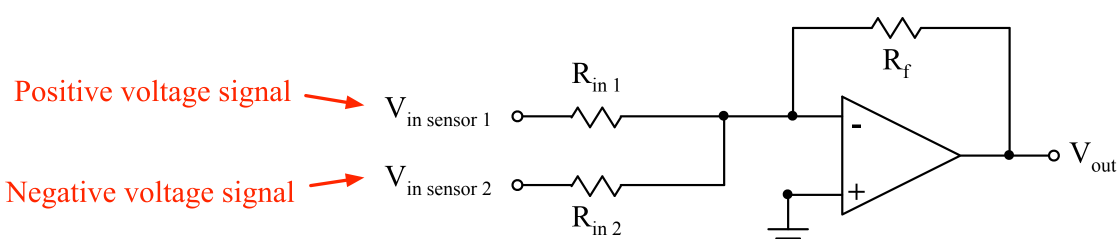
Motor Control System

You will control the movement of your motor using a summing amplifier.



The signal from sensor 1 will be a positive voltage, while the signal from sensor 2 will be a negative voltage. The op amp will sum their signals.

- The resulting V_{out} will be a positive or negative voltage value, depending on which sensor sees the brighter light signal.
- The amplifier's Gain controls how fast the motor will respond to the moving light.



Human Tracking Systems

Human Sensors

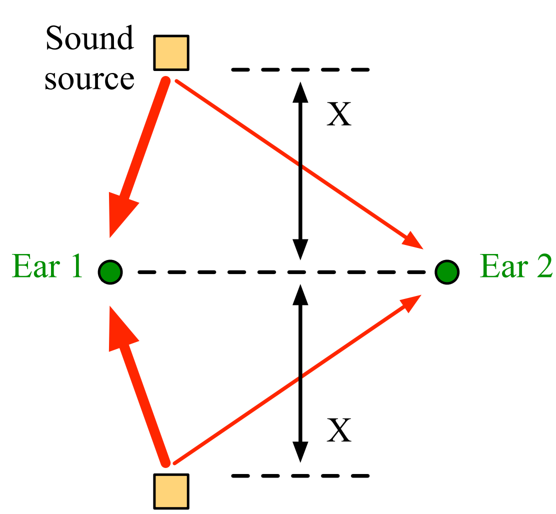
Like your control system, humans also have paired sensors to enable object tracking.

- Two eyes to follow visual movement.
- Two ears to determine the direction of an incoming sound.
- Two nostrils to determine the direction of an incoming smell.

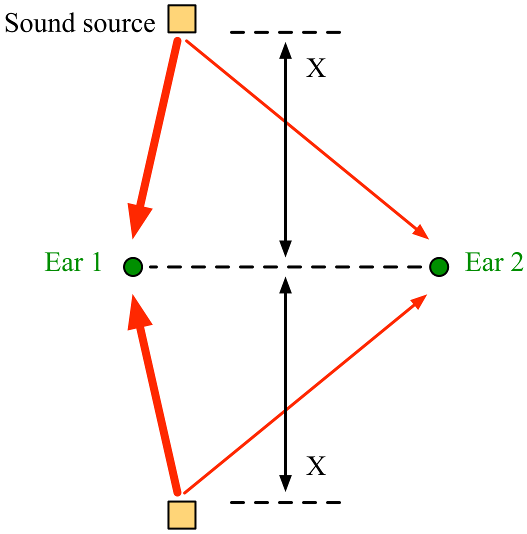
Human hearing is not so simple.

- With two simple audio sensors you can tell if a sound is coming from left or right, but you can't distinguish if it is coming from in front or from behind.

But humans are able identify if a sound is coming from in front, behind, above, or below. How is this possible?



The Solution is Signal Processing



The shape of our ears enables us to distinguish between sounds coming from front-back, and above-below.

- This is because our ears slightly distort the sound, depending on its direction.
- Our brains interpret these distortions, and determine appropriate sound localization.

3D audio technologies apply similar distortions to sound, in order to fool your brain into thinking that the sound coming from a speaker located in front of you, is coming from different points in a room or even behind you.

- This is an example of signal processing, which is a subject you will learn in upper year courses in Electrical and Computer Engineering.

Hand-Crank Flashlight

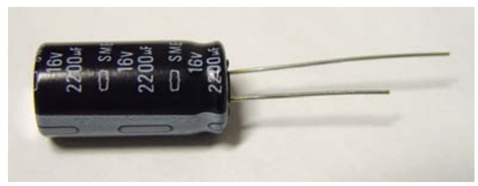
Generator & Capacitor

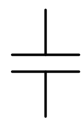
Your hand-crank flashlight will need a generator and an energy storage device.

Your DC motor will function as a generator if you turn the motor shaft with your hand.

- Do this gently so you don't break it.
- A slow turn will generate about 8 V.

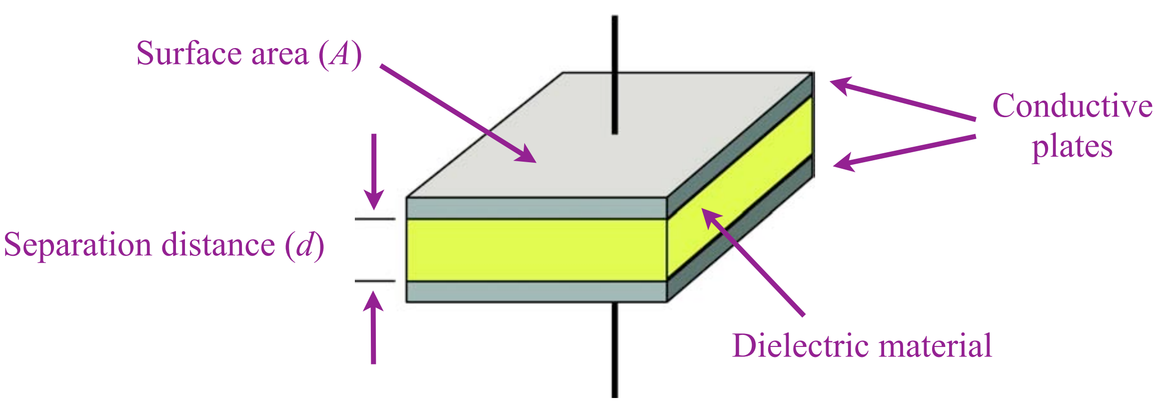
You will use a capacitor to store the energy you generate.



Circuit symbol for a capacitor 

Capacitors

A capacitor is an electronic device that can store electric charge. It consists of a pair of conductors separated by a thin insulator (dielectric), or an air gap.



$$C \propto \frac{A}{d}$$

The "capacitance" of a capacitor increases with increasing area (A) and decreasing separation between the plates (d).

- The unit of capacitance is the Farad (F).

It is named after Michael Faraday.

Capacitor Values

Typical capacitors used in common circuits range from nF (10^{-9} F) to mF (10^{-3} F).

- The capacitor that you will use today has a value of 2200 μF.

Super-capacitors are now becoming available that have ratings of 10's - 1000's F. Some are now replacing batteries for small levels of energy storage.

- Super-capacitors can be used for regenerative braking in electric vehicles, rechargeable power supplies, flashlights, and other applications.
- Compared to batteries, capacitors can charge very fast (seconds), and they have a longer working life (millions of charge cycles).

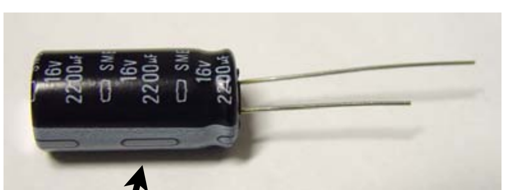
Super-capacitor flashlight charged by a hand-crank.

Super-capacitor flashlight charged by induction.

Polarized Capacitors

Polarized capacitors require one of the electrodes to be positive relative to the other.

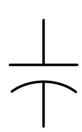
- The capacitor that you are using today is a polarized capacitor.



Charging a polarized capacitor the wrong way can damage it. And over charging it significantly can cause it to explode.

Dashed line indicates the negative side of the capacitor.

Circuit symbol of a polarized capacitor



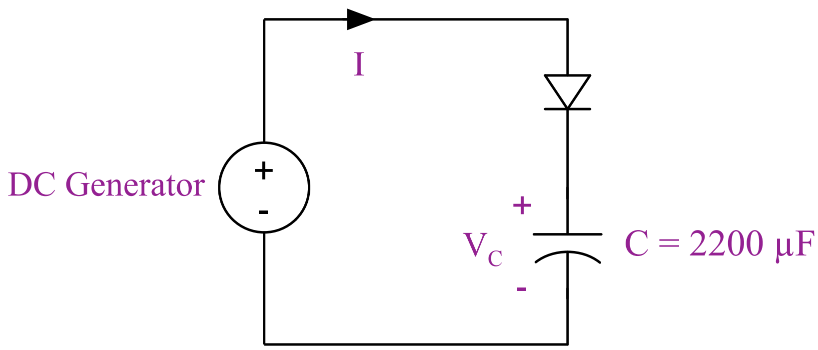
Connect this side to positive voltage.

Connect this side to negative voltage.

Energy Storage Circuit

By turning your motor backwards, you will generate electric current. You want to store this energy in your capacitor, but you don't want it to leak out when you stop turning the motor.

- You will use a diode to prevent electric current from flowing out of the capacitor.

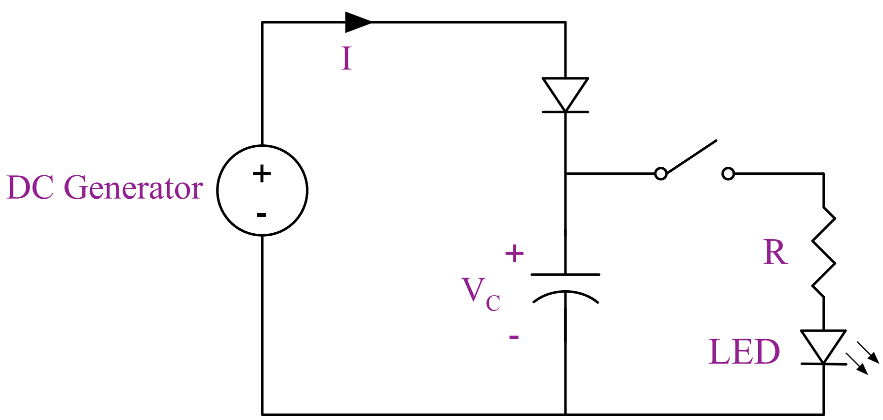


In the above circuit, once the capacitor is charged to a voltage V_C, energy can't escape when the generator stops, because current can't flow backwards through the diode.

Hand-Crank Flashlight

The energy stored in your capacitor will be used to power an LED.

- The flashlight circuit is connected in parallel with the capacitor.
- The switch controls when the capacitor is connected to the LED.

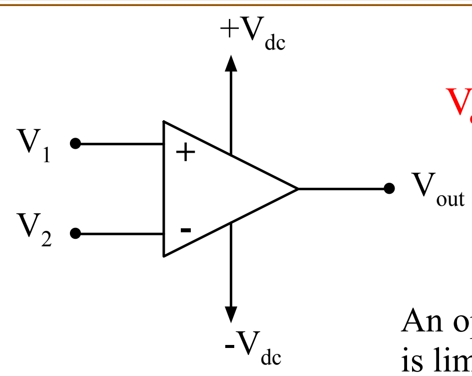


The resistor R is used to limit the current flowing through the LED, so that the LED does not burn out.

Important Things To Remember

Important Points

Op amp in the open loop (no feedback) configuration.

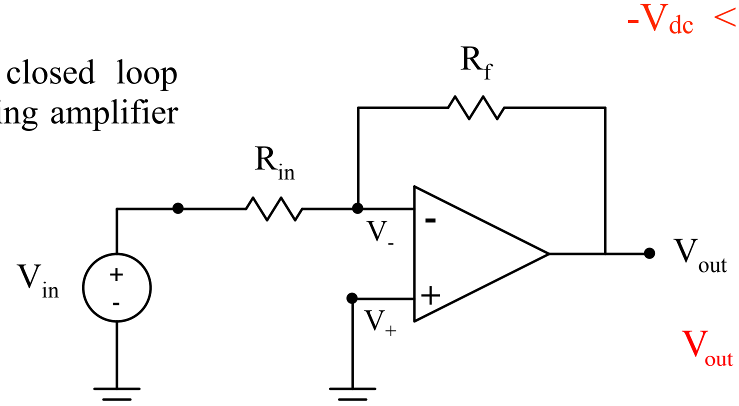


$$V_{out} = A \times (V_1 - V_2)$$

An op amp's output voltage is limited to be between:

$$-V_{dc} < V_{out} < +V_{dc}$$

Op amp in the closed loop (feedback) inverting amplifier configuration.



$$V_{out} = -V_{in} \times \frac{R_f}{R_{in}}$$