# Lecture #2

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## Basic Intent

This lecture is intended to overview the basic sensor terminology as it is generally used on product data sheets, and in the technical literature. This overview is presented in general terms, as well as in the description of a specific sensor, an off-the-shelf accelerometer, ADXL50A. Then, a summary of the basic electronic circuits we will be covering this quarter is presented.

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## Where do Sensors Come From?

There are a lot of sensors out there, and we'll do our best to cover a significant fraction of them this quarter. In all cases, the sensors we're going to be looking at are the result of some sort of invention, and it is interesting to think about how such things come to be.

In this day and age, there are researchers at companies, universities, and out there on their own competing to invent, design, build and sell the sensors which are going to be the next big wave in the industry. This competition has been going on for decades, and there are several basic facts at work :

1. Many of the obvious, easy inventions have already been tried out and completed or abandoned. As a potential sensor inventor, it is important to realize that there are a lot of people out there thinking about similar problems, and every day isn't going to be filled with really new ideas. Put in the harshest terms : most of the things you might think of have already been thought of.
2. Some of the people working in this business have great resources at their disposal. For example, University professors get to hire crowds of the smartest people on the planet (students), pay them a pittance, and watch them invent and test ideas. Or other professors (like me) get to teach classes where they ask their students to come up with cool ideas, work out some details, and then write the whole thing up in a term paper… Other examples include researchers at national labs or big industrial labs, where access to state of the art materials and equipment is key to finding the next really important sensor. It is VERY HARD to compete with all of these people. So, access to resources (people, equipment,…) is a big advantage.
3. There are some really important problems out there. If the Auto Industry says it is interested in buying 20 million gyroscopes at a price of $10 each every year, you can be sure that hundreds of people are trying to meet that challenge. So, there are

some industries which get to set the challenges which are the focus of inventor interest.

In light of this, I have some basic advice to people who might be interested in being inventors or product developers. Simply, I would discourage most people from getting into the game of trying to invent the next really important sensor. However, there is another game that I think is much easier to play, and much more likely to be lucrative. In a nutshell, I think it is much easier to be the inventor who uses the next cool sensor in a product that the sensor was not originally intended for. Here's an example : The Auto industry wants to use gyros for automatic skid control. Because of this, there are a lot of people working on ways to develop inexpensive gyros to detect auto skidding. There are a lot of other applications of gyros with this basic performance potential. I think the smart play is to assume that the auto industry will get what it wants sooner or later, and focus your efforts on thinking about other applications of a decent, small $10 gyro.

To win this game, you need to think about some of the things that the big players want to have available, and think about other things you could do with them. Who are the big players?

1. Auto Industry. There are 15 million cars sold a year in the US. Most components cost $5. If the auto industry wants something, they usually get it. Right now, they want to detect skids, detect the location and orientation of the passengers, and they want to provide navigational assistance to drivers.
2. Medical Industry. You only have to watch ER or any other hospital-based drama on TV to be shown several examples each hour of sensor-based medical technology. The big things this industry wants are blood chemistry sensors, low-cost, high speed diagnostics, implantable therapeutic devices, and DNA testing.
3. The Department of Defense. The cold war might be over, and there might not be any credible enemies out there, but the DOD still has the largest basic research budget in the world. The DOD loves sensors, and is very interested in technologies that allow us to wage war without putting personnel at risk. Night vision, navigation, "smart" soldier, smart munitions, bullets, etc, Stealth technologies for Sonar and Radar, and many more. The DOD usually gets what they want, and they have the $$$ to pay for people to work on their problems, so things will emerge.

So, read up on the cutting edge in these communities, and make assumptions about things coming out sooner or later, and be prepared to use those things in new ways…

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# Introduction to Sensor Terminology

For our purposes, a Sensor is a device which converts a physical phenomena into an electrical signal. As such, sensors represent part of the interface between the physical world and the world of electrical devices, such as computers. The other part of this interface is represented by Actuators, which convert electrical signals into physical phenomena.

Why do we care so much about this interface? In recent years, enormous capability for information processing has been developed within the electronics industry. The largest example of this capability is the personal computer. In addition, the availability of inexpensive microprocessors is having a tremendous impact on the design of products ranging from automobiles to microwave ovens to toys. In recent years, versions of these products which utilize microprocessors for control of functionality are becoming widely available. In automobiles, such capability is necessary to achieve compliance with pollution restrictions. In other cases, such capability simply offers an inexpensive performance advantage.

All of these microprocessors need electrical input voltages in order to receive instructions and information. So, along with the availability of inexpensive microprocessors has grown an opportunity for the use of sensors in a wide variety of products.

In addition, since the output of the sensor is an electrical signal, we tend to characterize sensors in the same way we characterize electronic devices. The data sheets for many sensors are formatted just like electronic product data sheets.

However, there are many formats out there, and nothing at all like an international standard for sensor specifications. We will encounter a variety of interpretations of sensor performance parameters, and sometimes a lot of confusion will emerge. It is important for you to realize that this confusion is not due to our inability to explain the meaning of the terms - it is a result of the fact that different parts of the sensor community have gotten comfortable using these terms differently.

It is important to realize the function of the data sheet in order to deal with this variability. The data sheet is primarily a marketing document. It will be designed to highlight the positive attributes of the sensor, emphasize some of the potential uses of the sensor, and might neglect to comment on some of the negative characteristics of the sensor. In many cases, the sensor has been designed to meet a particular performance specification for a specific customer, and the data sheet will concentrate on the performance parameters of greatest interest to this customer. In this case, the vendor and customer might have grown accustomed to unusual definitions for certain sensor performance parameters. As a potential new user of such a sensor, it is initially your problem to recognize this situation, and interpret things reasonably.

So, expect that you will encounter odd definitions here and there, and expect that you will find that most sensor data sheets are missing some information that you might be most interested in. That is the nature of the business.

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# Sensor Performance Characteristics Definitions

**Transfer Function**:

The functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics. For expensive sensors which are individually calibrated, this might take the form of the certified calibration curve.

**Sensitivity**:

The sensitivity is defined in terms of the relationship between input physical signal and output electrical signal. The sensitivity is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with respect to physical signal. Typical units: Volts/Kelvin. A Thermometer would have "high sensitivity" if a small temperature change resulted in a large voltage change.

**Span or Dynamic Range**:

The range of input physical signals which may be converted to electrical signals by the sensor. Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier as the range over which other performance characteristics described in the data sheets are expected to apply. Typical units: Kelvin

**Accuracy**:

Generally defined as the largest expected error between actual and ideal output signals. Typical Units: Kelvin. Sometimes this is quoted as a fraction of the full scale output. For example, a thermometer might be guaranteed accurate to within 5% of FSO (Full Scale Output)

**Hysteresis**:

Some sensors do not return to the same output value when the input stimulus is cycled up or down. The width of the expected error in terms of the measured quantity is defined as the hysteresis. Typical units: Kelvin or % of FSO

**Nonlinearity (often called Linearity)**:

The maximum deviation from a linear transfer function over the specified dynamic range. There are several measures of this error. The most common compares the actual transfer function with the `best straight line', which lies midway between the two parallel lines which encompasses the entire transfer function over the specified dynamic range of the device. This choice of comparison method is popular because it makes most sensors look the best.

**Noise**:

All sensors produce some output noise in addition to the output signal. In some cases, the noise of the sensor is less than the noise of the next element in the electronics, or less than the fluctuations in the physical signal, in which case it is not important. Many other cases exist in which the noise of the sensor limits the performance of the system based on the sensor. Noise is generally distributed across the frequency spectrum. Many common noise sources produce a white noise distribution, which is to say that the spectral noise density is the same at all frequencies. Johnson noise in a resistor is a good example of such a noise distribution. For white noise, the spectral noise density is characterized in units of

Volts/Root(Hz). A distribution of this nature adds noise to a measurement with amplitude proportional to the square root of the measurement bandwidth. Since there is an inverse relationship between the bandwidth and measurement time, it can be said that the noise decreases with the square root of the measurement time.

**Resolution**:

The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out. Many sensors are limited by noise with a white spectral distribution. In these cases, the resolution may be specified in units of physical signal/Root(Hz). Then, the actual resolution for a particular measurement may be obtained by multiplying this quantity by the square root of the measurement bandwidth. Sensor data sheets generally quote resolution in units of signal/Root(Hz) or they give a minimum detectable signal for a specific measurement. If the shape of the noise distribution is also specified, it is possible to generalize these results to any measurement.

**Bandwidth**:

All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cutoff frequencies, respectively. The bandwidth of a sensor is the frequency range between these two frequencies.

These definitions are adapted from those in Fraden, and will be used in this manner throughout the course.

# Sensor Performance Characteristics of an Example Device

To add substance to these definitions, we will identify the numerical values of these parameters for an off-the-shelf accelerometer, **ADXL50A** from **Analog Devices**. View the **ADXL50A Data Sheets** with **Adobe** **Acrobat**.

**Transfer Function**

The functional relationship between voltage and acceleration is stated as

$$V(Acc) = 1.8V + \left( Acc \times 19 \frac{mV}{g} \right)$$

This expression may be used to predict the behavior of the sensor, and contains information about the sensitivity and the offset at the output of the sensor.

**Sensitivity**

The sensitivity of the sensor is given by the derivative of the voltage with respect to acceleration at the initial operating point. For this device, the sensitivity is 19 mV/g.

**Dynamic Range**
For ADXL50A accelerometer, the stated dynamic range is +/- 50g. For signals outside this range, the signal output is saturated at either 0.25V or 4.75V. The device can withstand up to 2000g without damage.
**Hysteresis**
There is no fundamental source of hysteresis in this device. There is no mention of hysteresis in the **Data Sheets**.
**Temperature Coefficient**
In this device, temperature can introduce a change in sensitivity. The change is less than 1% over the range from -40 to +85 degrees Celsius. There is also a shift in offset of up to 35 mV.
**Linearity**
In this case, the linearity is the difference between the actual transfer function and the best straight line over the specified operating range. For this device, this is stated as less than 0.2% of the full scale output. The **Data Sheets** (fig. 5) show the expected deviation from linearity.
**Accuracy**
The accuracy is essentially limited by the nonlinearity and the temperature coefficients. Altogether, the device is accurate to within 3% over the full scale signal range and over temperatures from -40 to +85 degrees Celsius.
**Noise**
Noise in this device comes from the electronic measuring circuit, and is expressed as 125 uV/sqrt(Hz). This noise density should be used to calculate the actual noise for a particular measurement. For example, if the output is filtered by a 10Hz low-pass, the RMS Noise would be

$$V_{RMSNoise} = 125 \frac{\mu V}{\sqrt{Hz}} \times \sqrt{10Hz} = 395 \mu V$$

**Resolution**
The resolution is the minimum detectable signal fluctuation. This is given by the voltage noise density divided by the sensitivity

$$\text{Resolution} = \frac{\text{Noise Density}}{\text{Sensitivity}} = \frac{125 \frac{\mu V}{\sqrt{Hz}}}{19 \frac{mV}{g}} = 6.6 \frac{mg}{\sqrt{Hz}}$$

Again, for a real experiment with a 10Hz bandwidth, the resolution would come to 20mg.
**Bandwidth**
The bandwidth of this sensor depends on choice of an external capacitor. For C = 0.022 uF, the Bandwidth is approx. 1300Hz. For C = 0.007 uF, B/W = 10kHz.

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# Introduction to Sensor Electronics

The electronics which go along with the physical sensor element are often very important to the overall device. The sensor electronics can limit the performance, cost, and range of applicability. If carried out properly, the design of the sensor electronics can improve the characteristics of the entire device.
As for the rest of this course, the intent is not to prepare you to design sensors in great detail. Nevertheless, it is important to include some discussion of sensor electronics. We will focus on basic techniques for processing the signals most typically produced by a sensor.
Most sensors do not directly produce voltages. Instead, most sensors act like passive devices, such as resistors, whose values change in response to external stimuli. In order to produce voltages suitable for input to a microprocessors and their analog to digital converters, the resistor needs to be `biased' and the output signal needs to be `amplified'.

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# Types of Sensors

**Resistive Sensor Circuits**

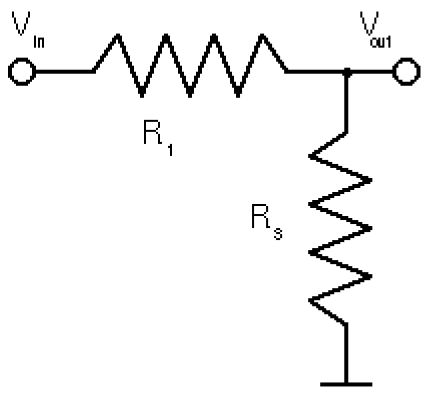


Fig. 1: Voltage Divider

$$V_s = \frac{R_s}{R_1 + R_s} V_{in}$$

$$if\, R_1 >> R_s,\; V_s = \frac{R_s}{R_1} V_{in}$$

Resistive devices obey Ohm's law, which basically states that when current flows through a resistor, there will be a voltage difference across the resistor. So, one way to measure resistance is to force a current to flow and measure the voltage drop. Current sources can be built in number of ways (see Horowitz and Hill for loads of good examples). One of the easiest current sources to build is to take a voltage source and a stable resistor whose resistance is much larger than the one you're interested in measuring. The reference resistor is called a load resistor. Analyzing the connected load and sense resistors as shown in Fig. 1, we can see that the current flowing through the circuit is nearly constant, since most of the resistance in the circuit is constant. Therefore, the voltage across the sense resistor is nearly proportional to the resistance of the sense resistor.

As stated, the load resistor must be much larger than the sense resistor for this circuit to offer good linearity. As a result, the output voltage will be much smaller than the input voltage. Therefore, some amplification will be needed.

**Capacitance measuring circuits**

Many sensors respond to physical signals by producing a change in capacitance. How is capacitance measured? Essentially, all capacitors have an impedance which is given by

$$impedance = \frac{1}{i\omega C} = \frac{1}{i2\pi fC}$$

where `f' is the oscillation frequency in Hz, `w' is in rad/sec, and `C' is the capacitance in Farads. The `i' in this equation is the square root of -1, and signifies the phase shift between the current through a capacitor and the voltage across the capacitor.

Now, ideal capacitors cannot pass current at DC, since there is a physical separation between the conductive elements. However, oscillating voltages induce charge oscillations on the plates of the capacitor, which act as if there is physical charge flowing through the circuit. Since the oscillation reverses direction before substantial charges accumulate, there are no problems. The effective resistance of the capacitor is a meaningful characteristic, as long as we are talking about oscillating voltages.

With this in mind, the capacitor looks very much like a resistor. Therefore, we may measure capacitance by building voltage divider circuits as in Fig. 1, and we may use either a resistor or a capacitor as the load resistance. It is generally easiest to use a resistor, since inexpensive resistors are available which have much smaller temperature coefficients than any reference capacitor. Following this analogy, we may build capacitance bridges as well. The only substantial difference is that these circuits must be biased with oscillating voltages. Since the `resistance' of the capacitor depends on the frequency of the AC bias, it is important to select this frequency carefully. By doing so, all of the advantages of bridges for resistance measurement are also available for capacitance measurement.

However, providing an AC bias is a substantial hassle. Moreover, converting the AC signal to a dc signal for a microprocessor interface can be a substantial hassle. On the other hand, the availability of a modulated signal creates an opportunity for use of some advanced sampling and processing techniques. Several good examples are described in the textbook, and there are several more in any good circuits book, such as Horowitz and Hill. Generally speaking, voltage oscillations must be used to bias the sensor. It can also be used to trigger voltage sampling circuits in a way that automatically subtracts the voltages from opposite clock phases. Such a technique is very valuable, because signals which oscillate at the correct frequency are added up, while any noise signals at all other frequencies are subtracted away. One reason these circuits have become popular in recent years is that they may be easily designed and fabricated using ordinary digital VLSI fabrication tools. Clocks and switches are easily made from transistors in CMOS circuits. Therefore, such designs can be included at very small additional cost - remember that the oscillator circuit has to be there to bias the sensor anyway.

So, capacitance measuring circuits are increasingly implemented as integrated clock/sample circuits of various kinds. Such circuits are capable of good capacitance measurement, but not of very high performance measurement, since the clocked switches inject noise charges into the circuit. These injected charges result in voltage offsets and errors which are very difficult to eliminate entirely. Therefore, very accurate capacitance measurement still requires expensive precision circuitry.

**Inductance measurement circuits**

Inductances are also essentially resistive elements. The `resistance' of an inductor is given by i2(Pi)fL, and this resistance may be compared with the resistance of any other passive element in a divider circuit or in a bridge circuit as shown in Fig. 1 above. Inductive sensors generally require expensive techniques for the fabrication of the sensor mechanical structure, so inexpensive circuits are not generally of much use. In large part, this is because inductors are generally 3-dimensional devices, consisting of a wire coiled around a form. As a result, inductive measuring circuits are most often of the traditional variety, relying on resistance divider approaches.

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# Limitations

**Limitations to resistance measurement**

- **Lead Resistance - The wires leading from the resistive sensor element have resistance of their own. These resistances may be large enough to add errors to the measurement, and they may have temperature dependencies which are large enough to matter. One useful solution to the problem is the use of the so-called 4-wire resistance approach (Fig. 2). In this case, current (from a current source as in Fig. 1) is passed through the leads and through the sensor element. A second pair of wires is independently attached to the sensor leads, and a voltage reading is made across these two wires alone.**

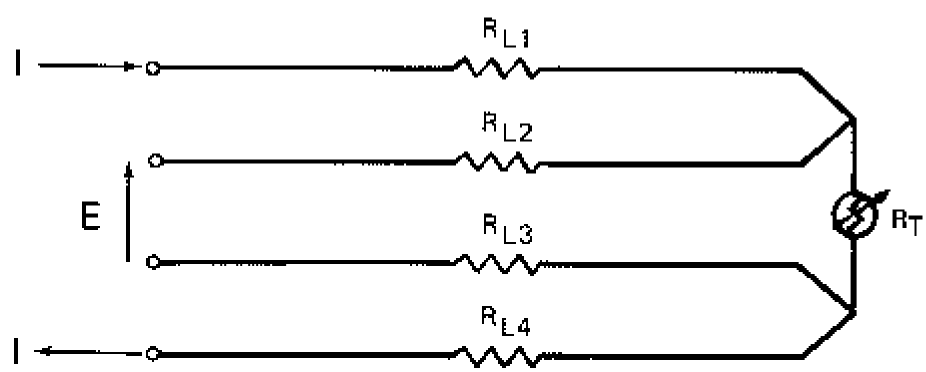


**Fig. 2: Lead Compensation**

**It is assumed that the voltage measuring instrument does not draw significant current (see next point), so it simply measures the voltage**

**drop across the sensor element alone. Such a 4-wire configuration is especially important when the sensor resistance is small, and the lead resistance is most likely to be a significant problem.**

- **Output Impedance - The measuring network has a characteristic resistance which, simply put, places a lower limit on the value of a resistance which may be connected across the output terminals without changing the output voltage. For example, if the thermistor resistance is 10K and the load resistor resistance is 1 meg, the output impedance of this circuit is approximately 10K. If a 1K resistor is connected across the output leads, the output voltage would be reduced by about 90%. This is because the load applied to the circuit (1K) is much smaller than the output impedance of the circuit (10K), and the output is `loaded down'. So, we must be concerned with the effective resistance of any measuring instrument that we might attach to the output of such a circuit. This is a well-known problem, so measuring instruments are often designed to offer maximum input impedance, so as to minimize loading effects. In our discussions we must be careful to arrange for instrument input impedance to be much greater than sensor output impedance.**

**Limitations to measurement of capacitance**

- **Stray Capacitance - Any wire in a real world environment has a finite capacitance with respect to ground. If we have a sensor which has an output which looks like a capacitor, we must be careful with the wires which run from the sensor to the rest of the circuit. These stray capacitances appear as additional capacitances in the measuring circuit, and can cause errors. One source of error is the changes in capacitance which results from these wires moving about with respect to ground, causing capacitance fluctuations which might be confused with the signal. Since these effects can be due to acoustic pressure-induced vibrations in the positions of objects, they are often referred to as microphonics. An important way to minimize stray capacitances is to minimize the separation between the sensor element and the rest of the circuit. Another way to minimize the effects of stray capacitances is mentioned later - the virtual ground amplifier.**

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# Filters

**Electronic filters are important for separating signals from noise in a measurement. During this course, we'll look at a few simple filters, and I'll expect you to be able to work through simple circuits with some of these filters in them.**

- **Low pass - A low-pass filter (fig 3.) uses a resistor and a capacitor in a voltage divider configuration. In this case, the `resistance' of the capacitor decreases**

**at high frequency, so the output voltage decreases as a the input frequency increases. So, this circuit effectively filters out the high frequencies and `passes' the low frequencies.**

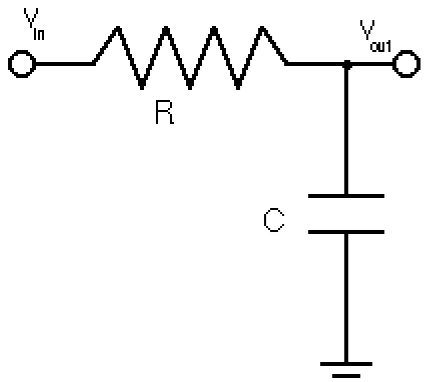


**Fig. 3: Low-pass Filter**

**The mathematical analysis is as follows :**
**Using the complex notation for the impedance, let**

$$Z_1 = R,\ Z_2 = \frac{1}{i\omega C}$$

**Using the voltage divider equation in Fig. 1**

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} V_{in}$$

**Substituting for Z1 and Z2**

$$V_{out} = \frac{\frac{1}{i\omega C}}{R + \frac{1}{i\omega C}} V_{in} = \frac{1}{i\omega RC + 1} V_{in}$$

**The magnitude of Vout is**

$$|V_{out}| = \sqrt{\frac{1}{(\omega RC)^2 + 1}} |V_{in}|$$

**and the phase of Vout is**

$$\phi = \tan^{-1}(-\omega RC)$$

- **High-pass - The high pass filter is exactly analogous to the low pass, except that the roles of the resistor and capacitor are reversed. The analysis of a high-pass filter is as follows :**

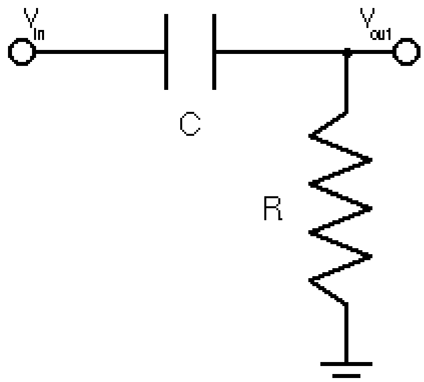


**Fig. 4: High-pass Filter**

**Similar to low-pass filter,**

$$V_{out} = \frac{R}{R + \frac{1}{i\omega C}} V_{in}$$

**The magnitude is**

$$|V_{out}| = \frac{R}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} |V_{in}|$$

**and the phase is**

$$\phi = \tan^{-1}\left(\frac{-1}{\omega RC}\right)$$

- **Band-pass - By combining low-pass and high-pass filters together, we can create a band-pass filter that allows signals between two preset oscillation frequencies. Its diagram and the derivations are as follows:**

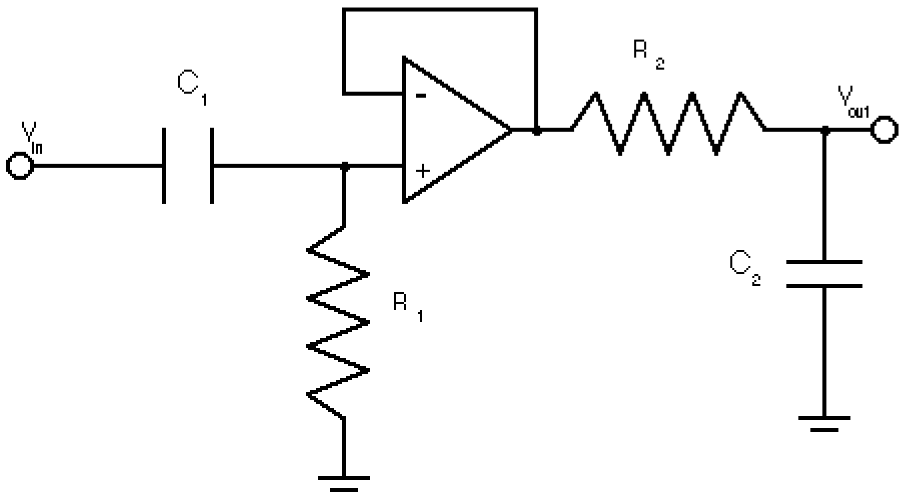


**Fig. 5: Band-pass Filter**

**Let the high-pass filter have the oscillation frequency w1 and the low-pass filter have the frequency w2 such that**

$$\omega_{1} = \frac{1}{R_1 C_1},\ \omega_{2} = \frac{1}{R_2 C_2},\ \omega_1 < \omega_2$$

**Then the relation between Vout and Vin is**

$$V_{out} = \left(\frac{1}{i\omega_2 R_2 C_2 + 1}\right)\left(\frac{i\omega_1 R_1 C_1}{i\omega_1 R_1 C_1 + 1}\right) V_{in}$$

**The operational amplifier in the middle of the circuit was added in this circuit to isolate the high-pass from the low-pass filter so that they do not effectively load each other. The op-amp simply works as a buffer in this case. In the following section, the role of the op-amps will be discussed more in detail. To further understand the purpose and theory of the follower op-amp configuration, see Operational amplifiers.**

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# Operational amplifiers

**Op-Amps are electronic devices which are of enormous generic use for signal processing. The use of op-amps can be complicated, but there are a few simple rules and a few simple circuit building blocks which we need to be familiar with to understand many common sensors and the circuits used with them.**
**An op-amp is essentially a simple 2-input, 1-output device. The output voltage is equal to the difference between the non-inverting input and the inverting input**

**multiplied by some extremely large value (10^5). Use of op-amps as simple amplifiers is uncommon.**

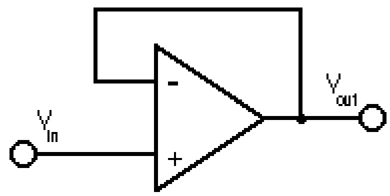


**Fig 6: Non-inverting Unity Gain Amplifier**

**One really valuable concept for use of op-amps is that of feedback. For instance consider the circuit shown in Fig. 5. This is called the follower configuration. Notice that the inverting input is tied directly to the output. In this case, if the output is less than the input, the difference between the inputs is a positive quantity, and the output voltage will be increased. This adjustment process continues - until the output is at the same voltage as the non-inverting input. Then, everything stays fixed, and the output will follow the voltage of the non-inverting input. This circuit appears to be useless, until you consider that the input impedance of the op-amp can be as high as 10^9 ohms, while the output can be many orders of magnitude smaller. Therefore, this follower circuit is a good way to isolate circuit stages with high output impedance from stages with low input impedance.**
**This op-amp circuit can be analyzed very easily, using the op-amp golden rules:**

1. **No current flows into the inputs of the op-amp**
2. **When configured for negative feedback, the output will be at whatever value makes the input voltages equal.**

**Even though these golden rules only apply to ideal operational amplifiers, the op-amps can in most cases be treated as ideal. Let's use these rules to analyze some more circuits...**

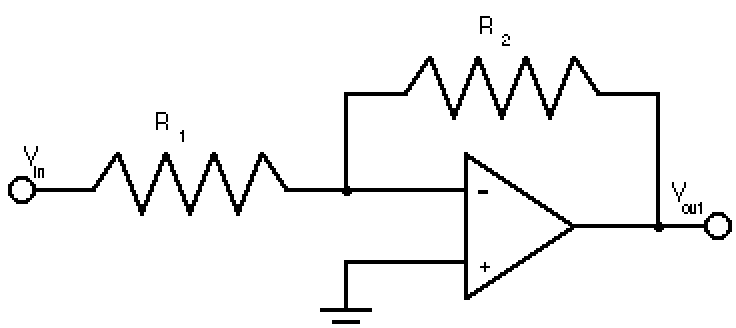


**Fig. 7: Inverting Amplifier**

**Fig. 7 shows an example of an inverting amplifier. We can derive the equation by taking following steps.**

1. **Point B is ground. Therefore, point A is also ground. (Rule 2)**
2. **Since the current flowing from Vin to Vout is constant (Rule 1), Vout/R2 = -Vin/R1**
3. **Therefore, voltage gain = Vout/Vin = -R2/R1**

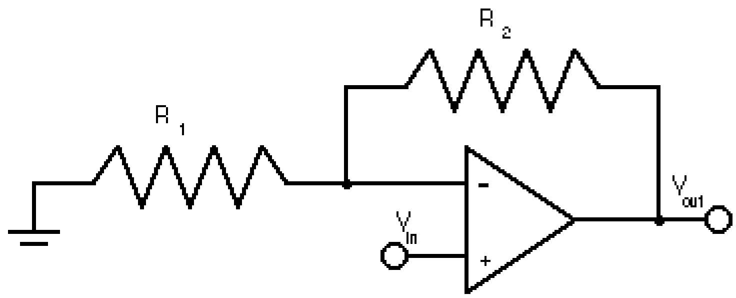


**Fig. 8: Non-inverting Amplifier**

**Fig. 8 illustrates another useful configuration of an op-amp. This is a non-inverting amplifier, which is slightly different expression than the inverting amplifier. Taking it step-by-step,**

1. **Va = Vin (Rule 2)**
2. **Since Va comes from a voltage divider, Va = (R1/(R1 + R2)) Vout**
3. **Therefore, Vin = (R1/(R1 + R2)) Vout**
4. **Vout/Vin = (R1 + R2)/R1 = 1 + R2/R1**

**The op-amp rules are simple enough that I'll expect you to be able to use them to work through simple circuits and figure out what the voltages are doing.**

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# Summary


**This lecture has overviewed the basic characteristics of sensors that you can expect to find specified in sensor data sheets. The details of those definitions are discussed for the case of a resistance thermometer, and numerical values are produced for a typical device. Finally, some background on electrical measurement of sensor outputs is given. Some details regarding the behavior of simple passive filters and operational amplifiers are also given.**