IR Remote Control

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Do you have a remote control for your television at home? If you do, it is probably an infrared remote (IR). When you push a button on the IR remote, a series of flashes of IR light are emitted. Those flashes send a code to the TV, which the TV decodes, and then applies the appropriate action. If you press the power button on the remote, then it sends a specific code to the TV, instructing it to turn on the power. If you press the volume increase button, then the remote sends another code to the TV and the TV increases the volume. In this paper you will learn how IR remote controls work.

Many electronic systems utilize **electromagnetic radiation** to transmit signals between devices. The transmission method is sometimes called **wireless**, because the devices are not connected by a wire. Radio broadcasts are transmitted through the air from a radio station antenna to a radio receiver antenna. The transmission is achieved by radio waves, a type of electromagnetic radiation. Your IR TV remote also sends signals through the air, but by infrared light, which is another type of electromagnetic radiation. In addition to sending signals, electromagnetic radiation can be employed for other purposes. Our homes are illuminated at night by lamps that emit visible light, another type of electromagnetic radiation. Your dentist may take photos of your teeth using an x-ray machine. X-rays are another type of electromagnetic radiation. Food is heated in your microwave oven by microwaves, another type of electromagnetic radiation.

There are several types of electromagnetic radiation. The types are distinguished by the **wavelength** of the electromagnetic radiation. While these different types may seem very different, from a physics point of view, they are the same thing. It is the wavelength that determines the special properties of each type of electromagnetic radiation. The table below lists the types of electromagnetic radiation and their range in wavelength.

Type	Wavelength
Radio	More than 10 centimeters (10 cm)
Microwave	0.01 cm to 10 cm
Infrared light	700 nanometers to 0.01 cm
Visible light	400 nm to 700 nm
Ultraviolet light	1.0 nm to 400 nm
X-rays	0.01 nm to 1.0 nm
Gamma-rays	Less than 0.01 nm

 nm = nanometer, there are one billion nanometers in one meter

The full range of electromagnetic radiation wavelengths is quite dramatic. The wavelength of a gamma-ray is extremely short, less than 0.00000000001 meter long. That length is much too short for you to see, even in a microscope. In contrast, radio waves can be longer than a football field.

The range of wavelengths detected by the human eye is very restricted. The shortest wavelength is about 400 nanometers (nm). Light of about 400 nm wavelength is seen as the color violet by humans. The longest wavelengths visible to humans are about 700 nm and we see these wavelengths as the color red. As the wavelength of light increases from 400 to 700 nm, we see the colors of the rainbow, in this order: violet, blue, green, yellow, orange and red.

Wavelengths longer than 700 nm but shorter than 0.01 cm are called **infrared light**. Humans can't see infrared light. If you press a button on your IR remote control, you won't see any flashes of light. However, you can feel intense infrared light. Slightly more than half of the energy of sunlight reaching the Earth's surface is in the form of IR light. When IR light strikes our bodies, some of it is absorbed and converted into heat energy. That is why the Sun feels warm to us on a sunny summer day.

As the wavelength of electromagnetic radiation shortens, the energy of that radiation increases. That is to say, the individual particles of electromagnetic radiation, called **photons**, are more energetic at shorter wavelengths. If you stay outdoors too long on a sunny summer day, you may get sunburned. The sunburn is caused by ultraviolet (UV) light. While the Sun provides more energy as IR light, the individual photons of UV light are more energetic than the individual photons of IR light. There just happens to be many more photons of IR light than UV light received from the Sun.

X-rays have even shorter wavelengths than UV light. X-ray photons are so energetic that they are capable of easily passing through your teeth and body. That is why dentists can use x-rays to take images of the interior of your teeth. Medical doctors also use x-rays to image your skeleton, which is handy if you happen to break a bone.

I find electromagnetic radiation a mysterious phenomenon. We can't see electromagnetic waves, but scientists have demonstrated the existence of the waves by various experimental procedures.

Perhaps we can use the classic analogy of a stone dropped in a pond of water. As the stone enters the pond, it disturbs the surface of the water, sending out a series of waves upon the surface. If we look carefully, we notice that these waves are nothing more than changes in the height of the water surface. Imagine that we cut through the water surface with a pane of glass so that we can see the shape of the waves from the side. Then we could make a drawing of the waves like the one on the right. The waves are represented by a red line. We can measure the wavelength by determining the distance from one wave peak to the next. In fact, we can measure the wavelength at any point along the undulating red line, as long as the two end points of our measurement represent the same position
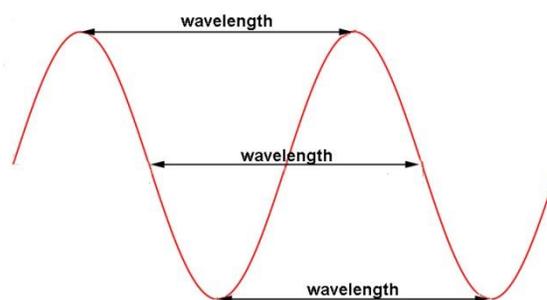
in the wave cycle.

In our lesson on DC motors we had a demonstration of the **magnetic field** lines around a magnet.   The invisible magnetic field lines were visualized by sprinkling iron filings around the magnet. Invisible **electric fields** occur around electrically charged particles, just as magnetic fields occur around magnets. Recall that opposite magnetic poles attract each other and like magnetic poles repel each other. The same phenomenon is observed with electric charge.   Like charges repel each other and opposite charges attract. An instrument called an electrometer can be used to observe the repelling effect of like charges (http://en.wikipedia.org/wiki/Electrometer). When electrons are used to charge a piece of gold foil, folded like pages in a book, the two halves of the foil will move away from each other. This is a demonstration of the electric field surrounding the two halves of the foil.

Electromagnetic radiation is a combination of electric and magnetic fields in the shape of waves that travel through space. These waves travel together, aligned in planes that are at right angles to each other and to the direction of travel (see this page for a diagram of the waves, animated: http://www.astronomynotes.com/light/s2.htm). Since we can't see electric and magnetic fields, it should not be a surprise that the waves of electromagnetic radiation are invisible to humans. Humans can detect visible light, a type of electromagnetic radiation, but they cannot see the actual light waves.

Electric current traveling through a wire is not electromagnetic radiation (although it can create electromagnetic radiation). Nevertheless, we can depict (draw) electric current as waves. This is particularly helpful if the current is rapidly changing. The alternating current (AC) delivered to your home is a good example. The changing current can be depicted as a wave much like the one in red on the previous page. There can be other shapes of waves for different types of dynamic current. The various shapes can be displayed with an instrument called an **oscilloscope**.
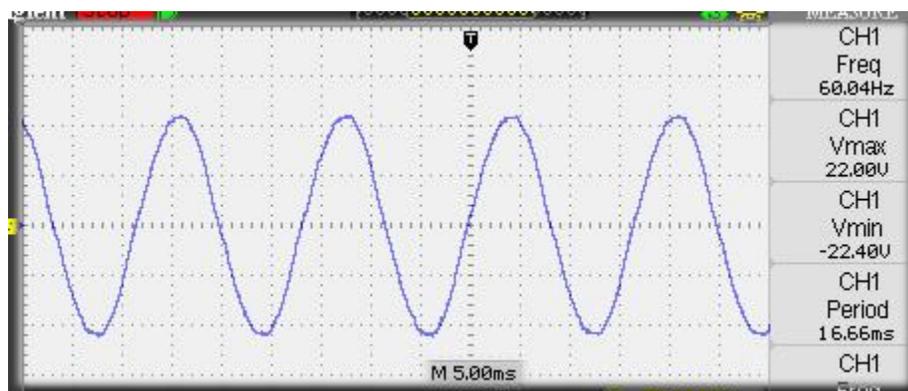

The image above is a copy of the screen of my digital oscilloscope. The waves displayed are called **sine waves** due to their shape (the word sine comes from the math called trigonometry, but we won't go there now). The oscilloscope probe was attached to the output wires of a 120/12 volt AC transformer. The waves represent the alternating voltage (which creates alternating current). Notice the grid lines on the screen. In the vertical direction, a square equals 10 volts and in the horizontal direction a square equals 5.0 milliseconds (a millisecond is one thousandth of a second). The heavier horizontal grid line represents 0 volts. Portions of the wave above 0 volts have positive voltage and portions below 0 volts

have negative voltage. Positive voltage will cause the current to flow in the opposite direction from negative voltage. Since the waves are both above and below the 0 volts line, we know this is alternating voltage. The tops of the waves are about 22 volts while the bottoms of the waves are about -22 volts.

The oscilloscope also provides some information on the right side of the screen. The frequency of the waves is 60.04 Hz. The term Hertz (Hz) is named after the famous German physicist Heinrich Hertz (http://en.wikipedia.org/wiki/Heinrich_Hertz), who proved the existence of electromagnetic waves. The term Hertz is the same as cycles per second or waves per second. In the case of our AC source, there are 60.04 cycles per second or Hz. If our oscilloscope displayed one second of time exactly in the horizontal direction, then we could count just slightly more than 60 waves on the screen (60.04). That means the current flow changes direction about 120 times each second (one wave or cycle equals flow in one direction followed by flow in the other direction). The standard frequency for AC supplied by utilities in the USA is 60 Hz.

Waves can be described in terms of frequency (Hz) or in terms of wavelength. For electromagnetic radiation a distance measurement is commonly used for the wavelength. In the case of our AC voltage displayed on the oscilloscope, we use a measurement of **time** for the wavelength. The oscilloscope provides the amount of time for one wavelength (called the period), which is 16.66 milliseconds for our AC source. If we multiply the time period of one wave by the number of waves in one second, the result should be one second: 16.66 ms per wave X 60.04 waves = 1,000 ms or 1.0 second.
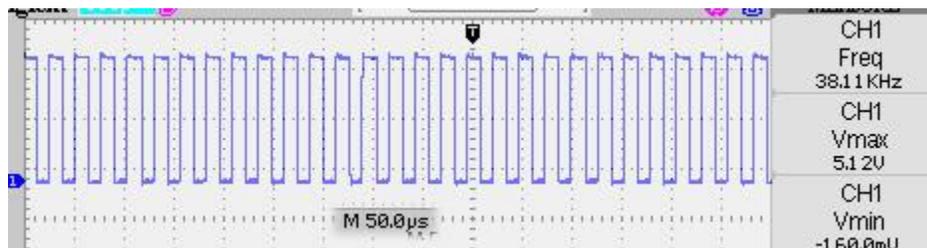

The image above is another one from my digital oscilloscope. In this case the oscilloscope probe was connected to the IC1 output pin 4 of the IR add-on module, which powers the IR emitter. If you have already read the lesson on this module, you may remember that the IR emitter is adjusted to flash at a rate of 38 kHz (38,000 Hz).

This wave pattern is called a square wave. It represents the pulsating signal. You will notice that the waves have flat tops and bottoms. The bottoms of the waves are close to 0 volts while the tops of the waves are about 5 volts. The wave pattern represents a pulsating voltage (on, off, on, off, on, off, etc.).

This voltage source is turning on and off 38,000 times a second. We could not possibly appreciate the nature of this signal using just a meter. The oscilloscope allows us to see all the details of the changing voltage, by displaying those changes as waves.

The oscilloscope also displays the frequency of the pulses on the right side of the screen (38.11 kHz). We can also make an estimate of the frequency by counting the number of waves covering a certain number of squares on the screen. I count 21 waves covering 11 squares. Each square of the screen

equals 50 microseconds and 11 squares equal 550 microseconds. Therefore, the wavelength is 26 microseconds (550 microseconds/21 waves = 26 microseconds per wave). There are 1,000,000 microseconds in one second. Frequency is the number of cycles (waves) in one second. Therefore, if we divide 1,000,000 microseconds by 26 microseconds per cycle, we get 38,000 cycles per second or 38 kHz. Our estimate is only good to two significant figures, but compares favorably with the more accurate display of 38.11 kHz provided by the oscilloscope.
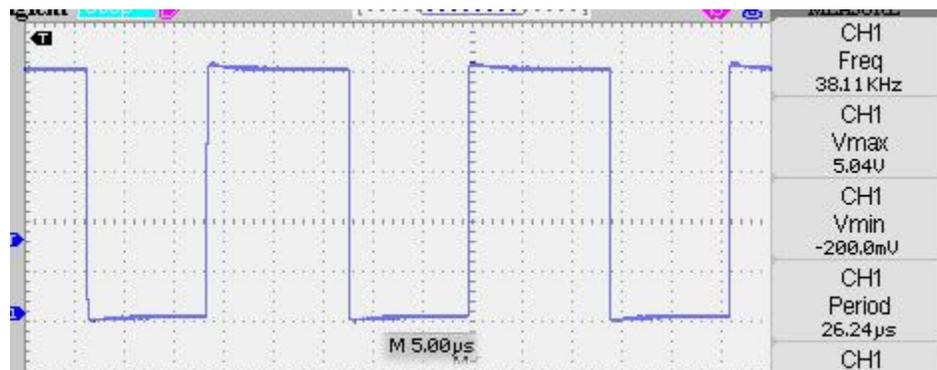
By adjusting the oscilloscope display we can magnify our view of the square waves. In the trace above, the squares on the screen grid have a value of 5 microseconds horizontally, one tenth the display on the previous page. In the vertical direction one square equals one volt. This magnified view of the waves allows us to see that the waves are not perfectly square. We need to magnify our view even further to see more detail.
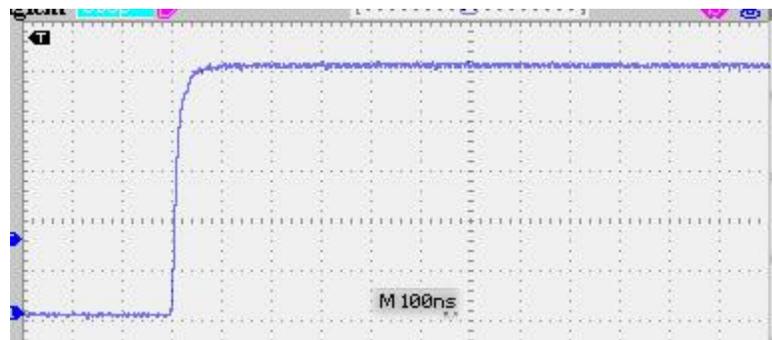
In the image above, the oscilloscope has been adjusted to display a very short period of time, 100 nanoseconds per grid square. A nanosecond is one billionth of a second. In this view we can see only part of one wave. On the left the wave is low, around 0 volts. Then rapidly the voltage rises to about 5 volts. Even though the rise in voltage is very fast, it is not instantaneous. We can see that the vertical line representing the rise in voltage is slightly angled to the right. The space between two horizontal grid dots on the screen represents 20 nanoseconds. As we follow the voltage rise from 0 volts, the time it takes to reach 4 volts is about one dot to the right or 20 nanoseconds. It takes about 40 nanoseconds (2 dots to the right) for the voltage to rise from 0 to 5 volts at the top of the wave. In other words, it takes about 40 billionths of a second to go from 0 to 5 volts. This is a very short period of time compared to the wavelength of 26,000 nanoseconds. These kinds of measurements show how useful an oscilloscope can be in examining the fine detail of electrical dynamics.

Oscilloscope Exercise
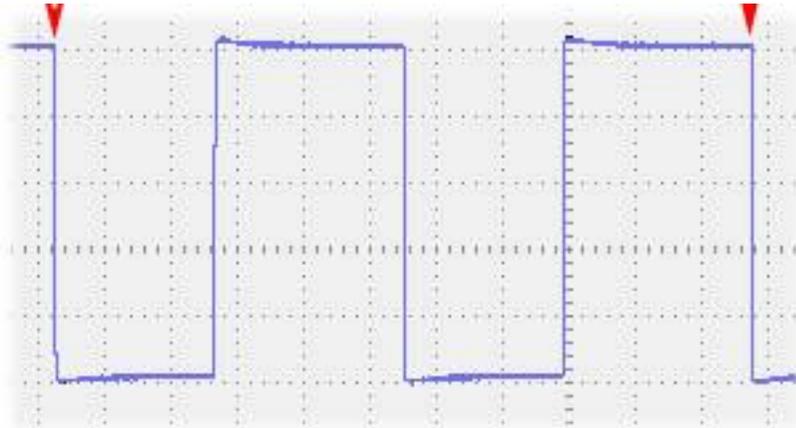
You will use the oscilloscope trace above for this exercise. As you can see, these are square waves. I have applied red arrows to points where the voltage begins to drop. The arrows mark off exactly two waves (the space between the arrows contains exactly two waves). Remember that time is measured on the horizontal scale. For this particular wave trace, each square of the grid equals 20 microseconds. Notice that the lines marking the squares are composed of dots. These dots mark 5 spaces within each square. Therefore, the distance between two dots horizontally equals 4 microseconds (20/5 = 4)

1. Count only the number of complete squares between the two arrows _____

2. Multiply the number in step 1 by 20 microseconds (ms) _____

3. Count the spaces between dots for squares between the arrows that are not complete squares _____

4. Multiply the number of spaces by 4 microseconds _____

5. Add the number of microseconds from steps 2 and 4 _____

The answer in step five is the number of microseconds spanned by two waves. In order to calculate the wavelength, we need to know the number of microseconds for one wave.

6. Divide the answer in step 5 by 2 _____ (wavelength)

The answer in step six is the number of microseconds for one wave, also known as the wavelength. Now you will calculate the frequency (Hz). Frequency is the number of waves (or cycles) per second. Remember that there are 1,000,000 microseconds in one second. Therefore, if you divide 1,000,000 microseconds by the number of microseconds for one wave, the answer will be the frequency (Hz).

7. Divide 1,000,000 microseconds by the answer in step 6 _____ (frequency)
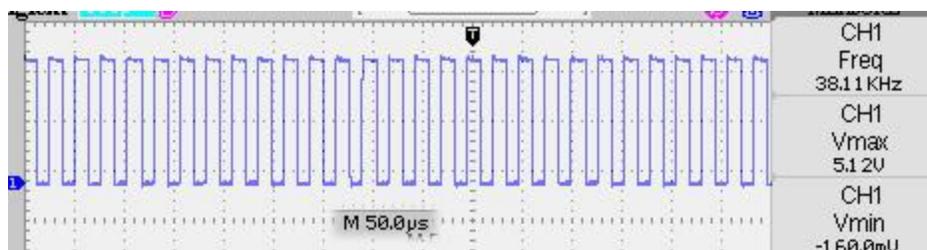
Let's take a look again at the signal applied to the IR emitter of our IR add-on module for the line following robot. We can't send a variety of codes using this elementary wave pattern. For our add-on module our signaling needs are simple. We just want to detect an IR pulse rate of 38 kHz. There is no need to send out different signals for different actions. Such is not the case for an IR TV remote. The remote must send out many different codes, which can't be done with a simple wave pattern as seen above.

In order to send complex signals, we need to **modulate** the wave pattern. You may have noticed that the radio in your parents' car is capable of tuning AM and FM radio broadcasts. AM is short for **Amplitude Modulation** and FM is short for **Frequency Modulation**. These are two types of modulation which add the sound signal to the broadcast frequency. The figure to the right depicts Amplitude Modulation. The broadcast frequency (carrier wave) is the blue line. The carrier wave is a radio wave. Notice that the variable height (amplitude) of the blue wave traces out another wave, the sound wave envelope, depicted in red. The radio receiver tunes (selects) a station by its carrier wave frequency, then discards the carrier wave and converts the sound wave envelope into sound. By modulating the height of the carrier wave, we have created another wave pattern. Modulation is the key to sending information by way of electromagnetic radiation.
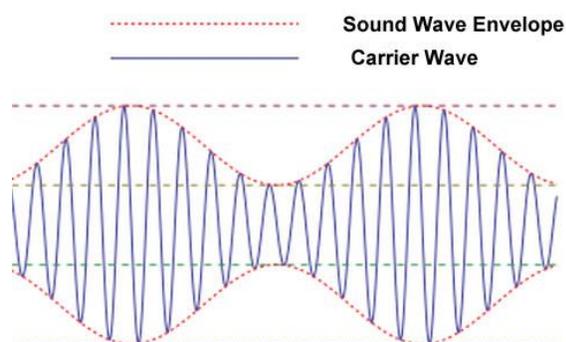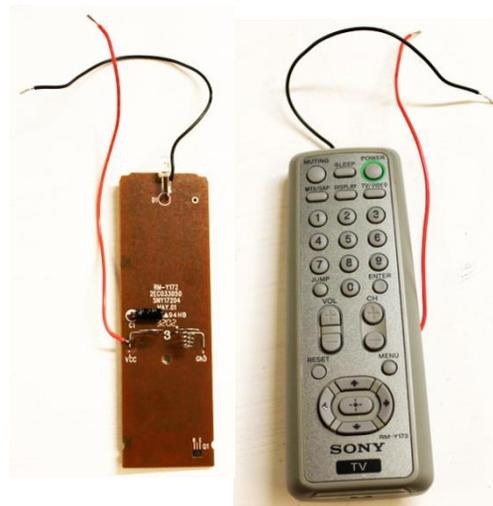
In the case of the IR remote, the carrier wave is NOT the infrared light wave. The carrier wave is the **pulse rate** of the infrared light. I have an old Sony TV remote which has an IR pulse rate of about 40 kHz. That frequency is modulated by the remote to send out codes. We have three wave patterns to consider: 1) wavelength of the IR light, 2) frequency of the IR light pulses, 3) modulation of the IR light pulses.

The IR receiver in the TV is designed to detect IR light of a relatively narrow range of wavelengths. This is the first measure in rejecting unwanted electromagnetic radiation signals. Secondly, the IR receiver accepts IR light only if it is pulsing within a certain range of frequencies. This second measure is equivalent to a radio receiver selecting a broadcast station by tuning to its carrier wave frequency. Therefore, in order for the IR receiver to detect a signal from the remote, that signal must be IR light within a certain range of wavelengths and ALSO have a pulsing rate within a certain range of frequencies.

IR remotes use different kinds of modulation protocols to send codes to the TV. Unfortunately, there is not a standard that all TV manufacturers follow. However, we can still learn the basics of IR remote control by the study of one remote. We will use my Sony remote, which I have selected because I could find technical details about its modulation protocol.

We can start our study by connecting the remote to the oscilloscope. That will allow us to see the wave modulations on the oscilloscope screen. To do that, I soldered two wires to the remote. The negative wire (black) was soldered to the cathode of the IR emitter LED and the positive wire (red) to the positive terminal of the battery holder. Then I connected the wires to the probe of the oscilloscope. With the oscilloscope running, a button is pushed on the remote, which results in an oscilloscope display of the modulated waves.

The image to the right is the oscilloscope trace displayed when the power button is pushed on the remote.   The time scale setting on the oscilloscope is too compressed to enable us to see the individual waves of the carrier. The carrier waves are so crowded on the screen that they look like solid blocks of blue color. But notice that there are waves that can be seen on the screen. They have different wavelengths. This is the modulated code for power.
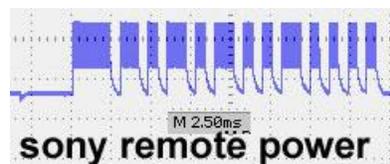
Let's select the portion of the oscilloscope trace circled in red at the right and expand it so that we can see the individual waves of the carrier. If we adjust the oscilloscope to a
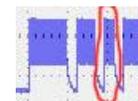
grid square equal to 100 microseconds, then we can see the carrier waves. In the image to the right I can count 24 waves covering a distance of 6 grid squares. Each square is 100 microseconds (100 µs) so the 24 waves span a time of 600 microseconds and each wave spans a time period of 25 microseconds (600/24 = 25).
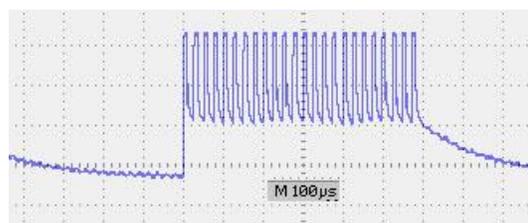
If one wave has a period of 25 microseconds, then how many waves would equal one second? One second equals 1,000,000 microseconds so there are 40,000 waves per second or 40 kHz (1,000,000/25 = 40,000 waves per second). This is the frequency of the carrier waves for the Sony remote.

If we magnify the oscilloscope trace more, to 25 µs per grid square, the oscilloscope will display the frequency of the carrier wave as seen to the right. Notice that the oscilloscope has measured the frequency to be 40.32 kHz.
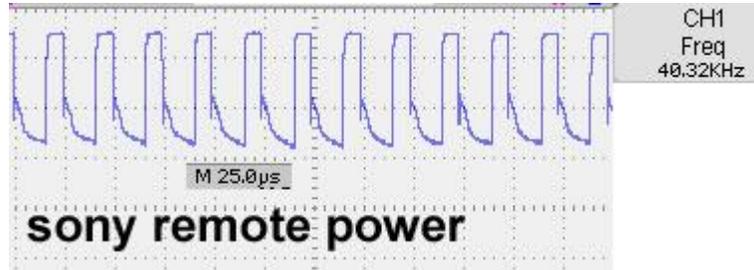
Now suppose we turn the 40 kHz pulses on and off in a pattern like that to the right. The black rectangles represent many 40 kHz waves squeezed together on the page so that they look solid. The white spaces between the black blocks are spans of time when the pulses are turned off. Suppose that the pulses are turned on for 1.2 milliseconds and then off for 0.6 milliseconds. And we assign this as the digit 1 in binary code (the numerical system of digital devices). Then we assign the pattern of 0.6 milliseconds on and 0.6 milliseconds off as the digit 0 in binary. We have created a **pulse width modulation** of the 40 kHz carrier that is capable of transmitting numerical codes to the TV.
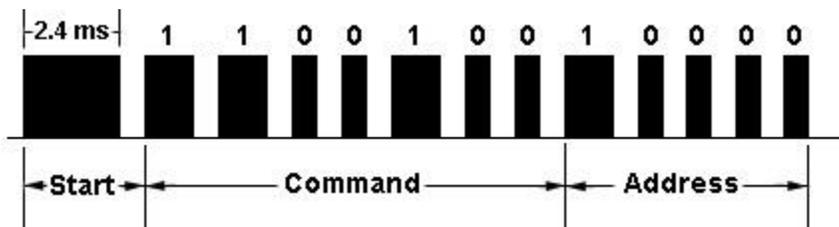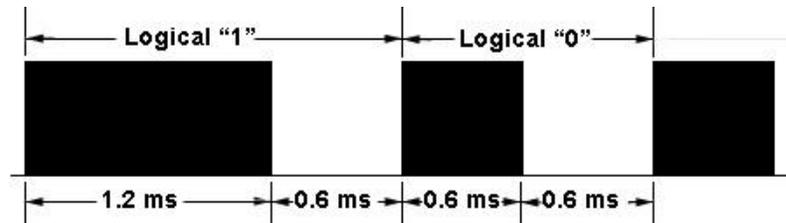
My old Sony remote uses the SIRC Protocol to send codes by pulse width modulation. A code using that protocol is displayed above. Each code message starts with a pulse that lasts 2.4 milliseconds followed by a 0.6 millisecond pause (space). This is called the **start** burst, which alerts the TV to ready itself to receive the code. The next 7 pulses deliver a 7-bit binary number called the **command** followed by a 5-bit binary number called the **address**. The address is the code for the device. For example, the device address for a TV is the decimal number 1 and the address for a CD player is 17. In this case we want the TV to respond to our remote control, so the address number must be one.

Binary numbers

Recall that transistors can be used as switches to turn a circuit on or off. Computers utilize millions or billions of transistors to process data. This is done using a binary number system (base two). In binary there are just two digits: 0 and 1. This works well with digital electronic devices when the transistors are set in one of two states: off or on. These two states can be used to represent the two digits in binary.

A number system familiar to you is **decimal** (base ten). In decimal there are ten digits: 0123456789. How do you suppose that system originated? Take a look at your hands. You have 5 digits (fingers and thumb) on each hand, providing an easy way to count things in decimal.

It is difficult to predict what will happen in digital electronics in the future but it is possible that a device may be developed that would operate on decimal rather than binary. Ternary computers have been developed that operate on a base three number system (http://en.wikipedia.org/wiki/Ternary_computer). While it may be fun to speculate about the future of computing, at the present our machines use binary, and it is this system you need to understand in order to understand how the IR remote works.

The table to the right lists the first ten numbers in decimal and the equivalent in binary. Think about the counting procedure used in decimal. We start with the number 0. As we count, the number increases from 1 to 9. At that point we run out of digits to use and we add another place and insert the digit 1 in the second place and the digit 0 in the first place: 10. Counting in binary is the same. We start with 0. Next is the digit 1. Now in binary we have run out of digits to use, so we add another place. The decimal number 2 is the same as 10 in binary. As we count in binary, it is necessary to add places quickly. The decimal number 8 requires four places in binary (1000).

Decimal	Binary
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001

Usually numbers are written with the least significant digit on the right. For example, the digit 2 is the least significant digit of the decimal number 12. In the case of the Sony remote, the least significant digit is on the left, the reverse of the conventional order.

The image to the right is the oscilloscope trace for the Sony remote when the power button is pushed. I have added the binary digits above the modulated waves. A digit of 1 has a pulse that is longer (wider) than a digit of 0. If we write out the command digits as they appear on the oscilloscope screen they are 1010100. In order to write the binary number in the conventional fashion, we need to reverse the order of the digits: 0010101.
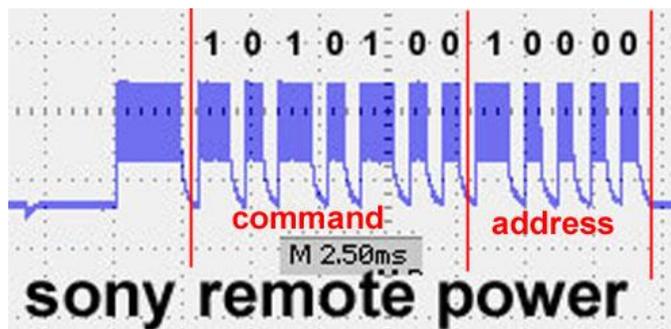
We can convert a binary number to a decimal number using the table to the right. The top row contains a 7-place binary number (7 bit). If a place contains a 1 digit, then look down one row to see the equivalent value in decimal. Now look at the binary number 0010101 in the table (the Sony power code). Below that row is placed the decimal conversion. Add all the decimal conversions together to find the equivalent number in decimal. The number 0010101 in binary is

equivalent to 21 in decimal. The command in decimal is the number 21. Looking up this number in a table for the SIRC Protocol, we find that the command number 21 is for power.

Notice that the address number in binary is 1000 in the oscilloscope trace on the previous page. Reversing that we get 00001 in binary, which is equal to the number 1 in decimal. Looking up this number in a table for the SIRC Protocol, we find that the address number 1 is for a TV. In other words, this code is intended to turn on a TV rather than some other device, such as a CD player.

The key to this system is that the 40 kHz carrier waves are **modulated** by turning the pulses on and off for specified periods of time to create a binary code. This kind of modulation is called **pulse width modulation**. If you find this confusing do not worry. I will do a demonstration at one of our meetings with the oscilloscope. Then I think it will be clear.

So far we have looked only at the oscilloscope display for the IR emitter of the remote. Now we should take a look at what the processed signal looks like at the TV. I don't have an old Sony TV that works with my old remote. In any case, I would not want to tear apart the TV so that I could connect my oscilloscope to it. Instead, I used the IR receiver module (IC2) of the IR add-on module as a substitute.

Using my breadboard layout of the IR add-on module, I connected the positive probe of the oscilloscope to the same row containing the anode of the LED D6, which is connected to the IR receiver module through IC1. This provides the signal as processed by the IR receiver. The signal image is seen on the right. Here we can see that the carrier waves have been removed (there are no 40 kHz carrier waves present, only the code provided by the modulation).
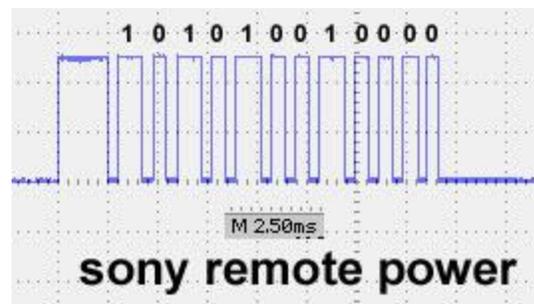
(continued on next page)
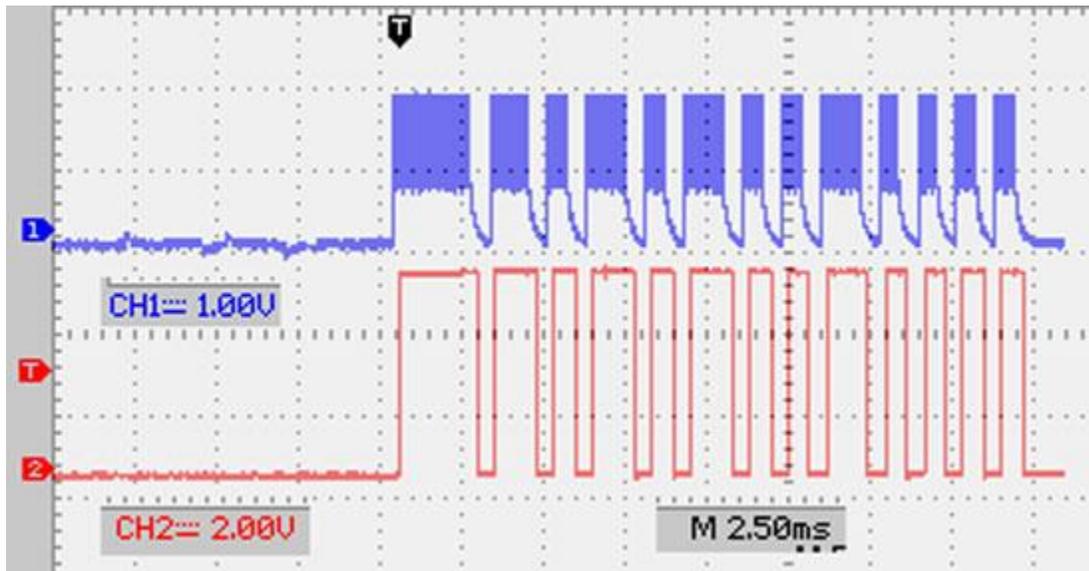
My oscilloscope has two channels, which means I can look at two signals at the same time. The image above is a dual trace, the upper (blue) one from the IR remote and the lower (red) one from the IR receiver on my breadboard layout. Notice that the signal from the receiver is missing the carrier waves. Part of the function of the IR receiver module is to eliminate the carrier wave, providing only the modulated code to the TV for processing.

Decoding exercises

Now let's see if you can decode some signals from the Sony remote.

Exercise 1. Write out the 7 place command binary number of the oscilloscope trace on the right by placing digits 0 or 1 above the pulses. Remember that the very wide pulse on the left side is the start burst and should not be counted in your decoding of the command number. The wide pulses represent the digit 1 and the narrow pulses the digit 0. Also remember that there is a number code for **Command** as well as a number code for **Address**. I am asking only for the Command number, which is the first 7 digits after the start burst.
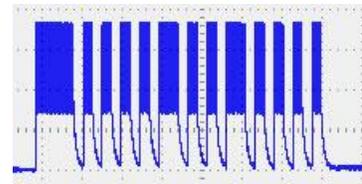
write the binary number in standard order (reverse the order of digits you wrote above the pulses)_____

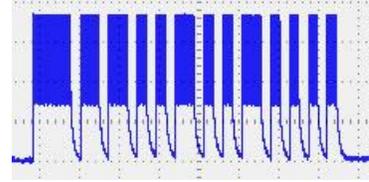calculate the decimal equivalent number (convert the binary to decimal)_____

the name of button pressed on remote is (use the table on the next page for help with your answer)_____

Exercise 2. Write out the 7 place command binary number of the oscilloscope trace on the right by placing digits 0 or 1 above the pulses.

write the binary number in standard order (reverse the order of digits you wrote above the pulses)_____

calculate the decimal equivalent number (convert the binary to decimal)_____

the name of button pressed on remote is (use the table on the next page for help with your answer)_____

Exercise 3. Write out the 7 place command binary number of the oscilloscope trace on the right by placing digits 0 or 1 above the pulses.

write the binary number in standard order (reverse the order of digits you wrote above the pulses)_____

calculate the decimal equivalent number (convert the binary to decimal)_____

the name of button pressed on remote is (use the table on the next page for help with your answer)_____
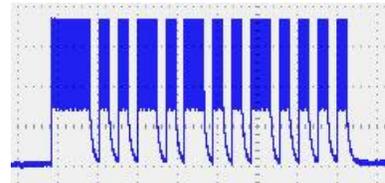
When you have finished exercises in this paper, show them to Mr. La Favre.

SIRC Protocol	
Command number (decimal)	Remote button
16	Channel +
17	Channel -
18	Volume +
19	Volume -
20	Mute
21	Power