The World of Weather

part I

This section of the book is an introduction to the world of weather and weather measurement. We'll start off by looking at some of the common weather measurements, the units of measure, and how the weather sensors work. You'll also learn a little history about home and hobbyist weather stations.

Next, we'll look at several types of weather stations you can build or buy. There are many weather stations on the market. Some are fully assembled and ready to go, while others are purchased as a kit. You'll also begin to learn about weather stations that are built from the ground up, the real focus of this book.

Finally, I'll finish up this section with an introduction to 1-Wire. I'll start off by explaining what it is, how it works, how to hook it up, and tips for making it work reliably. You read about some of the 1-Wire devices and weather sensors, preparing you to start building your station.

Some of this information you may already know, but at the conclusion of this section, we'll both be using the same terms and you'll understand some my techno-speak. Don't worry too much if you don't understand everything presented in these first few chapters. Once you start building your weather station in Part II, most of these topics will begin to make sense.

in this part

chapter 1

Measuring the Weather

in this chapter

- ☑ Weather Basics
- ☑ A Little Bit of History
- ☑ Measuring the Weather
- ☑ Weather Sensors You Can Buy
- ☑ Ideas for Building Your Weather Station

I've always been fascinated by measuring weather. I still remember back in the 1960s when I was a kid. I would ride my bike several miles to the downtown bank. Up on a pole was the coolest thing — a sign that displayed the temperature digitally. Keep in mind that computers hadn't been invented yet. Heck, integrated circuits weren't even invented yet. So how did they do that? Measure temperature and light up incandescent lights to display the value. How high tech!

It wasn't until about 15 years later that I built my first digital thermometer. It consisted of a simple temperature sensor connected to a digital voltage meter. It cost me about $100 to build. It sat on my desk when I wasn't showing it off to my other nerd friends (the term "geek" wasn't used yet). I would periodically look at it and think to myself, "Wow, the temperature went up 0.1 degrees!!"

Well, over the years things have changed considerably. First, digital integrated circuits became commonplace. Soon, lots of things became "digital": clocks, radios, oven timers, and even thermometers. Then computers hit the scene. Soon "digital" was replaced by "intelligent." Products could now process the data they collected. Microwave ovens know when your food is cooked. Your car knows exactly how much gas to mix with air for the optimal fuel combustion. And, yep, weather data can be collected and processed to control heating, air conditioning, irrigation sprinklers, and thousands of other possibilities.

Climate Is What You Expect, Weather Is What You Get

We've all heard the local weather forecasters on TV talking about the weather. They talk about yesterday's highs and lows, current conditions, and try to predict the weather for the next few days. They show colorful maps that show temperatures for the surrounding area and maybe a national map. If there are storms in the area, they may show a radar map highlighting conditions for the area. But what about the local weather conditions for your area? What about the weather in your backyard?

What is weather? Dictionary.com defines weather as "The state of the atmosphere at a given time and place, with respect to variables such as temperature, moisture, wind velocity, and barometric pressure." So to really know what the weather is, you'll need some way to measure the weather conditions.

In recent years, home and hobbyist weather station equipment has become very popular. I guess it might be part of the information age we live in. Many people want to know about the weather conditions in their immediate area. It could be for commercial reasons. They may have a farm or are raising livestock and need to know exactly what the local conditions are. Others, like me, may be simply fascinated by building and running their own weather station.

A Few Terms Defined

Before I start discussing measurements, I'm going to define a few terms. First off, I'm going to define what I mean by the terms *analog* and *digital*. I realize that most of the techno-geeks that are reading this are rolling their eyes. But just for clarification, I'm going to cover it anyway.

Analog refers to a value that is *continuously variable*. Remember the old-style wall clocks that you had to plug in to an outlet? The second hand moved smoothly around the clock face without any steps or distinct values. This is an example of analog. Sure, there were markings on the face, but you had to interpret the value. This was a real analog clock. Almost all weather measurements are analog. Values change smoothly and continuously. Sure, your digital thermometer converts it to digital, but as far as the sensor sees it, it is analog.

Digital, on the other hand, refers to a measurement that has *discrete*, distinct steps. Referring back to the clock analogy, a digital clock displays the minutes in 1-minute increments. It's 10:15 for a whole minute (unless your digital clock has a seconds display), and then it clicks over to 10:16.

Almost all modern weather stations convert their analog measurements to digital. The number of steps between each digital value is defined as *resolution*. For example, even though wind direction can be any value between 0.0 and 359.9 degrees, my weather station converts it into 1 of 16 possible directions. Its resolution is 360/16 or 22.5 degrees. The temperature sensor's output is in 0.5-degree steps. So its resolution is 0.5 degrees even though the display goes down to 0.1-degree steps.

In the next few pages, you will see the term *linear*. In this context, I'm referring to a sensor whose output is a one-to-one straight line in response to an input. In contrast, some sensors exhibit a *non-linear* or *exponential* response.

As long as I'm defining terms, there's one more to cover. *Accuracy* is, yep you guessed it, how accurate the measurements or sensor is. Why is this important? Some vendors advertise their weather station as being accurate to within ½ degree at room temperature. Yet at higher temperatures, the accuracy is only 5 degrees. That's a big error, especially if you live in the desert. A common mistake is to assume that because the display is digital, it must be right. Don't fall into this trap.

Some of the better weather stations provide *calibration* adjustments to allow you to adjust the accuracy. But now you have to have a reference to compare to, so you'll need to know how accurate the reference is, and it can get pretty complicated. Some of the calibration techniques are discussed in Part II.

Temperature Measurement

By far the most common and important weather measurement is temperature. It affects your everyday life: What clothes should you wear? Should you turn on the air conditioning or the heater? Do you need to run your sprinklers? Is there going to be ice on the road as you drive to work? Are your plants going to freeze tonight?

Scientific types define temperature as the amount of heat an object or the air contains, with absolute zero (no heat) defined as the state where all molecular activity stops. Therefore, heat can be viewed, in a sense, as the amount of molecular activity of an object. Although there are several measurement systems, the three most common are Celsius, Fahrenheit, and Kelvin.

In the 1700s, Swedish astronomer Anders Celsius developed a new temperature scale. He based it on two points. He defined his first point to be 0 degrees; the temperature at which pure water *froze* at sea level. His second point was 100 degrees, and was defined as the temperature at which pure water *boiled* at sea level. The Celsius scale is the standard used today throughout most the world, except for the U.S.

Just a few years before, German physicist Gabriel Fahrenheit was working on his own temperature scale, which was also based on two different points. He defined 0 degrees as the lowest temperature he could generate in his lab using ice and ammonia salts. His other point was 100 degrees and was based on what he believed to be the average body temperature (which he thought was constant). Over the years, the Fahrenheit scale has been revised slightly because the points he chose weren't constant. The two points now used (not surprisingly) are the freezing point of water at sea level (32 ˚F) and the boiling point of water at sea level (212 ˚F). On this new scale, body temperature is now 98.6 degrees. The Fahrenheit scale is used only in the U.S. and a few of its territories.

The third and less commonly used scale for weather is Kelvin. Kelvin uses the same degree size as Celsius, but is adjusted so that 0 degrees is absolute zero. This helps with thermodynamic calculations by eliminating negative numbers. You can convert degrees Kelvin to Celsius by adding 273.16. Guess what? You'll be using the Kelvin scale later in this book to calculate dewpoint from the temperature and humidity!

Temperature Conversion between Celsius, Fahrenheit, and Kelvin

°K = °C – 273.16

°C = (°F – 32) ÷ 1.8

°F = (°C x 1.8) + 32

Table 1-1 compares the Kelvin, Celsius, and Fahrenheit scales.

Table 1-1 Comparison of Temperature Scales

Temperature	*°K*	*°C*	*°F*
Absolute Zero	0	–273.16	–459.7
Liquid Helium	4	269.16	–452.5
Liquid Nitrogen	77	–196.16	–321.1
Freezing Point of Water	273.16	0	32
Room Temperature	294.2	21.1	70.0
Hot Day	313.16	40	104
Boiling Point of Water	373.16	100	212

Mechanical Thermometers

Changes in temperature cause many different changes in materials. From high school physics, you learned that heat causes things to expand, whereas cold causes them to contract. Heat also causes an increase in molecular activity.

Most early thermometers used thermal expansion as the basis for temperature measurement. The two examples that come to mind are glass-bulb and dial-type thermometers. Figure 1-1 shows several examples.

We've all seen glass-bulb thermometers. They're used as fever thermometers, inexpensive indoor and outdoor thermometers, and pool water thermometers. They consist of a graduated glass tube with a reservoir of liquid at the bottom, usually mercury or red-dyed alcohol. As the liquid expands, it is forced up through the tube. The temperature is read by comparing the height of the liquid to graduated markings. Most glass-bulb thermometers are evacuated and sealed at the top to prevent the liquid from being spilled or evaporating.

Dial-type thermometers use a coil of wire or metal connected to a pointer. Some of the coils are made up of two different metals that have different coefficients of expansion. As the coil heats up, it expands, causing the pointer to rotate around a graduated dial. They are generally more rugged and have higher temperature ranges than glass-bulb thermometers. Your outdoor barbeque may have one in the cover for sensing the inside temperature. Most of the mechanical home thermostats have a coil thermometer. Instead of a pointer, a small switch is attached to the coil. When the temperature reaches a certain temperature, it causes the switch to make contact, turning on your heater or air conditioner.

FIGURE 1-1: Glass-bulb and dial-type thermometers.

Mechanical thermometers are great if you're standing there looking at them. But what if you need to log the value? What if you need remote temperature sensing? Ah! What you need is a *temperature sensor*.

Temperature Sensors

Temperature sensors are devices that rely on the electrical changes that occur in the sensor material due to changes in temperature, rather than on mechanical changes. This causes a voltage, resistance, or current change in the output of the device. This can then be measured and displayed, or recorded with a computer. The cool part is that the sensor can be located far from the display. Temperature sensors can be scattered all over a building, with one central monitoring station. This section takes a look at several of the common temperature sensors and how they work.

Thermocouples

Thermocouples are one of the oldest temperature sensors around and are voltage-producing devices. They work on a principle that Thomas Seebeck discovered back in the 1800s. If two dissimilar metals are connected together and heated, they produce a small voltage. This voltage is proportional to temperature: the hotter the connection, the higher the voltage. Thermocouples are classified by the metals they are constructed from. A common type, Type J, is constructed of one wire made from iron and the other wire from a copper/nickel alloy. Table 1-2 lists some of the common thermocouple types.

Thermocouples have a few advantages:

- They are very inexpensive, costing only a few cents to make.
- They are extremely rugged and reliable; they are just two connected wires!
- They have a high and very large temperature range. Because they are metal, they can be used from –100 to over 1000 degrees F!
- Because thermocouples are basically two wires shorted together, they have a very low impedance, which allows them to be placed hundreds of feet away from the measuring device.
- Variation from one thermocouple to another is small. Re-calibration is usually not required when replacing with a same-type thermocouple.

Now for the disadvantages:

- The output voltage is small, usually only tens of millivolts.
- The output voltage is not linear to temperature. Special conversion tables or equations are used to convert the output voltage to actual temperature.
- A reference junction is required when connecting to the measurement system.

Because the output voltage is small, they have poor resolution, usually only 2 to 20 degrees. Thermocouples come in many different ranges, sizes, and packages. Figure 1-2 shows a close-up of a thermocouple junction. For more information on thermocouples, Omega Engineering offers just about any type and style you can imagine. It also has a great online tutorial. See `www.omega.com/thermocouples.html`.

Table 1-2 Common Thermocouple Types and Ranges

Type	*Wire 1*	*Wire 2*	*Nominal Range*
J	Iron	Copper-Nickel	0 to 750 °C
K	Nickel-Chromium	Nickel-Aluminum	–200 to 1250 °C
E	Nickel-Chromium	Copper-Nickel	–200 to 900 °C
T	Copper	Copper-Nickel	–250 to 300 °C

Thermistors

Almost as old as thermocouples, thermistors were discovered by Michael Faraday back in the 1800s, and are still widely used today. The term “thermistor” comes from a contraction of the words “thermal” and “resistor.” Thermistors are, you guessed it, a device whose resistance changes with temperature. Thermistors are used in weather stations, digital thermometers, temperature-sensing fans, and well, just about everywhere you need to sense temperature.

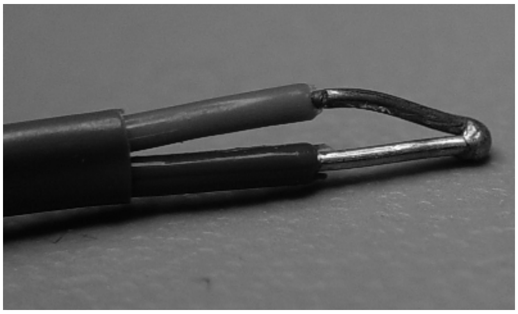

FIGURE 1-2: Close-up of a thermocouple junction.

There are two types of thermistors: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). NTC thermistors' resistance decreases as temperature increases, whereas PTC thermistors' resistance increases as temperature increases. Thermistors come in many sizes, packages, and temperature ranges. They are characterized primarily by two factors: their nominal resistance at 25 °C, and the rate of change of resistance to temperature. Figure 1-3 shows some common thermistors. You can find a great source of information at `www.ussensor.com`.

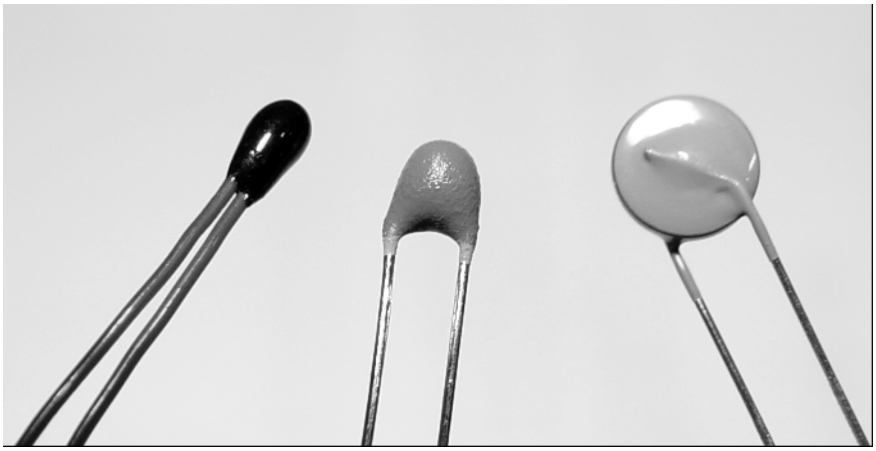

FIGURE 1-3: Common leaded thermistors.

Semiconductor Sensors

Most weather stations, including the one you're going to build in Part II, use semiconductor temperature sensors. These are usually two or three terminal integrated circuit devices that provide a temperature output as a voltage, current, or digital. Many of these devices are also calibrated at the time of manufacture, making them much easier to use. Take a look at some of the more common ones.

Junction Voltage

Although the name sounds high-tech, this is nothing more than a diode (for the real techno-savvy reader, it's technically called a bandgap reference). If you flow a constant current through a diode (or a transistor configured as a diode), the voltage drop developed across it varies with temperature. It turns out that this voltage is fairly linear in the temperature range needed for a typical weather station. Measuring this voltage and applying a simple gain and offset can convert the voltage directly to temperature. Using diodes as a temperature sensor is somewhat outdated. There are devices that measure the junction voltage and scale it for you.

Temperature ICs

This type of sensor is the most common used by hobbyists constructing their own weather stations. Semiconductor manufacturers have taken the junction voltage design and added signal conditioning electronics to provide a calibrated linear output proportional to temperature. There are many types on the market today. Some provide a voltage output, a current output, and some provide a digital output. Here are my current favorites from each category.

The LM34/LM35 are three-terminal voltage output devices. The LM34 provides an output voltage that is scaled to the Fahrenheit temperature, and the LM35's output voltage is scaled to Celsius temperature. Both devices run on 5 to 30 volts. They provide linear +10 millivolts per degree output. A typical circuit is shown in Figure 1-4.

The AD590 is a two-terminal current output device. By simply applying 4 to 30 volts, a current is developed across the device that is proportional to temperature. It is factory calibrated to provide 1 microamp per degree Kelvin. Referring back to Table 1-1, at room temperature, the current flow through the AD590 would be 294.2 microamps. Typically, the output is connected to a resistor to convert the current to a voltage for measurement. Figure 1-5 shows a typical circuit. The main advantage to using a current device is that the device can be located a considerable distance from the measurement equipment with no loss of accuracy or noise problems.

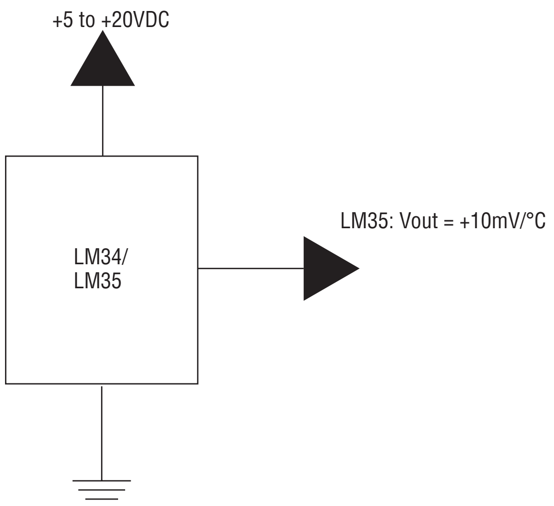

FIGURE 1-4: LM34 / LM35 temp sensor circuit.

Voltage, Resistance, and Current

Many of the sensors you'll read about have a voltage, resistance, or current output. Most weather station applications need a voltage output. To convert current and resistance to voltage, use Ohm's Law:

E = I * R

Where

E = Voltage

I = Current

R = Resistance

For example, suppose you have a device that outputs 5.0 milliamps at 50 °C. If you flow that current through, say, a 1000-ohm resistor, the voltage across the resistor would be E = 0.005 * 1000 or 5.0 volts.

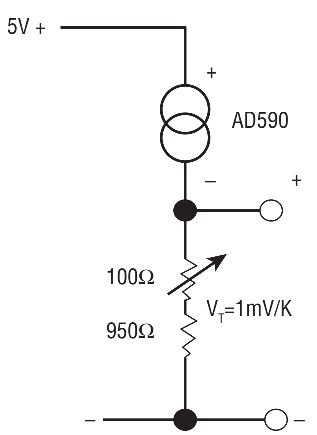

FIGURE 1-5: AD590 temp sensor circuit.

The DS18B20 is a direct-to-digital temperature sensor. This means that it measures the temperature and converts the output directly into a digital value. You'll need to interface it to some sort of digital circuit to read the values. In this case, the output is the Dallas Semiconductor/ Maxim IC's 1-Wire interface. This device outputs its temperature in 0.5 °C increments from –55 °C to +125 °C (–67 °F to +257 °F). Its rated accuracy is +/– 0.5 °C. Hmmm… sounds like a great weather station sensor to me! If you've looked ahead in this book, you might have noticed that the weather station you're going to build uses the 1-Wire interface. There's a whole chapter on 1-Wire coming up, so I'm not going to get into the details yet. But here's a hint: you're going to connect to this device and get the temperature digitally with only one wire. Maybe that's how they got the name…

Many digital temperature sensors are on the market today. Most have temperature ranges and resolutions that meet our needs for a weather station. The issue is connecting it to the weather station computer. Most of the interfaces are limited to just a few feet, hardly enough to get the sensor outside. If you're shopping for your own sensor, keep this in mind.

Analog-to-Digital Converters Explained

Suppose you have a sensor that outputs its value in a voltage. It could be temperature, maybe light levels, it doesn't matter. How do you measure that voltage with your computer? You'll need an *analog-to-digital converter* (called an A-to-D in techno-speak). There are many types of A-to-Ds. There are spec'd by the input voltage, conversion time, number of bits in the output, and the output interface.

- **Input Voltage:** The input range of the A-to-D must handle your expected voltage range. Suppose your temperature device outputs –9 volts at its minimum temperature and +8 volts at its maximum temperature. You will need an A-to-D that can handle that range. A-to-Ds come in several different ranges. Common ranges are 0 to +5V, 0 to +10V, and –10V to +10V.
- **Conversion Time:** This is the time it takes to convert the analog voltage to a digital value. It is usually expressed in microseconds to milliseconds, although some can take seconds. Unless you have a lot of sensors to convert, this is not a big concern for weather measurement.
- **Number of Bits:** This defines the resolution of the A-to-D. The higher the number of bits, the better the resolution. For example, suppose you're using an A-to-D that has an input range of –10 to +10 volts, and your temperature sensor outputs –10 volts at –40 degrees, and +10 volts at +180 degrees. That's 220 degrees total range. If you have an 8-bit converter, the resolution is 220/256 or 0.86 degrees. Not bad. However, if you use a 12-bit converter, the resolution is 220/4096 or 0.05 degrees. That's pretty good! Keep in mind that in practice, the sensor's output won't match your A-to-D's input as nicely as this example.
- **Output Interface:** There are many types of outputs from A-to-Ds. Most can be classified as serial or parallel. Serial A-to-Ds output their data on a single line, bit-by-bit, similar to the serial port on your computer. There are also a few control lines to signal when the A-to-D is ready. Common serial interfaces include I2C, SPI/Microwire, and 1-Wire. Parallel A-to-Ds have a data line for each bit, so a 12-bit A-to-D would have 12 lines plus a few control lines. These are generally used when connecting directly to a processor or processing electronics, and aren't too useful for building a weather station.

Humidity and Dewpoint Measurement

Humidity is probably the second most common weather measurement. It affects our comfort, how much water we give our lawns, and how fast water evaporates. It determines how effective evaporate coolers will work. In factories that work with electronics, humidity is monitored closely, because low humidity levels cause an increase in static discharge (ESD), potentially damaging sensitive electronic parts.

Several types of humidity sensors are available on the market: bare sensors, sensor modules, and sensor ICs. Most of the bare sensors require some electronics to convert their output to a usable form. This can be either a circuit board module or a sensor integrated into an IC. Humidity sensors used in weather stations usually contain electronics to convert the sensor's output to a DC voltage so that it can be applied to an A-to-D converter.

Humidity measurement devices are also called *hygrometers*. I'll use the term *sensor* when I'm talking about the device that just converts humidity to an electrical signal, and hygrometer when I'm talking about a device that measures *and displays* humidity.

When weather folks talk about humidity, what they are really talking about is *relative humidity*. Relative humidity (RH) refers to how much water vapor is in the air and is expressed as % RH. Why is it "relative?" It turns out that the warmer the air, the more water it can hold. And vice versa; as it cools, it can't hold as much water. Therefore, RH is relative to temperature.

An example of this is fog. Suppose you have an air mass that has high moisture content (80% or more), maybe it just rained, or this is moist air that blew in off of the coast. In the evening hours, the temperature starts dropping. At some point, as the air cools, it can no longer hold all of the moisture it contains (100%), and so it will condense, forming fog. By the way, the temperature point were the water condenses is call the *dewpoint*, which you learn about in just a second.

Humidity is measured in percent, with 100% RH representing air that is fully *saturated* with water vapor, and 0% humidity representing completely dry air (no water vapor). We experience 100% (or close) quite often; in fog, when it's been raining for a while, and in the shower when it's all steamy. About the driest we experience is a little less 10%, and that's on a dry day in the desert.

Mechanical Hygrometers

Swiss physicist Horace Benedict de Saussure invented the first hygrometer in the late 1700s. He discovered that certain organic substances expanded when exposed to moisture, and contracted when dried out. Guess what he used in his first hygrometer? Human hair! He attached one end of a hair to a fixed post, and the other end was attached to a lever arm and pulled gently by a spring. As moisture increased, the hair stretched and moved the arm. Until the 1960s, the most common humidity sensing material was blonde Swedish women's hair!

These days, using human hair is cost-prohibitive. Most mechanical hygrometers use a very light coiled spring that has a coating of a special moisture-absorbing material on one side. As the material absorbs moisture it expands, causing the spring to rotate. Figure 1-6 shows a common mechanical hygrometer with a close-up of the mechanism in Figure 1-7.

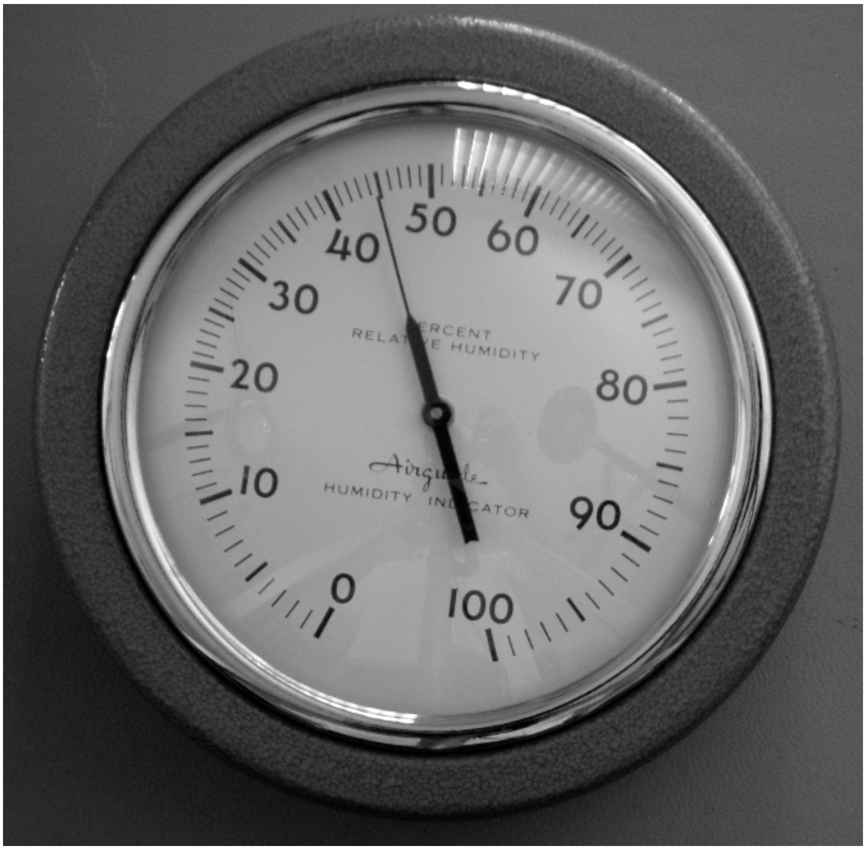

FIGURE 1-6: Mechanical hygrometer.

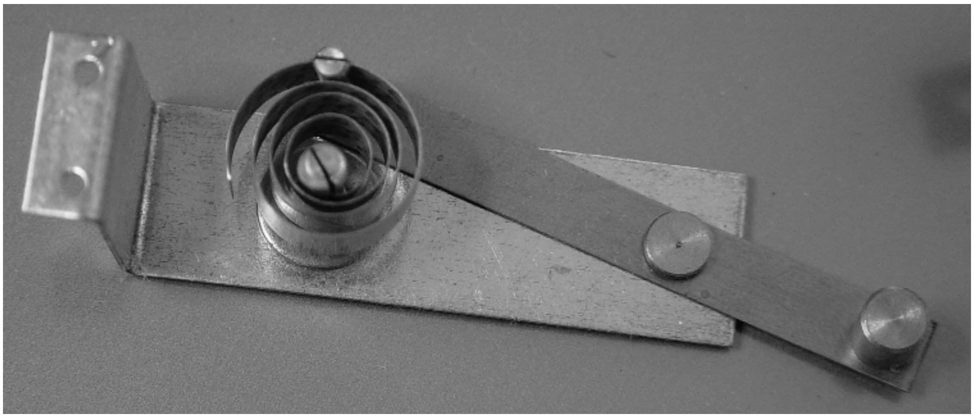

FIGURE 1-7: Internal hygrometer mechanics.

The psychrometer is another instrument to measure the moisture in the air. It uses the principle of evaporative cooling to measure humidity. As most of us know, when water evaporates, it produces a cooling effect. The amount of cooling is related to how dry the air is. The drier the air, the more cooling takes place.

The psychrometer typically uses two glass-bulb thermometers. One of the thermometers has a small cotton "sock" over the glass bulb, which is saturated with water (the "wet bulb") and the other is left uncovered (the "dry bulb"). Air is forced across the two glass bulbs, either by a fan or by twirling the Psychrometer in the air (a "sling" psychrometer). The wet sock causes the evaporative cooling effect on the wet bulb. After a few minutes, the dry bulb and wet bulb temperatures are read and a table is used to look up the corresponding humidity level. Not very high-tech, but reasonably accurate. I have a sling psychrometer that I use to check the calibration of my weather station (see Figure 1-8) without having to disconnect it from operation.

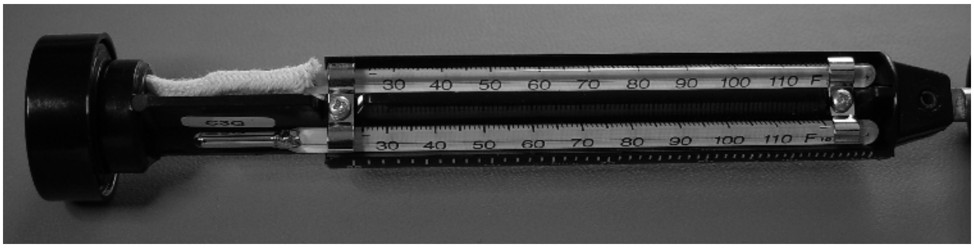

FIGURE 1-8: Sling psychrometer. Note the cotton sock over one of the glass bulbs.

Humidity Sensors

Up until about 10 years ago, there were just a couple of humidity sensors on the market. Now, like temperature sensors, there are many types of humidity sensors. A quick search on the web returns hundreds of results. Most change resistance or capacitance with relative humidity. Because they can't all be covered here, this section looks at some of the more popular ones.

Capacitive

The most common humidity sensors are capacitive and many use similar technology: A special dielectric material is sandwiched between two plates, forming a capacitor. The dielectric material used absorbs moisture and changes capacitance as a function of the moisture it contains. Typical capacitance ranges from about 160 pF at 0% RH to about 200 pF at 100% RH. One of the leading suppliers of capacitive sensors is Humirel. You can view its products online at `www.humirel.com`.

Capacitive humidity sensors are inexpensive, and reasonably reliable. The biggest drawback is that capacitance can't be measured directly. It has to be converted to a frequency or a voltage. This requires some support circuitry. You can build your own interface electronics, or many vendors offer support electronics for their sensor. Humirel offers a module that includes the necessary support circuitry on a small PC board along with the sensor. Either way, make sure that the circuit is properly waterproofed, especially if your sensor is mounted outdoors (which is kind of the point, isn't it?). Figure 1-9 shows the Humirel HS1011 capacitive sensors and the HMT1375 Module.

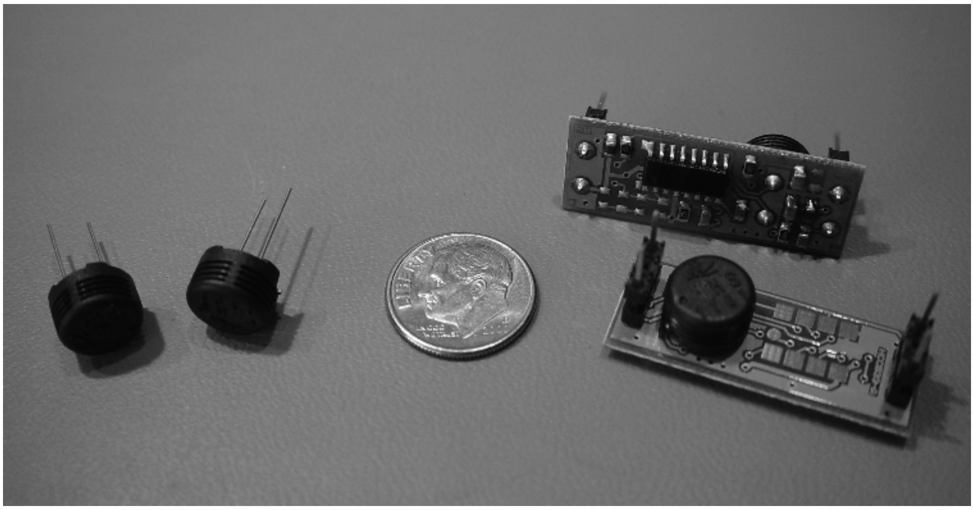

FIGURE 1-9: Humirel capacitive sensors and module.

Resistive

Resistive sensors measure the change in the resistance or impedance of a hydroscopic material. Most common resistive RH sensors use a conductive polymer or salt-coated surface with two electrodes. As the moisture level increases, the treated surface absorbs the moisture, and the resistance decreases. The relationship between RH and resistance is non-linear and requires additional circuitry to linearize the output.

The major drawback to using resistive sensors is that they require an AC voltage for operation. If there is any DC bias, the sensor will eventually polarize and become unusable.

Humidity ICs

Quite a few humidity sensors incorporate the interface electronics right in the package. I guess you could really look at these as mini-modules. Most use a capacitive sensor connected to an internal IC that provides either a voltage or digital output. Although there are quite a few to choose from, the two most popular are the Honey HIH series and the newer Sensirion SHT1x series. Both are shown on Figure 1-10.

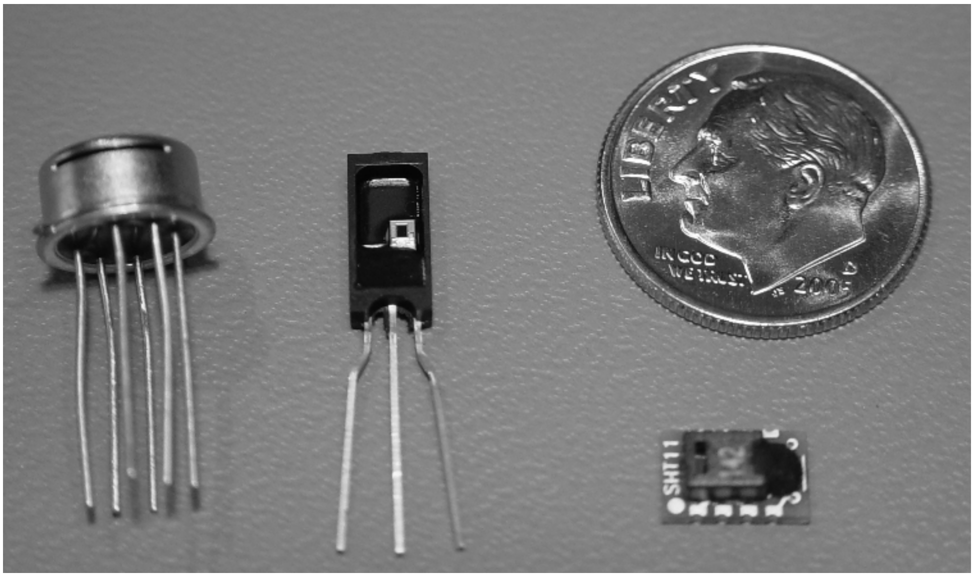

FIGURE 1-10: The Honeywell HIH3602 (left), HIH3610 (middle), and Sensirion SHT11 (right). Note the slit in the can on the Honeywell Sensor to allow air to reach the chip.

The Honeywell HIH series humidity sensor ICs are based on a capacitive sensing element connected to an integrated signal conditioner. They provide a linear voltage output proportional to RH and require between 4.0 and 5.8VDC to operate. They are a ratiometric device, which means that the output voltage is relative to the input voltage. At an input voltage of 5.0V, the output is factory calibrated for 0.8V at 0% RH and 3.9 volts at 100% RH. Accuracy of the HIH series is rated at +/– 2%, which suits most weather station applications. As you'll see in Chapter 7, there are methods to improve this value. The HIH serial devices are also available with a built-in temperature sensor.

The Sensirion SHT series humidity sensors also feature a capacitive sensor. Unlike the Honeywell device, the SHT1x provides a digital output. The capacitive sensor and an internal temperature sensor are connected to an internal analog-to-digital converter. The output is the industry standard I2C interface. These devices are designed to interface directly to a microprocessor for data collection. The SHT features 14-bit output, which provides resolution down to 0.03% RH. Depending on which model you choose, the factory calibration can vary from +/– 4.5% down to +/– 1.8%. The SHT devices operate on a power supply voltage of 2.4 to 5.5VDC.

When selecting a humidity sensor, the interface to your weather station equipment is the key factor. Using a sensor that contains internal electronics will greatly simplify your design. The drawback to all the sensors presented here is the distance you can run the wiring. Like temperature sensors, I2C interfaces are good for only a few feet. Voltage and resistance devices are generally limited to 20 or 30 feet, unless special wiring is used.

Dewpoint

Another important weather measurement is dewpoint. Like humidity, *dewpoint* is a measure of how much moisture is in the air. So why talk about dewpoint when we have humidity?

Relative humidity measurements have a significant drawback. For a given amount of moisture in the air, relative humidity changes with temperature. For example, suppose that the outside air measures 40% RH at 60 ˚F. Is it dry or is it humid? Forty percent doesn't seem dry. Take the same air, and warm it up to, say, 105 ˚F (I live in the desert, remember?). The RH would now measure only 9%. That's pretty dry air! What happened? As you learned earlier, the warmer air gets, the more moisture it can hold, and so the relative humidity goes down. Dewpoint, on the other hand, is a measure of the absolute moisture in the air, so it doesn't change with temperature. In this example, the dewpoint was 35 ˚F in both cases.

Here's another example. Suppose you live where it snows. Outside it measures 25 ˚F at about 50% humidity. That doesn't sound too dry, does it? So why is your skin chapped and your hands dry? Take the same air, move it indoors, and warm it to 75 ˚F. The humidity would now be 6% RH. Wow, that's dry! It turns out that dewpoint is a much better indicator of moisture in the air than relative humidity. It's just that most people are used to using humidity and don't really understand dewpoint. Keep in mind this is a simple example, and although the numbers are correct, the humidity in your house can be affected by other factors. Figure 1-11 gives you a feel for what dewpoint temperatures are considered dry, normal, or humid.

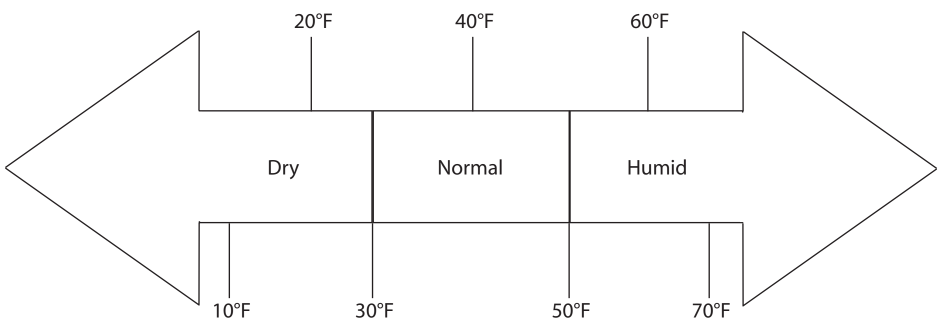

FIGURE 1-11: Dryness perception on the dewpoint scale.

Dewpoint is defined as the temperature at which water will condensate. I'm sure you've had a glass of iced tea or other cold drink collect water on the outside of the glass. That's an example of condensation. The glass temperature is below the dewpoint, and water is condensing on your glass.

Direct dewpoint measurement is complicated. One method is called the "Chilled Mirror Hygrometer." Take small mirror and bounce light off of it. Then start chilling the mirror in small steps. As some point when it gets cold enough, the mirror starts to get foggy (condensation forms) and the reflected light level drops. A temperature sensor mounted directly on the mirror is then checked to see the dewpoint temperature. Most modern dewpoint measuring devices actually measure humidity and temperature, and then calculate the dewpoint. That's the method you'll use in the weather station project.

Wind Speed and Direction

If you stop and think about it, wind is pretty amazing. Conditions in the atmosphere cause the air to *move*. Sometime it's a gentle breeze, sometimes winds can be fierce. As I'm writing this, the U.S. just went through one of its worst hurricane seasons ever. Hurricane Katrina's wind speeds reached more than 150 miles per hour. That's a powerful force.

Wind has two properties we measure: wind speed and the direction it's blowing from. Depending on your location, speed is measured in miles-per-hour (MPH), kilometers-per-hour (KPH), or nautical-miles-per-hour (knots or k). Wind direction is usually measured in degrees, with true north being the reference point of 0 degrees.

Wind Speed

To measure wind speed, you need a device that converts moving air to some electrical output you can measure. This device is called an *anemometer*. There are several types of anemometers; the most common is mechanical, but a few are ultrasonic or thermo-differential.

Mechanical

Typical mechanical anemometers consist of some type of blade that rotates as the wind blows against it. There are two types: omni-directional and directional.

Omni-directional anemometers are designed so that regardless of the wind direction, the force of the wind causes a rotational motion of the blades. Typically, these have three horizontal cupped blades. Wind blowing against the face of the cup imparts more force than wind striking the backside of the other two cups, and causes motion. A typical omni-directional anemometer is shown in Figure 1-12.

Directional anemometers usually have blades that are vertical. The challenge is to keep the blades facing the moving air. If the blades are directed such that the air is blowing from the side, there is no force to rotate the blades. The mechanism used to point the anemometer toward the wind is often a large fin. This mechanism is also used to determine wind direction. An example of a directional anemometer is shown in Figure 1-13. Regardless of the type, mechanical anemometers need to convert the rotational speed to some electrical property we can measure. Most often, this will be a voltage or frequency out.

FIGURE 1-12: Omni-directional anemometer.

FIGURE 1-13: Directional anemometer.

Voltage

Voltage anemometers connect the rotating blades to a small AC or DC generator inside the housing. This can be as simple as a magnet mounted on the rotating shaft with a fixed coil mounted nearby. The voltage out of the DC generator or frequency out of the AC generator is proportional to how fast the generator is turning. The output can drive a small meter or can be converted to a digital signal using an A-to-D converter.

Frequency

Frequency anemometers produce a series of pulses that increase in frequency as the rotational speed of the blades increases. This is commonly done in two ways: magnetically and optically. The magnetic method attaches a magnet to the rotating blades (usually on a separate rotor in the housing) such that it passes over one or more magnetic reed switches every revolution. Figure 1-14 shows an internal view of a magnet and reed switch anemometer.

The optical method uses a light-emitting diode (LED) and photodiode positioned so the LED is shining on the photodiode. As the rotating blade or disk passes in between the two, it blocks the beam, turning off the photodiode, as shown in Figure 1-15. In either method, the number of pulses are counted in a time period. The greater the number of pulses, the faster the wind is blowing.

FIGURE 1-14: Close-up of a magnet and reed switch.

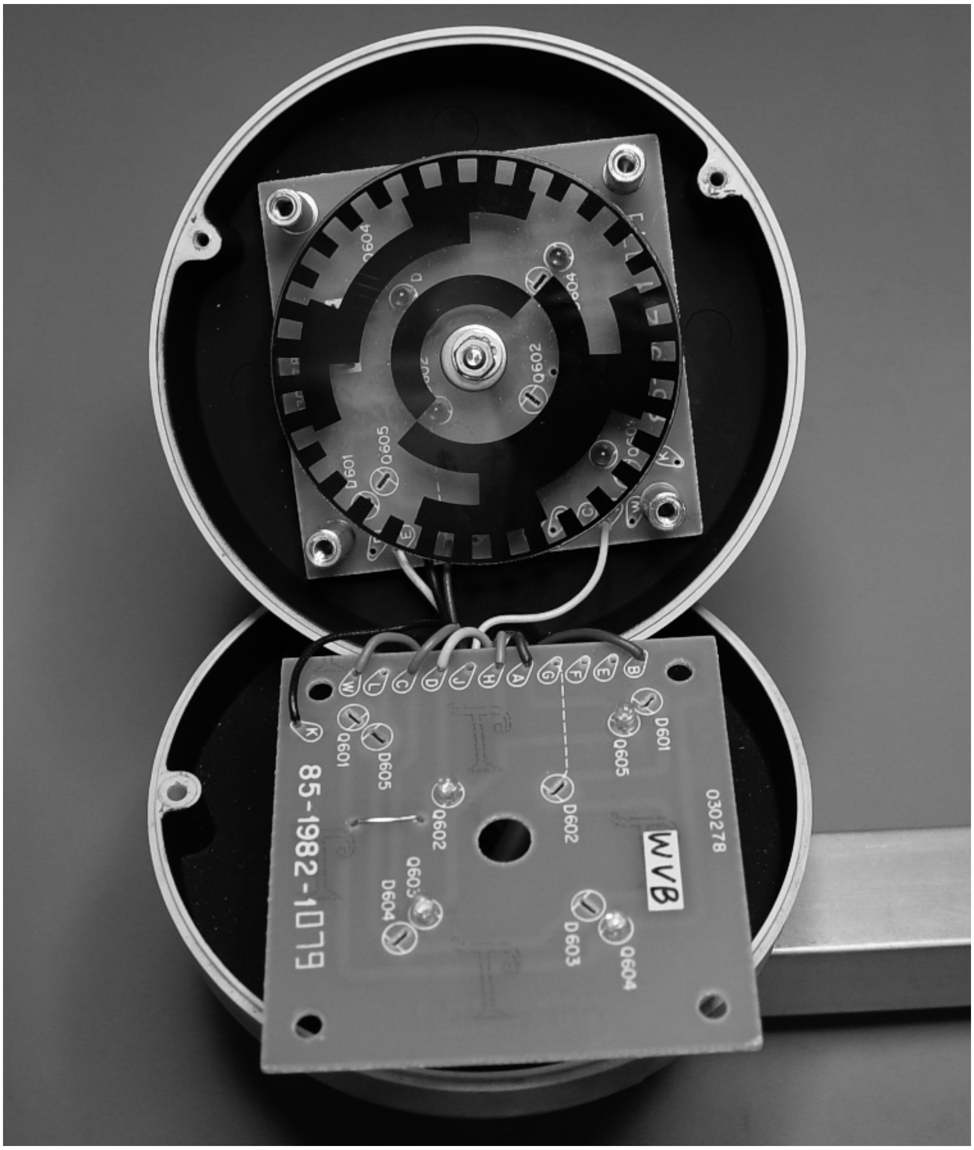

FIGURE 1-15: Optical anemometer. The photodiodes are on the circuit board in the foreground. Note the optical disk.

Wind speed measurements with mechanical anemometers are usually collected or averaged over several minutes. If you've been looking ahead, you may have discovered that the weather station you're going to build uses the magnet and reed switch method.

Ultrasonic

Ultrasonic anemometers work on the Doppler principle. Most of us have experienced the Doppler effect as a train blowing its horn has passed us. The horn takes a noticeable shift in pitch just as it goes by. Sound waves change pitch depending on whether the object producing or reflecting them is moving. As the object approaches, the sound waves are compressed, raising the pitch. As the object moves away, sound waves are stretched, and the sound lowers in pitch.

Ultrasonic anemometers use this principle to measure wind speed. A small speaker is mounted in a tube and emits a high-frequency (ultrasonic) tone down the tube. A small microphone mounted at the other end of the tube listens to the speaker. If there is no wind, the sound picked up by the microphone is the same frequency as sent. If there is some wind blowing down the tube toward the speaker, the sound waves are compressed as the microphone picks them up. The sound increases in pitch proportional to the wind speed. Conversely, if the wind is blowing away from the speaker toward the microphone, the sound is "stretched out" and is lower in pitch. By measuring the difference in pitch between the speaker and the microphone, the wind speed can be determined.

Ultrasonic anemometers can also be omni- or uni-directional. Just like its mechanical counterpart, the unidirectional version requires some sort of mechanical positioner to keep the ultrasonic elements pointed toward the wind. Omni-directional units use an interesting method. They have two sensors positioned at 90 degrees from each other. Taking the ratio of the measured wind speed from each sensor and applying a trigonometric calculation yields both the wind speed and direction.

The primary advantage to ultrasonic anemometers is that they can measure wind speed almost instantaneously. The drawbacks are that they tend to be expensive, and don't hold up well when exposed to outdoor weather for extended periods. They also require power to operate, which isn't always available at the weather station site.

Thermo-differential

As wind moves past an object, it "blows" some of the heat away. The faster the wind, the more cooling takes place. This principle can be used to measure wind speed. A few pages back, you read about thermistor temperature sensors. If you flow enough current through a thermistor, it will start to get warm, or "self-heat." Because a thermistor is a temperature-sensing device, you can also measure how hot it is. If you let it heat up and stabilize, then blow some wind across it, it will cool. The drop in temperature is directly proportional to wind speed.

Several different materials are used as heat-sensing elements. For example, some cars use platinum resistance wire in this fashion to measure the amount of air flowing through the intake manifold. Most thermo-differential sensors also use a second temperature sensor as a reference to determine the ambient temperature. That's where the term "differential" comes from. Thermo-differential sensors are generally very robust. However, they require considerable power to operate.

Wind Direction

Wind direction is measured by a wind vane. Wind vanes date back to the 1400s when Leon Battista Alberti, an Italian architect, invented the first mechanical anemometer and wind vane. Robert Hooke later improved the design and is often incorrectly credited as the real inventor. Early wind vanes were nothing more a large flat surface or "fin" attached to a pointer. The assembly was mounted on a pole and allowed to swivel. The fin seeks the position with the least wind resistance, which causes the pointer to face into the wind.

Modern-day wind vanes haven't changed much. Most still use a fin-and-pointer assembly as shown in Figure 1-16. The rotor is now attached to some sort of a sensor that converts the position to electrical signals. The signal is decoded to determine direction. Most weather vanes convert the rotational position to 1 of 16 possible compass points. Table 1-3 lists the 16 compass points and the corresponding degrees.

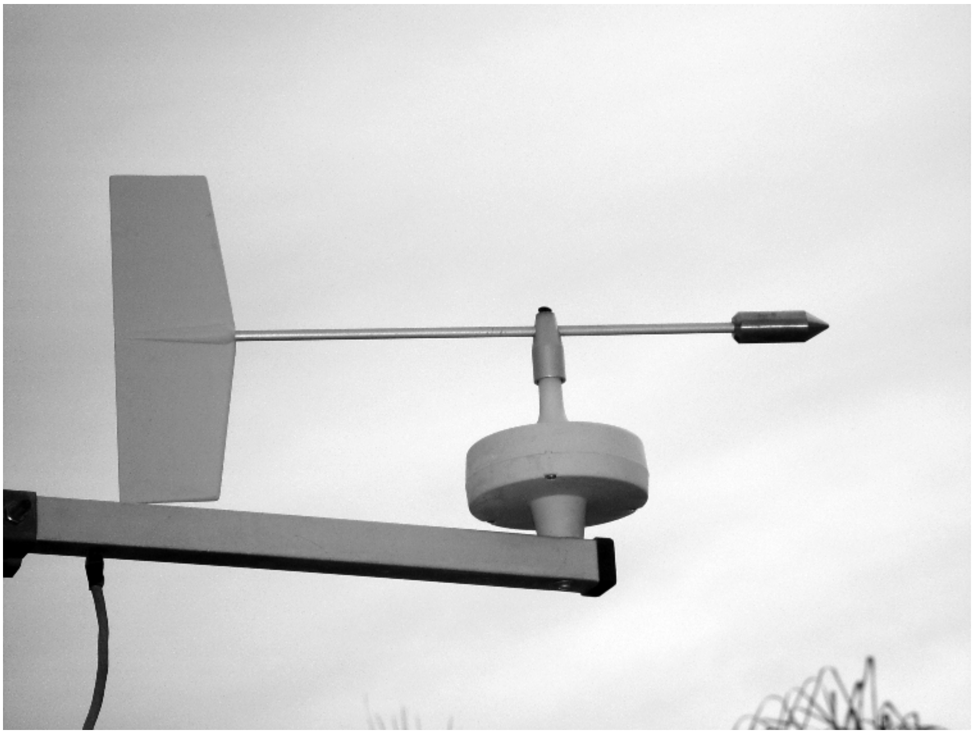

FIGURE 1-16: Weather station wind vane.

Table 1-3 Wind Direction Compass Points and Degrees

Compass Direction	*Degrees*	*Compass Direction*	*Degrees*
North	0	South	180
North-North-East	22.5	South-South-West	202.5
North-East	45	South-West	225
East-North-East	67.5	West-South-West	247.5
East	90	West	270
East-South-East	112.5	West-North-West	292.5
South-East	135	North-West	315
South-South-East	157.5	North-North-West	337.5

Three common types of wind vane position-sensing are used: resistive, magnetic, and optical. Each type converts the position of the wind vane to an electrical signal that is sensed by the weather station computer.

Resistive

This type of weather vane has the rotating shaft connected to a variable resistor (or potentiometer as it's called in the electronics world.) The variable resistor is connected to power, and produces a variable voltage depending on the resistance. This voltage can be connected to a meter for direct display, or to an A-to-D converter. Resistive wind vanes work well for weather stations. Because they contain only a single passive component, they require no power. A single 2- or 3-wire cable is all that is necessary to connect to a remote computer.

Magnetic

Magnetic wind vanes work similarly to the magnet and reed switch anemometers. Instead of the rotating magnet causing a single reed switch to turn on and off, multiple reed switches are placed in a circular pattern. Depending on the rotational position of the wind vane, the corresponding reed switch would be closed. The number of reed switches in the circular pattern determines the resolution of the wind direction. Typical home/hobbyist weather stations have resolution to 16 compass points or 22.5 degrees. Figure 1-17 shows a close-up view of the 1-Wire weather station circuit board. You can see eight reed switches. The unit is designed so that if the magnet falls between two switches, both are activated. This provides 1 of 16 possible directions.

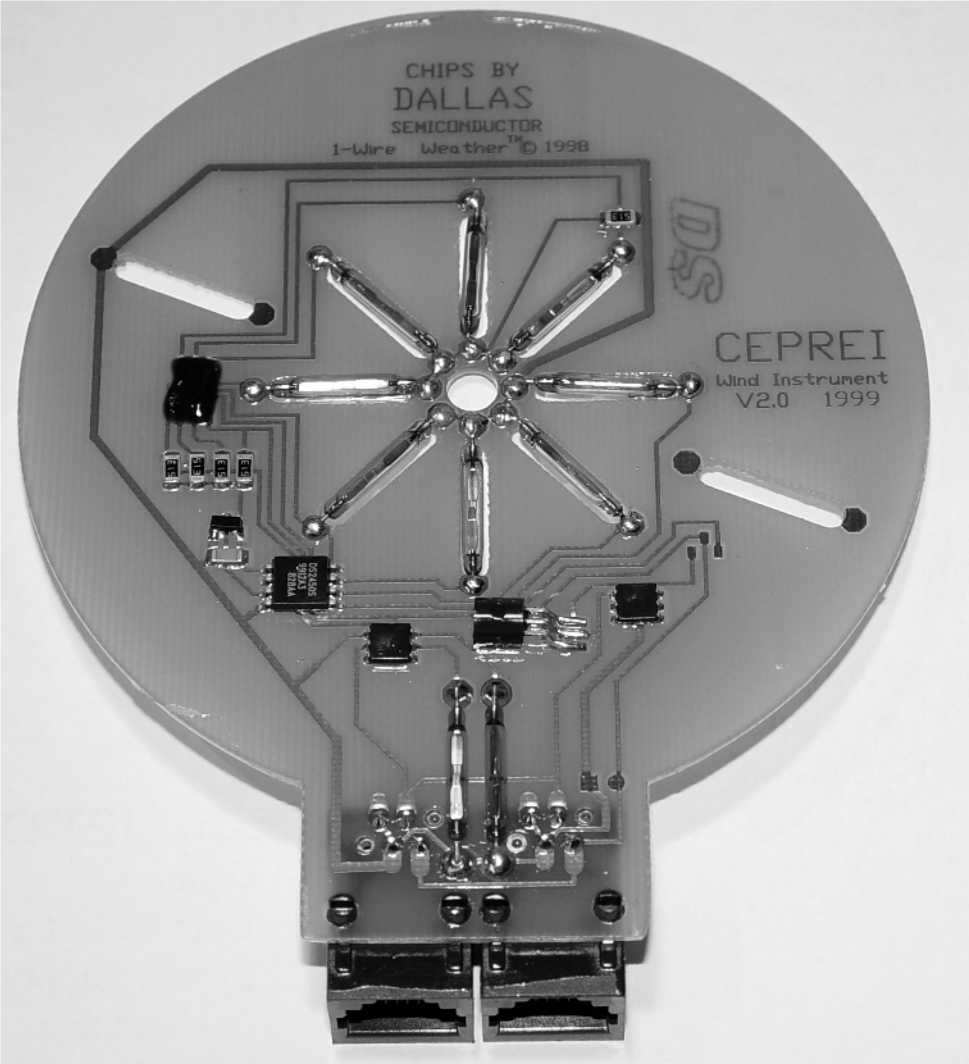

FIGURE 1-17: 1-Wire weather station circuit board. Note the eight reed switches in the center.

Optical

Optical wind vanes use the same principle as the optical anemometers. Instead of the rotating disk blocking and unblocking light to a single photodiode, four LEDs and photodiodes are used. A pattern is machined or painted on the disk so that the photodiodes produce a unique output for each of the 16 compass points.

Barometric Pressure

Back in the 1640s, the Italian physicist Evangelista Torricelli was experimenting with vacuums. He filled a long tube sealed at one end with mercury and inverted it, forming a vacuum in the sealed end. He noticed that from day to day, the level of the mercury in the tube changed. He theorized that the changes must be caused by variations in the atmosphere, inventing the first barometer.

What is barometric pressure you ask? It is the pressure of the weight of the air above us. It is caused by the earth's gravitational pull on the atmosphere. Without this gravitational pull, our atmosphere would just float off into space. Weather causes minor variations in the pressure, which can be measured with a barometer.

Although we're used to measuring pressure in pounds per square inch (PSI), barometric pressure is usually measured in Inches of Mercury (inHg) or millibars (mb). Table 1-4 shows the relationship between PSI, inHg and millibars.

When you think of measuring pressure, you most likely think of a tire gauge or maybe a pressure gauge on a tank. These types of gauges measure the pressure relative to the surrounding atmosphere. Because the surrounding air is what we want to measure, relative gauges won't work. What we need is an *absolute* gauge.

Table 1-4 Relationship between PSI, inHg and mb

Condition	*PSI*	*inHg*	*mb*
1 PSI	1.000	2.036	68.94
1 inHg	0.04912	1.000	33.86
1 mb	14.51	29.54	1000
Normal Pressure	14.69	29.92	1013
Very High Pressure	15.71	32.00	1084
Very Low Pressure	13.75	28.00	948.2

Mechanical Barometers

Mechanical barometers measure the absolute atmospheric pressure by comparing it to a vacuum. A small metal can that is designed to expand and contract is evacuated. This is called the bellows. One side of the bellows is held fixed in place. The other side is connected to a lever arm to amplify the small movement of the bellows. The lever arm is then attached to a pointer on a dial. As the outside pressure decreases, the bellows expands, causing the pointer to rotate. Figure 1-18 shows a close-up of a barometer mechanism. The round can is the bellows. It is connected to the lever arm, which pushes on the platform in the foreground. The small horizontal wire is actually a small chain that is wrapped around the needle shaft and converts the linear motion to rotational motion.

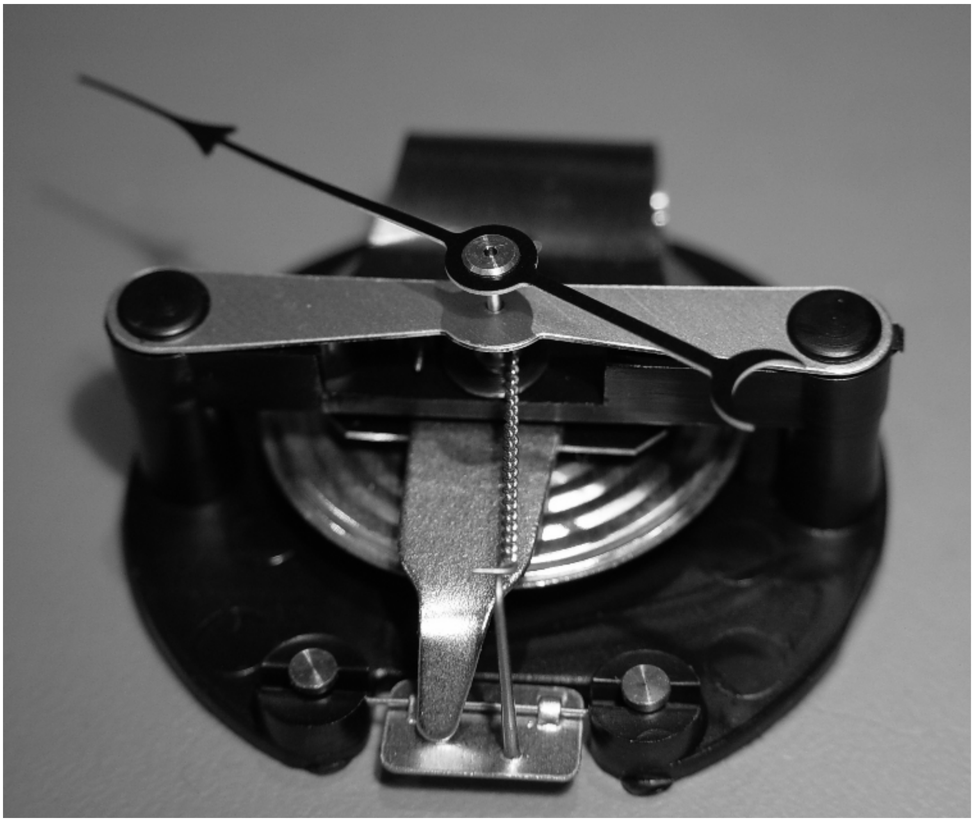

FIGURE 1-18: Mechanical barometer innards.

Barometric Pressure Sensors

Barometric pressure sensors work on a similar principle as mechanical gauges. Instead of a bellows, a small diaphragm is mounted over an evacuated chamber. The diaphragm is manufactured of a special piezo-resistive material that changes resistance in relation to stress. Variations in pressure cause variations in stress on the diaphragm, thereby causing a change in resistance.

There are two primary categories of pressure sensors: bare sensors and sensors that contain integral signal processing electronics. Bare sensors are usually a resistive bridge. DC voltage is applied to two input legs of the bridge, and a DC output is measured across the two output legs.

For weather station applications, having built-in electronics is critical. Because we are measuring extremely small changes in pressure, accuracy is critical in our design. Most pressure sensors are also sensitive to variations in temperature. To minimize this effect, devices with internal electronics contain temperature compensation circuitry, which minimizes the effects. The two most popular pressure sensors used by hobbyists are the Motorola MPC4115A and the Honeywell/SenSym SCX15AN. Both measure 0 to 15 PSI absolute pressure and are shown in Figure 1-19.

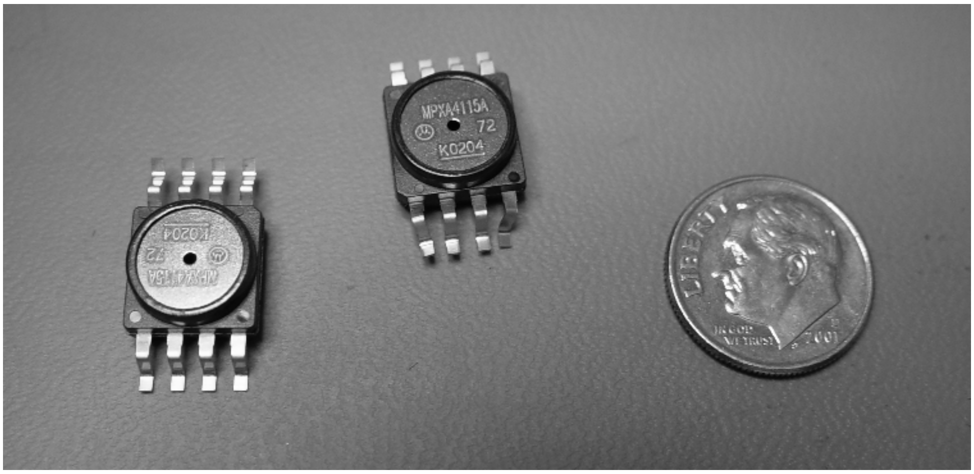

FIGURE 1-19: Motorola MPX4115A pressure sensors.

Station Pressure

While I'm discussing barometric pressure, there's one more topic to cover: station pressure versus absolute pressure. Say you're on the beach with your handy barometer and the pressure is normal at 29.92 inHg (or 1013 mb). You start driving inland a few miles and up in the hills. You look at your trusty barometer, and it reads 27.82 inHg (or 941.9 mb). What happened? Did the weather change?

Earlier, I stated that atmospheric pressure is caused by the weight of the air (at least that's how I think of it). So it makes sense that as you rise in altitude, there's less weight from the air above you, and the pressure decreases, until you leave the atmosphere where there is no pressure at all. In this example, you drove up to 2000 feet and the pressure was lower. This is the *absolute pressure*. Table 1-5 shows the effects of altitude on barometric pressure. So how do you compare barometric pressures at different locations? Weather meteorologists have devised a way. They've defined *station pressure* to be an altitude-compensated pressure measurement. When you calibrate your barometer, you will adjust it so that normal pressure reads 29.92 inHg regardless of your altitude. That way, regardless of where you are, pressure readings are all the same and can be compared.

Table 1-5 Absolute Barometric Pressure at Various Altitudes

Altitude (feet)	*inHg*	*Mb*
0	29.92	1013
1000	28.86	977.4
2000	27.83	942.3
3000	26.82	908.3
4000	25.85	875.2
5000	24.90	842.2
10000	20.58	696.8

Rainfall

As wind blows across lakes and oceans, it collects moisture. As the moisture rises in the atmosphere, it tends to cool. As you learned earlier in this chapter, the cooler the air, the less moisture it can hold. At some point, the air becomes so cold that the moisture condensates in the atmosphere, forming rain clouds. In a process that scientists aren't exactly sure about, the condensation begins to collect. As enough moisture collects in a drop, it becomes heavy, and eventually falls to earth as rain. Rain has to be at least 0.5 millimeters in size, otherwise it is considered *drizzle*.

Rumor has it that back in 1441, King Munjong of the Choson Dynasty invented the first "standardized" rain gauge. Because the amount of rain that fell in each village determined the potential for each farmer's harvest, he devised a standard rain fall collector and scale. The amount of rainfall recorded with his rain gauge was used to determine how much tax to charge the farmer.

Measuring rain is easy. Stick a bucket in your backyard, drop in a ruler, and then wait for it to rain. Getting the rain data into your computer is another matter. There are several ways to do this, but the most common are the tipping bucket and the drop counter.

Tipping Bucket

About 200 years after King Munjong designed his taxation device, Christopher Wren invented the tipping bucket rain gauge. A small calibrated "bucket" was positioned under a collection funnel. As it rained, the funnel collected the water and directed it into the bucket. When the bucket reached a certain level, it would become unbalanced and tip over, spilling the contents. As it tipped, it punched a hole in a paper tape, thereby recording the rainfall. After the contents emptied, the bucket would fall back into place, starting the collection over again.

The Standard Rain Gauge

The official rain gauge was invented more than 100 years ago. It has been used by official forecasters and weather agencies worldwide. It consists of a glass cylinder with a funnel mounted on top directing the collected water into a smaller glass tube mounted inside the glass under the funnel. The cylinder is 50 cm tall, and the funnel is 20 cm across. The tube under the funnel has a cross-sectional area exactly 1⁄10 the cross-sectional area of the funnel (6.32 cm) to provide a factor of 10 increase measurement accuracy.

Rain enters the funnel and drips into the lower tube. A scale mounted next to the tube is compared to the water level in the tube. The tube will measure up to 5 cm or 1.97 inches of water. If the water should overflow, the observer empties the inner tube and pours the overflow out of the glass into the tube.

Most of the weather agencies now use computerized tipping-bucket design rain gauges. But now you know the standard!

Over the years, the design hasn't changed much. Most modern designs use two "buckets" to collect water, so while one of the buckets is emptying, the other is filling. Weather station "buckets" generally hold about one tablespoon of water, so they're not really buckets, but that's what they're called. A small magnet is attached to the tipping mechanism. As the bucket tips, the magnet sweeps past a sensing device. This device then triggers a circuit that counts the tips. By counting the tips, you can now determine total rainfall (since you last reset the count) and by tracking the number of counts in a time period, you can determine the rain rate. Figure 1-20 shows a close-up of a tipping bucket rainfall counter.

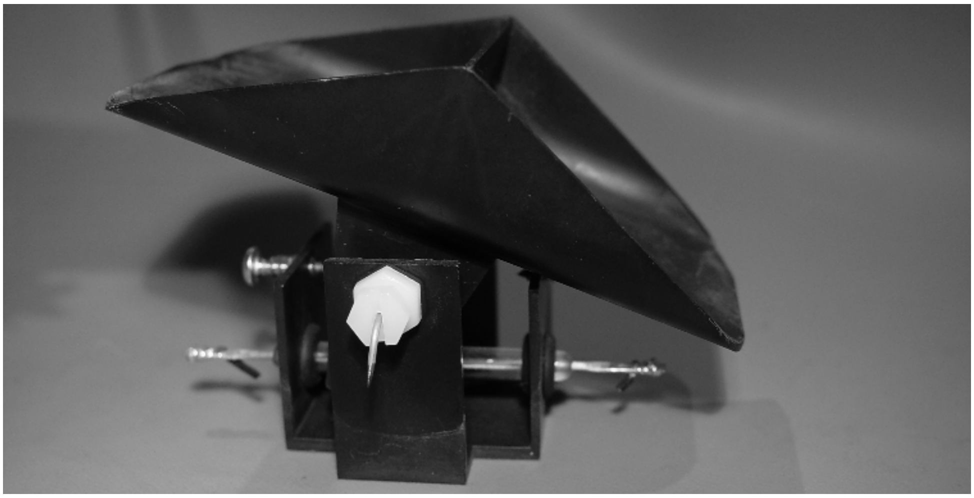

FIGURE 1-20: Tipping bucket rainfall counter. Can you see the reed switch in the center?

Drop Counter

The drop counter rain gauge also uses a funnel to collect rain. The funnel has a small hole at the bottom that allows water to drip out drop-by-drop. As the drip falls, it briefly touches a pair of wire contacts or electrodes. Because rain has a slight resistance to it, electronics in the rain gauge can count each drop as it touches the electrodes.

Wrap Up

This chapter briefly touched upon many aspects of weather and weather measurement, including the following:

- Temperature
- Humidity and dewpoint
- Wind speed and wind direction
- Barometric pressure
- Rain

You also read about some of the sensors used to measure these parameters. Hopefully, you understand a bit more about the weather and how to measure it. Keep in mind I have only presented just a few samples of many different ways to measure weather. New and better ways are constantly being developed.

If you're thinking about designing your own weather station, hopefully I've given you some insight into what it takes. The biggest hurdle is how to get the data from the outside sensors into your computer. Do you incorporate some electronics in your weather station and run a single cable or do you use a separate line for each sensor? Or just maybe the 1-Wire devices piqued your interest.

As you have guessed, using 1-Wire is a good solution. You've read about the 1-Wire temperature sensor, but how do you convert the other parameters to 1-Wire? Well, you'll see how as you progress through this book. But before you start learning more about 1-Wire, the next chapter looks at a couple of the popular commercial weather stations and shows how they work.