Chapter 3

A basic explanation of relays and switches

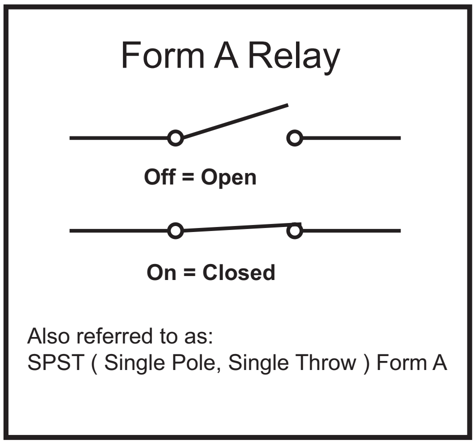
Relays and Switches

Forms and Terminology

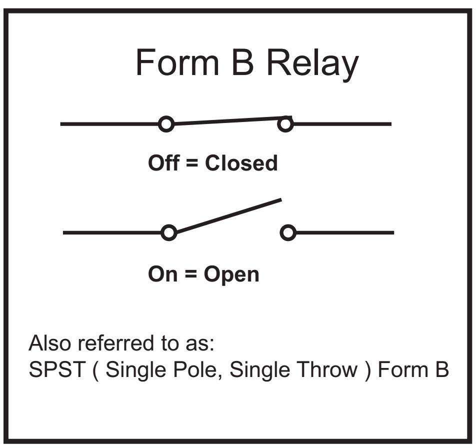
It is useful to understand the common terminology used to describe relays so that discussions later in this book are clear. All relays are usually described by the number of wires, contacts or "poles" that they switch, the number of positions or "throws" that they have, and the style or "form" that they take. There are thousands of relays and switches available but they can all be described using a few simple terms. It is easiest to just start listing the most common simplistic versions and you will catch on very quickly.

SPST – Single Pole, Single Throw

This is the most simplistic relay. It "makes" (connects) or "breaks" (disconnects) a path on a single wire. SPST relays are available in two forms.



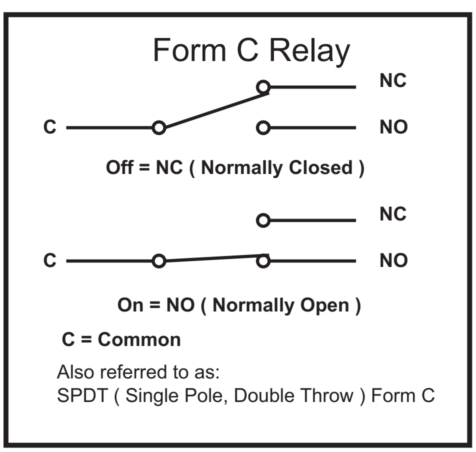
Form A relays are open in the off state and closed in the on state. They are sometimes referred to as "Normally Open" (NO) relays.



Form B relays are closed in the off state and open in the on state. They are sometimes referred to as "Normally Closed" (NC) relays.

These are the most common switches and relays in use. Most light switches, push buttons, and transistors are of this form and simply act as an ON/OFF switch for some device.

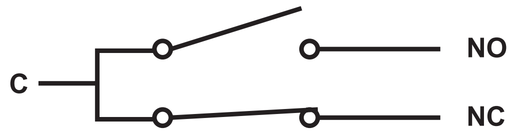
SPDT - Single Pole, Double Throw



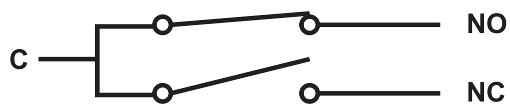
Form C relays are often referred to as SPDT, or simply A/B Switches.

This relay connects a single wire on one side to either of two wires on the other side. The single wire is often referred to as the "Common" and designated by a C on a pin out diagram. The wire connected to the common in the off position is referred to as the "Normally Closed" pin and is designated by NC. The wire that is not connected in the off position is referred to as the "Normally Open" pin and is designated by NO. This style has a single pole that pivots between the NC and NO positions. There is always a connection in the Off state and it can never be connected to both the NC and the NO at the same time. This is often referred to as "Break before Make" since it always has to disengage from the NC contact before engaging with the NO contact.

Form A/B Relay



Off = NC (Normally Closed)



On = NO (Normally Open)

C = Common

Also referred to as:
SPDT (Single Pole, Double Throw) Form A/B

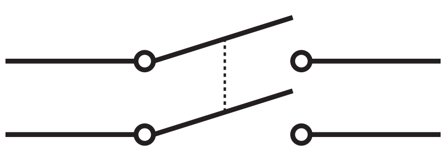
SPDT - Single Pole Double Throw - Form A/B:

This SPDT relay is built by combining a Form A SPST relay and a Form B SPST relay and attaching one end of the two relays together to become the C pin. In the Off state the Form B relay makes the connection to the NC pin and in the On state the Form B disconnects and Form A connects to the NO pin.

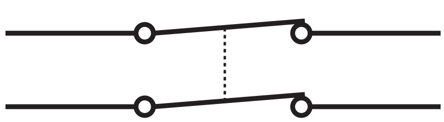
The obvious question would be "why?" when Form C relays are available. It turns out that this arrangement allows certain mechanical relay types to be used providing better specifications for some applications.

The other less obvious answer is that using this technique it is possible to build these relays as "Make before Break". In the Make-before-Break version, both the NC and NO pins are connected to C for a brief moment during the operation of the relay preventing the current flow from being cut-off. A feature that can be critical in some applications.

2 Pole Form A Relay



Off = Open



On = Closed

Also referred to as:
DPST (Double Pole, Single Throw) Form A

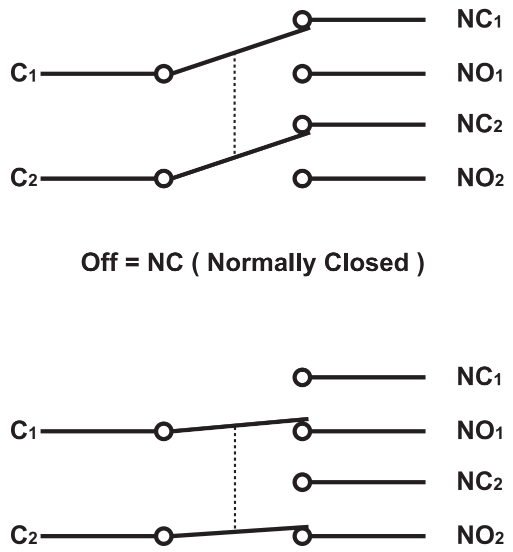
DPST – Double Pole, Single Throw

Also referred to as Two Pole Form A (or Form B) Relays. These relays have two separate relay contacts that are driven from a single drive. Both poles are either ON or OFF.

These relays are useful because they save cost and space over two relays with independent drives and because switching things in pairs is a very common application.

DPST Form B relays are identical to the drawing but the ON / OFF positions are reversed.

2 Pole Form C Relay



On = NO (Normally Open)

Also referred to as:
DPDT (Double Pole, Double Throw) Form C

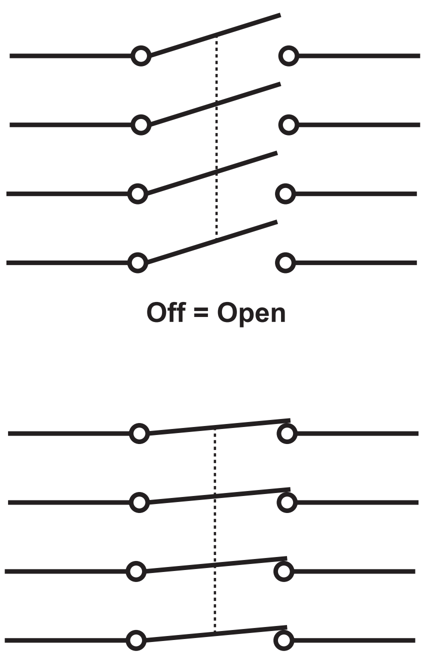
DPDT – Double Pole, Double Throw

Also referred to as Two Pole Form C Relays. These relays have two separate Form C relay contacts that are driven from a single drive. Both poles are connected to either the NC or NO positions.

These relays are useful because they save cost and space over two relays with independent drives and because switching things in pairs is a very common application.

Over the years, this relay configuration has become one of the most common since one relay can be used to replace many. Simply by not connecting to unused pins, you can used this relay as a SPST (Form A or B), SPDT, DPST (Form A or B) and a DPDT. This allows you to buy one standard relay style in large quantities and use it for a large variety of applications.

4 Pole Form A Relay



On = Closed

Also referred to as:
4PST (Four Pole, Single Throw) Form A

XPST - Form A or Form B relays

Once you get beyond 2 poles, Form A or Form B relays with multiple poles are simple referred to as XPST where X = the number of poles or contacts.

While at one time 4PST and 6PST relays were not uncommon, they are rarely seen anymore. It was found that increasing the number of poles beyond two tended to make small electro-mechanical relays less reliable and since demand for this feature was smaller they were not any cheaper to produce. The trend over the years has been to add poles by driving multiple DPST relays in parallel.

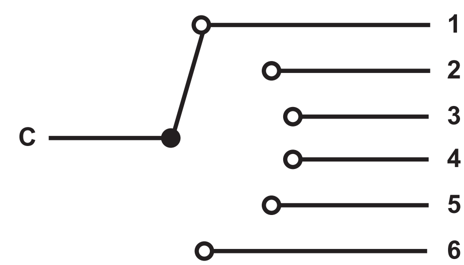
There are exceptions to this in the specialty market and there are still companies building reliable Form A relays with up to 60 poles driven in parallel.

XPDT - Form C relays

Form C relays with more than 2 poles are referred to in the same way. There are companies making 32PDT relays for specialty applications.

SPXT - Multi-throw relays

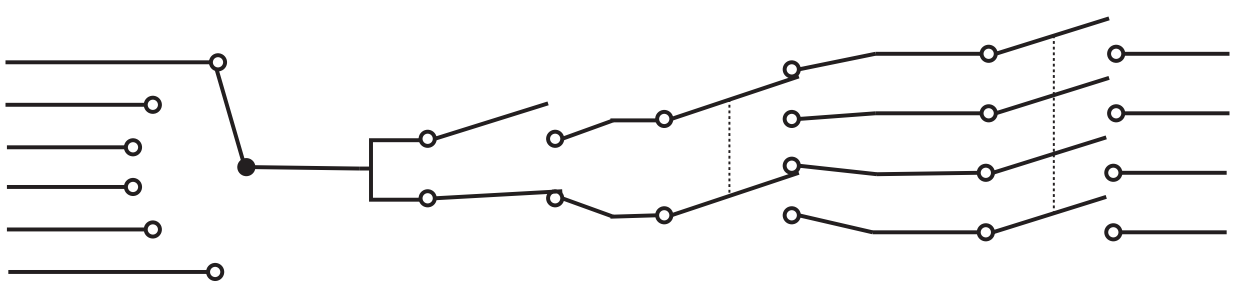
Once you get beyond "Double Throw" relays they use numbers to describe the number of throws and they are referred to as multi-throw relays. A SP6T relay allows you to switch the common to six different places but only one position at a time. These types of relays may or may not have an OFF state. Outside of manually controlled rotary switches the most common uses are for switching power and Microwave signals. A SP6T relay with an Off state is typically referred to as a Normally Open multi-throw relay.



SP6T Multi-Position Switch

Endless possibilities

There are 20P10T rotary switches readily available and oddball combinations in the electro-mechanical world such as SPST Form A + SPDT Form C combinations. But building special relay configurations is often much more expensive than just designing boards with multiple standard relays and a common drive. While much of what has been discussed in this section applies to both relays and switches, we will now be concentrating mainly on relays, since the term "switch" often implies manual operation and brings to mind pushbuttons, toggles and sliders. The definition of relay is: "an electrically operated switch" and since that is what this book is intended to cover we will limit ourselves to those discussions.



SP6T-SPDT Form A/B - DPDT-4PST combination relay circuit.
Used to limit marvelscopic wendalvane fumbling in the grammeter of the Hammond organ tone-wheel generator. or not.

Physical Types of Relays

There are two major categories of relays: Electro-Mechanical and Solid State. Electro-mechanical relays have been around since used for the telegraph in the 1830s. The first transistor, demonstrated on December 16th, 1947 was the first real solid state switch.

Electro-mechanical Relays

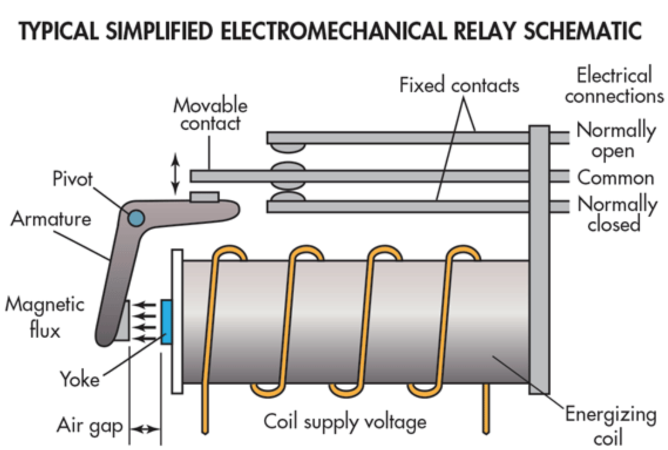
There are two common types of electro-mechanical relays: Armature and Reed. Both of these relay types rely on the principle of electro magnetism to move metallic contacts against each other. Basically a voltage is applied to a wound wire to induce a magnetic force which then acts on a mechanical device. The wound wire is referred to as a drive coil and is designed to provide the correct amount of force based on the voltage used. The drive coil is typically simply defined by it's resistance so that you can calculate the current and the power the relay will need at the voltage used.

Armature relays

Armature relays were invented in the 1830's during an explosion of inventions revolving around the field of electro magnetism. This was the dawning of electricity as a useful tool and it gave us electro magnets which could be turned on and off. Every elementary school child has wrapped a piece of wire around a nail, hooked it up to a battery and built an electro magnet. This resulted in relays and solenoids which lead to motors and generators and everything else that followed. An armature relay is simply a piece of metal that is moved when you turn on an electro magnet. The first relays were big and bulky and used for telegraphs.

Early armature relay at receive end of telegraph line

Over the next 180 years there would be thousands of designs. Some used springs, some used plungers, some used solenoids and some used rockers. If you look at the armature relays of today they haven't really changed much. Modern manufacturing techniques have greatly improved them as far as size and reliability and cost but they are still basically just an electro magnet moving a piece of metal.



Basic armature relay design

Today the differences between armature relays usually just come down to the specific application they are intended to serve. Of the 14 billion relays estimated to have been made in 2008 Armature relays are the most abundant type and are found everywhere. Cars, microwaves, washing machines, TVs, stereos computers and dishwashers make use of them in all shapes and sizes. While they are slowly being replaced by better and better solid state components, the world still uses billions of electro mechanical relays per year.

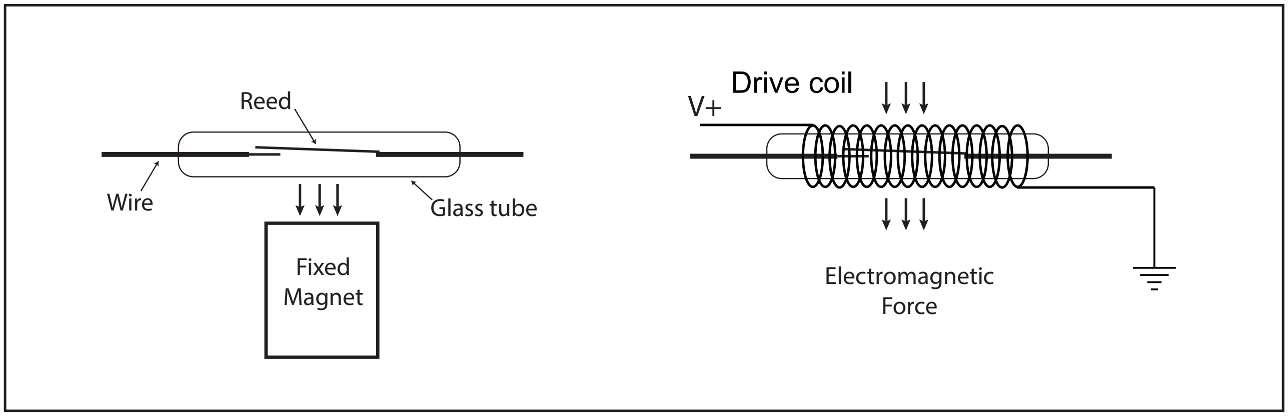
One of the big advantages to armature relays is that you can make them whatever size is necessary to perform a specific task. If you need to switch large amounts of power you simply increase the size of the contacts and the drive solenoid required to move it. If you need a 40 pole relay, you can simply attach 40 contacts to a single drive and give it enough current to move them all back and forth in unison. Solenoid and large electro-magnetic drives give you the freedom to move contacts over a large distance so they can be used for seriously high voltages (> 10 KV) and provide very high isolation. The contact assemblies can be constructed to add features you can not achieve with other types of relays such as “latching” which means the relay always stays in the last set position even if it loses power, a feature critical in some communications applications. Many of these ideas will be discussed later in other chapters.

While armature relays were the predominant type for the first 100 years that relays were being used, they had their drawbacks. They tended to be large, clunky, mechanical devices that were prone to failures and susceptible to environmental issues like vibration, corrosion and humidity. When relays began being used in automated test applications, they were not very good at passing very low level signals for measurements such as picoamps or microvolts. They had many mechanical moving parts so the life expectancy was in the range of 1 million operations, and the switch time to open or close was in the range of 10 to 20 milliseconds, which is slow by electrical standards. For a relay used to turn your car headlights on, or change your washing machine from rinse cycle to spin, these limitations were no big deal. 20 milliseconds was very fast and you would never approach 1 million cycles. But for automated switching applications such as phone exchanges or test, these limitations were expensive and problematic. All of which lead to the development of the reed relay.

As manufacturing techniques and engineering improved, so did the quality of armature relays. The armature relays of today once again dominate the markets and are very competitive with reed relays. They often offer a much lower price, with little sacrifice in specifications.

Reed Relays

Reed relays were invented in the 1920s, first built in the 30s and put into great use in telephone systems in the 50s and 60s. The basic idea is simple. A piece of rigid wire with a flat spot at the end is put into one end of a glass tube. Another piece of iron wire with a long flat area (the reed) is inserted into the other end and the glass tube is closed around the wires at each end. When you put a magnet near one side of the relay the long flat reed is pulled into contact with the flat spot on the other wire making a connection.



Soon it was discovered that you could use an electro magnet to activate the reed instead of a fixed magnet. Improvements were made by coating the contact areas with different materials and filling the glass tube with inert gases or simply evacuating the tube so the reed operates in a vacuum. This prevents the reed from oxidizing and reduces arching when the relay is opened and closed.

The reed relay had certain advantages over armature relays. They operated faster, were inexpensive to build, and because they had very few moving parts, they had a very long life expectancy. The fact that they were sealed in a glass tube made them impervious to environmental conditions such as humidity, or airborne gases. They also survive vibration and perform well in temperature extremes. They were found to be very good at switching extremely low voltages and currents.

It was discovered that you could simply wind the coil around the reed and activate the relay due to the magnetic flux lines pulling the reed in the right direction, which lead to smaller packaging. Just as we saw with armature relays, there were a variety of different styles built over the years, some with strange magnet and coil configurations or attempts to create outrageously complicated configurations. For the most part, reeds are used for switching low power signals of less than 10 Watts, and currents below 2 amps. Reeds are actually good at switching high voltages as long as there isn't any current involved. Because the relay contacts are very close together, they tend to be limited in frequency to applications below 100 MHz if high isolation between signals is required.

Each reed relay is typically a single pole and is available as Form A, Form B and Form C. If you want to make a multi-pole reed relay you simply use a larger coil and insert multiple reed capsules through the middle of it. Before 1980 it was most common to buy the reeds and drive coils separately and then build the configurations yourself by inserting the desired reed through the appropriate drive coil. This was time consuming, required a higher level of skill and did not lend itself to any type of automated assembly. Modern reed relays are mostly sold in packaged forms where the relay manufacturer has done all this and you receive a convenient little brick to place on the circuit board.

Basic Types of reed relays

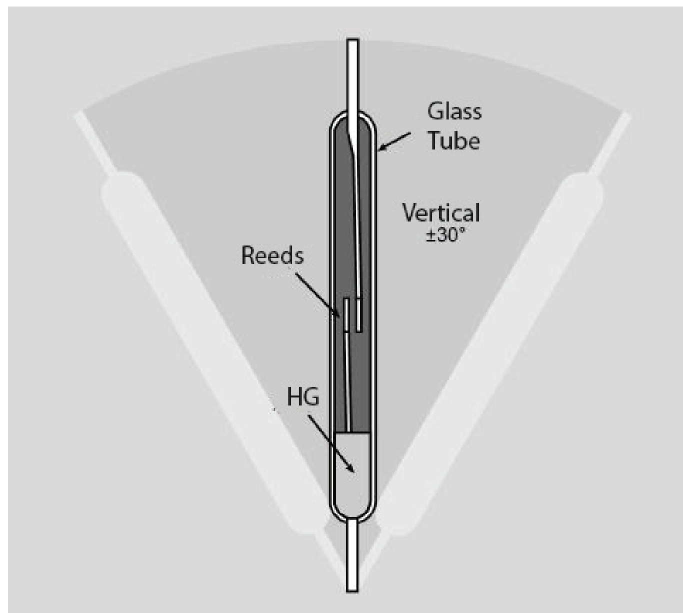
There are four basic types of reed relays three of which are becoming increasingly uncommon but it is good to know they exist.

Type S

This is a "standard reed" relay and is available in Form A, Form B and Form C styles. They are low cost and reliable. While they are capable of switching +/- 200 volts and withstanding breakdown voltages of +/- 400 volts, they typically will only switch up to an amp of current and will only carry up to 2 amps when closed. On the plus side, they will switch microvolts and picoamps making them extremely good for low level measurements. They are typically rated to 100 million cycles life expectancy and have a fairly fast switch time of 1 ms.

Type M or Hg or Mercury reeds

Often referred to as "mercury wetted reeds" or Hg reeds. This is a standard reed with a small amount of liquid mercury (Hg) applied to the reed. The Mercury wicks up the reed and coats the contacts. The Mercury prevents the contacts from pitting, forms a better contact area and prevents the contacts from "bouncing" which allows electrical arcs to damage the reed.



This feature allows them to switch much more power. A mercury reed of comparable size to a standard reed will hot switch twice as much voltage, twice as much current and 4 to 5 times the total power. Another advantage of Type M relays is that they tend to maintain the same low contact resistance until the very end of their 100 million cycle life expectancy. Most other relays (reed or armature) will gradually increase in contact resistance as they reach the end of their life expectancy, but mercury reeds will keep a constant resistance until shortly before they completely fail.

One of the down sides to Type M relays was that the mercury had to be kept at the bottom of the reed in order for the right amount to wick up on to the contacts. Tilting the relay more than about 15 degrees from vertical would allow too much mercury to wick to the top of the reed and the mercury would cause a short across the contacts. Because of this, mercury relays must be kept vertical to operate correctly, thus limiting their applications to stationary devices where they could be mounted in a vertical direction. People using equipment with mercury reeds that don't know this can encounter problems after shipping the device or moving it around to much, since the mercury will not always settle back down to the bottom of the relay. Often the device will simply need to be tapped down against a desk or table top to settle the mercury and fix the problem. Modern encapsulated mercury relays always have an arrow on the case which points upward. It is one easy way to identify mercury relays without looking up part numbers.

Another bad characteristic of mercury reeds is the obvious problem that they contain mercury. Mercury is known toxin that can build up in the body over time and cause brain, kidney and lung damage. Pregnant women exposed to mercury have higher rate of, and more serious birth defects.

The two most dangerous sources of mercury poisoning are mercury vapor and the mercury ingested from food, especially fish. Brain damage and neurological diseases were common among people who worked with mercury, especially gold miners and the makers of felt hats, who used mercury to form them. This led to the expression "mad as a hatter", and mercury poisoning was once referred to as "mad hatter" disease. Mercury in its liquid form is not easily absorbed through the skin, or even when ingested, and is therefore not a serious health risk when you are exposed to small amounts. But mercury has an extremely low boiling point, and will evaporate at room temperature, which means any area that has liquid mercury exposed to the air should be kept well ventilated. The small amount of liquid mercury found on the reed in a relay is sealed in a glass tube, then surrounded by a wound wire drive coil, then the assembly is typically potted and sealed using epoxy or rubber compounds, and this is all done in a metal or plastic case.

The vaporized mercury in a small florescent bulb that breaks, or the organic mercury in four or five salmons from polluted waters would pose a much greater health risk than a single broken mercury relay. But the mere mention of mercury makes environmentalists cringe and litigation lawyers salivate, so the cost of dealing with it has grown increasingly expensive. Between 2005 and 2009 the price of mercury wetted reed relays tripled, effectively wiping out the cost benefits in all but a few applications.

One interesting bit of trivia about mercury relays is that you are not allowed to use them (or any thing containing mercury) near any nuclear reactors such as power stations or nuclear powered submarines. When I first heard this and questioned why, I was told that it was because of the environmental hazard, which I found ironic and silly. It seemed like the last thing you would be worried about when a reactor core was melting down was whether there might be any mercury to get mixed in with the ensuing radioactive environmental nightmare. I found out later that the more realistic concern is based upon the fact that all reactors used a closed environment system of pumps for cooling and waste water. Even small amounts of mercury spilled onto the floor will seek the lowest level, and can run into drains, eventually ending up at one of the pumps where it could do serious damage to systems designed to prevent disasters.

High Voltage reeds

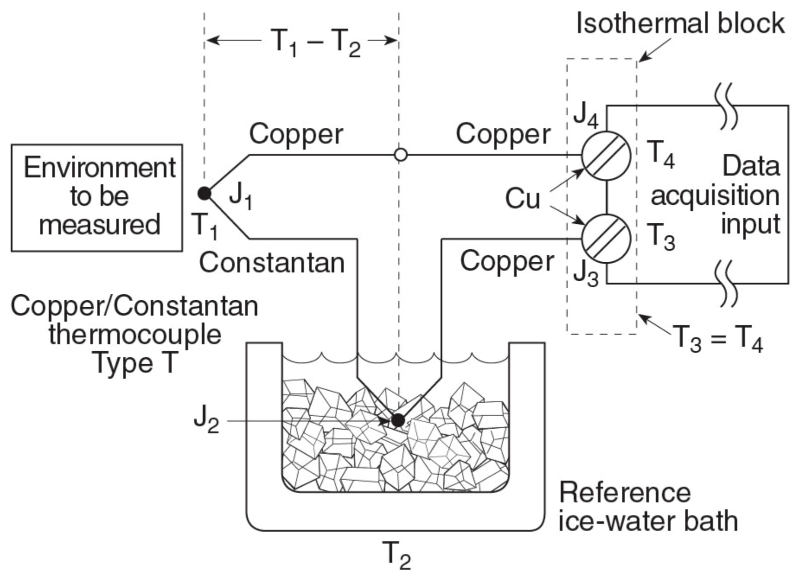
Because reed relays are encapsulated in a sealed glass tube, you can remove the oxygen from the tube and run them in a vacuum or fill the tube with an inert gas. This allows the contact gap between the two reeds to withstand much higher breakdown voltage levels. Because this minimizes arcing and there is no oxygen to burn, the contacts can withstand much higher voltage levels when switched. This lead to special high voltage reeds that will switch up to 1500 volts in small packages, and up to 10 KV in larger sizes. They are typically limited in the amount of total power they can hot switch, but they will carry a decent amount of current once they are closed (1 to 3 amps), and will still work well at very low currents, making them ideal for high voltage isolation measurements.

Low Thermal reeds

Low thermal reeds were developed to deal with a special application in data acquisition. Many of the temperature, pressure, and strain gages used to measure things were two wire devices that generated a known voltage corresponding to a specific temperature, pressure or strain. You tie these wires to a meter and measure the data as conditions changed. These devices often put out an extremely low voltage over a fairly narrow range requiring accuracies of microvolts in order to get repeatable, valid readings.

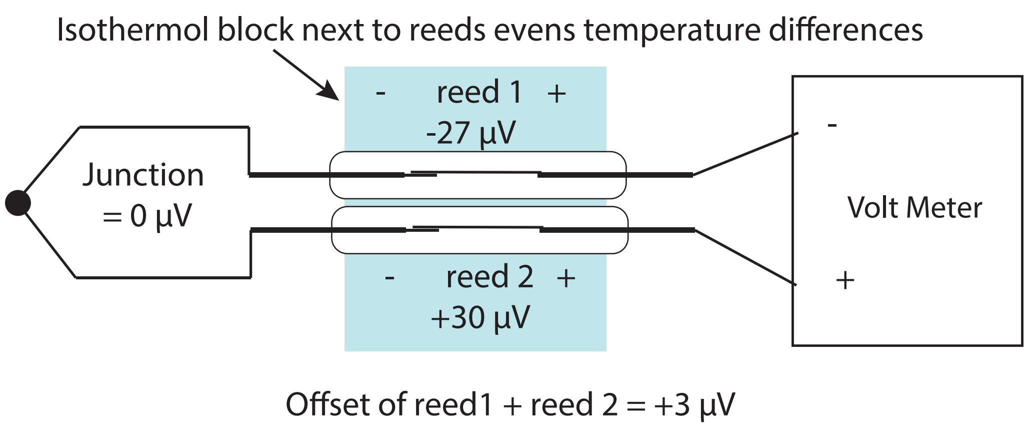
While it is easy to do this with one gauge, it gets increasingly difficult when you have to switch your meter between a large number of gages. What made it even more difficult is that wire connections are often done using different metals such as steel screws on copper wires, or gold contacts crimped onto copper wires. It's a well known fact that when different metals are tied together, the junction actually produces a slight voltage. This is, in fact how many of the gages work. To complicate things further, the offsets will change with temperature, so you have to maintain a constant temperature wherever junctions occur. This contact electromotive force (EMF) or Galvani Potential is well studied, and is both useful, or troublesome, depending on what you are trying to do.

In the example to the right, you can see the measures they have taken to minimize the offset voltages through a single circuit. Isothermal blocks are used at wiring junctions to minimize changes in temperature, and like metals are used to avoid the generated EMF at the wiring junction close to the data acquisition.



When you add switches to this circuit it gets even more complicated. Since the metals used to make reliable relays can give off fairly high EMF, relay manufactures came up with a series of "Low Thermal" relays to be used for these applications. These relays have two features that make them perform much better in these applications.

Basically whenever they build two pole reed relays (or armature for that matter), they can measure the EMF generated by each reed, and look for relays that have closely matched EMF. The closer they are matched, the lower the total offset. The figure below shows how this works based on Kirchoff's law. Often the relay manufacturer may be running thousands of relays off assembly lines everyday so it is just a matter of matching EMF based on a simple measurement. You can buy relays with < 5 uV, < 2 uV or even down to < 0.5 uV. The price usually goes up as the offset value gets lower.



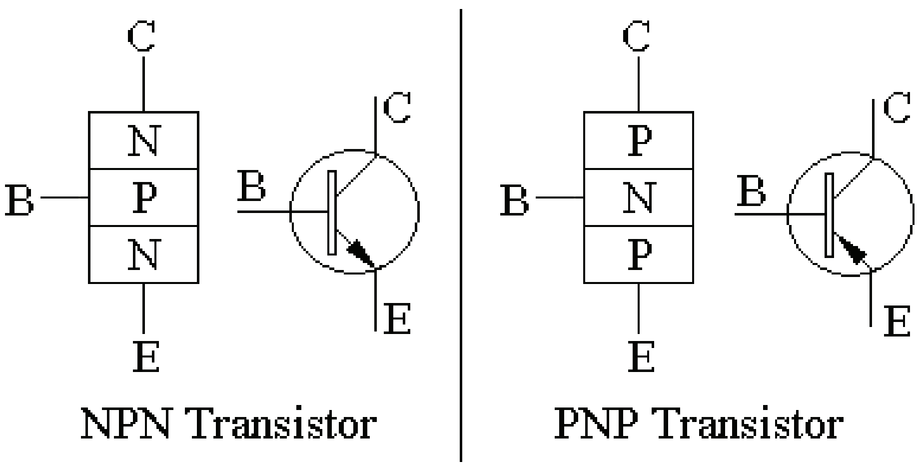
They then build an isothermal block of material (usually metal), into the assembly to distribute heat so the temperature of both reeds stays the same. This prevents one reed from changing value quicker than the other as they warm or cool.

Solid State Relays

Transistors

As stated earlier in the book, the first solid state switches (transistors) were demonstrated on December 16th of 1947 by American physicists John Bardeen, Walter Brattain, and William Shockley. They have arguably changed the world faster than any other device in history. While early simplistic transistors were extremely limited in what they can switch, they allowed the inexpensive construction of complicated logic circuits, leading to Integrated Circuits (IC's), digital computing and digital communications. They consumed very little power and could be manufactured in very small sizes which meant a lot of switches could be packed into a very small area.

Early transistors basically consisted of PNP or NPN junctions as a three pin device. Put a voltage to the Base and you can get current to flow from the Common to the Emitter or the other way round.



Basic Transistor theory

Different transistor packages

I could easily spend the next hundred pages of this book discussing transistor theory but I'm not going to. I spent an entire semester of college studying the theory and physics behind them and the amount of that information I have used in the last 32 years could have been taught to me in 30 minutes. Ironically, they never explained to us how to read semi conductor data sheets, which is something I've had to do almost every day of my career. A useful bit of information for any reader debating skipping college. If transistors interest you, there is a lot of information available from people who know much more about them than myself.

What the transistor really did was open up the field of study known as solid state electronics or semi conductors. This has lead to diodes, op amps, LED's, logic circuits, memory circuits, gate arrays, microprocessors and a huge selection of digital devices.

What transistors did for programmable switching systems at first was not to replace mechanical relays, but rather to give us an inexpensive method of turning mechanical relays on/off, and a means of controlling how that happened through inexpensive logic circuits. While transistors were great for presenting an on or off condition with standard logic voltages, they were not great at dealing with real world signals. They were limited in voltage range, susceptible to things like static electricity and had a high contact resistance or voltage drop across the contacts. As technology progresses, these barriers are being broken down further every year. As better and better materials were found and better techniques were developed for building devices, the range of usefulness for solid state switches has expanded.

At this point in time, solid state switches are basically "application specific", meaning if you have an application for which solid state switches are being mass produced they can be the best choice. You need to recognize their limitations in order to make that choice.

The Pros and Cons of solid state relays

Solid state relays and devices have come a long way. You can now get solid state relays that can replace electro mechanical relays in almost any application. The only problem is they will only work in that specific application, and often they will not have specs as good as a mechanical relay. There are thousands of choices and each one provides a specific advantage for a certain need. You can get power mosfets for building switching power supplies, pin diode or semi conductor RF switches for cell phones, digital bus switches for memory lanes, serial data switches for ECL, PECL, LVDS and CML, hockey puck power switches, micro miniature logic level switches, and the list goes on and on. Rather than try to detail these in a single section of this book, I'll bring them up in application specific content when they stand out as an obvious replacement for mechanical relays.

The Pros

Solid state switches have two advantages that can not be argued with: speed and life expectancy. While the fastest reed relays may have switch speeds as low as 0.5 milli seconds, many solid state switches have switch speeds in the 10's of micro seconds range and some can react in nano seconds. And where a mechanical relay with 100 million operation life expectancy is considered very good, solid state relay life is often just estimated in the 10 trillion range because it is impossible to cycle them long enough to get an accurate number.

One way to put it into realistic terms is to think about the fact that there are 31,536,000 seconds in a year. So if you have a decent, 100 million cycle mechanical relay and you're turning it on /off once per second it will last about three years. Turn it on/off 50 times per second (the realistic limitation) and your hitting the life expectancy in less than a month.

Now take a solid state switch with a 1 microsecond switch time and have it turn on/off 50,000 times per second. You hit the mechanical switch life expectancy in about 30 minutes. At the end of one day you have hit 4.3 billion operations. In a year you are at 1.5 trillion operations. Obviously at some point they just turn off the life expectancy test and give is some ridiculous number as a spec.

The speed and life expectancy specifications are due to the way a solid state switch works. There are no moving parts and often the junctions are very small making it fast and reliable.

There are other positive side effects of using semi conductor devices for switching that are not always so obvious. Pin diode switches always have a lower frequency cutoff range. By that I mean that they will not switch signals below a certain frequency. While on first glance this may appear to be a limitation, in reality they are often used to switch very specific high frequency bands, and having the built in high pass filter can eliminate problems associated with low frequency noise or DC offsets. Power mosfets are often designed to switch AC signals only at the 0 volt crossing point which means they can hot switch high power AC signals without any trouble.

The Cons

Most of the cons have already been noted, the biggest being that they are application specific. While a mechanical relay may be able to handle +/- 500 volt signals or +/- 2 amp signals and will work from DC to 500 MHz, a solid state device will probably only do one of these three things well. Solid state high frequency switches with good isolation tend to be very limited in power handling, and solid state high frequency switches that will handle a lot of power tend to suffer in areas such as isolation.

Solid state switches are also more susceptible to electro static discharge so they must be handled with those precautions in mind.

	General Purpose Relay Type These are general specs. There are specialty relays available in all these types that can exceed these specs. This chart is only intended to provide a “big picture” characterization.		
Specification	Reed Relays	Armature Relays	Solid State Relays
Switched voltage range	Typically 100 uV to 200 V, Type M and type HV up to 1000 V peak.	Data types 100 uV to 200 V, Power types 100 mV to 500 V peak.	DC --0.1 V to 500 V, RF types -80 to +40 dBm
Switched current range	Typically 1 to 2 amps max	Data types 1 to 2 amps, Power types up to 40 Amps	Samll Mosfets up to 8 amps, large power fets up to 200 amps.
Max Switched Power	Typically 10 watts, Type M and HV up to 50 watts.	Data types up to 50 watts, Power types up to 1500 VA.	Small Mosfets up to 50 Watts, power fets with 0 crossing up to 5000 VA.
Breakdown Voltage	Typically +/- 400 V, Type M and HV up to 1500 V. Specialties up to 10KV.	Data types up to 300 V, Power types up to 750 V. Specialties up to 100 KV.	Typically less than 400 V. Stacked mosfets to 30KV but with high on resistance.
Carry Current	Typically < 2 amps. Specialties up to 5 amps.	Ratings to 25 amps are common. Specialties and contactors to hundreds of amps.	Application specific. Varies widely from ma’s to hundreds of amps.
Power Consumption	100 to 300 mW typical.	200 to 800 mW typical. Specialties can go as high as 10 W per relay.	Typically very low. Well under 50 mW.
Life expectancy (Mechanical)	100 Million operations typical.	1 to 10 Million operations typical.	In many ways infinite. Will usually outlast the product or usage. Estimates > 10E13 operations.
Life expectancy (Rated Load)	Typically 10% of mechanical life. Varies between manufactures according to how they are spec’ed.	Typically 1 to 10% of mechanical life. Varies between manufactures according to how they are spec’ed.	Same as mechanical life since no moving parts. Life is basically infinite for practical use.
Switching Speed	Typically 0.5 to 3 ms.	Typically 1 to 25 ms depending on size.	Typically 50 ns to 1 ms.
Cost (2016)	Typically $2.00 to $20.00.	Typically $0.50 to $15.00. Specialties can go for hundreds of dollars.	Varies greatly from < 1 cent to hundreds of dollars. Application specific.
Size	Typically about 1” x .5” x ,5 +/- 50%.	Can range anywhere from .5’ x .5” x .5” to the size of a beer can. Depends on power involved.	From < 1 nanometer to the size of hockey pucks.
Temperature range (operating)	Commercial: 0 ° to 70 °C Industrial: −40 ° to 85 °C Military: −55 ° to 125 °C	Commercial: 0 ° to 70 °C Industrial: −40 ° to 85 °C Military: −55 ° to 125 °C	Commercial: 0 ° to 70 °C Industrial: −40 ° to 85 °C Military: −55 ° to 125 °C
Capacitance	1 to 4 pf typical	< 1 pf	Varies a lot based on application
Usable Frequency Range	DC to 2 GHz	DC to 65 GHz	Varies a lot. Most solid state relays that will switch frequencies above 1 GHz have a lower frequency cutoff.

Glossary of Terms and Specifications

The following is an explanation of terms and specifications commonly used to define relays and switches. They are grouped according to subject or spec such as voltage, current, power etc.. RF specs are listed separately as they usually pertain to different kinds of relays and apply to signals above a certain frequency range.

To best understand the specs you need to realize the difference between an ideal relay and a real relay. The drawing below shows an ideal relay compared with a more accurate schematic of a real relay. Where the ideal relay simply has infinite resistance across open contacts, and 0 ohms resistance across closed contacts, in reality there are many other factors to consider. For a circuit with a single relay, these factors are so small that they rarely effect the circuit. But for situations where you are working with very small signals, very large signals, or very high frequency signals, these factors become important. And when you are combining hundreds of relays in a large system, these factors can quickly add up to have drastic effects on your circuit.

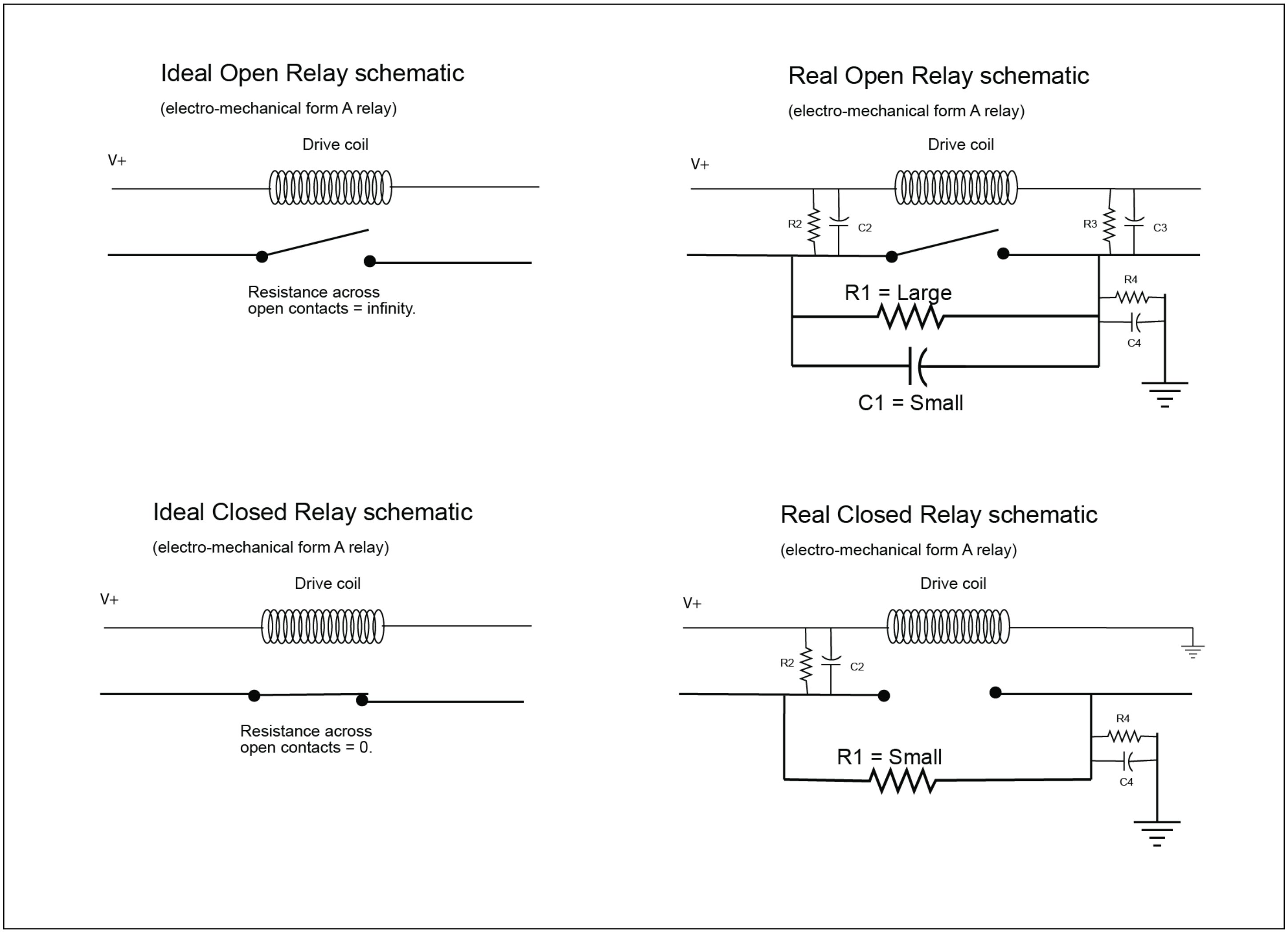


Figure 1 -- Relay Schematics

Relay Specification Explanations

These are the common specifications listed for relays and what they mean.

Maximum Switched Voltage - This usually means the maximum voltage that can be switched without degrading the relay contacts. Some relays will list this spec with a foot note saying how much the life expectancy will be shortened when switching higher voltage levels. This specification differs greatly from breakdown voltage which is the voltage levels that can be carried by the switch once it is closed. Breakdown voltage is normally much higher which means you can use a relay with a lower switched voltage spec., as long as you turn the voltage off while turning the relay on or off. It is important to note the switched power spec when considering switched voltage because many relays will switch a lot of voltage as long as there is no current. You need to calculate the total switched power when considering switching any high voltage. Most relays base this spec on switching to a purely resistive load. This is important because switching to a capacitive load can cause large current spikes as the relay closes, and switching to an inductive load can cause large voltage spikes when the relay opens. See the entry for Loads for an in depth explanation. A relays maximum switched voltage spec is typically based on the contact materials and the gas surrounding the contacts. Reed relays will typically withstand high switching voltages because they are sealed within a glass tube and surrounded by a vacuum or an inert gas.

Breakdown Voltage -- Basically the same thing as “carry voltage”. This is the maximum voltage level that the relay can withstand before it runs the risk of arcing. It is usually broken down into two specifications: “Across Open Contacts” is the specification for the voltage level that the relay will withstand when it is open. This is important in switching systems since you normally have many relays tied together so it is important that they isolate the closed path. The other spec is usually listed as “Contacts to Coil” , “Contacts to Case” or “Contacts to Ground”. This is basically the spec where the relay will arc to anywhere else. This is usually only important if you are using only one relay and don’t need to worry about the “across open contacts” spec. once the relay is closed. The “across open contacts” spec is typically lower and the only one that usually matters in switching systems. A relays breakdown voltage spec is usually based on the separation between contacts, and the gas surrounding the contacts. Reed relays usually achieve high breakdown voltages by enclosing the relay contacts in a vacuum or surrounding them with an inert gas. Armature relays can achieve very high breakdown voltages by simply moving the contacts far away from each other.

Maximum Switched Current -- This is the maximum amount of current that the contacts are rated to handle as the switch opens and closes. As the contacts come together to complete the circuit there is always the initial spark at the contacts first touch and often slightly bounce. Hot switching too much current will destroy relay contacts faster than almost anything else as this spark will burn the contacts. Things like Mercury wetted relays were basically invented to improve performance in this area. Many solid state switches will handle hot switching a lot of current on AC loads by only opening and closing as the AC signal crosses 0 volts. Armature relays typically just make the contacts larger to handle hot switching of currents. Switched current is greatly effected by the capacitance in the system. Capacitive loads will have a very large instantaneous current when you first close the relay. Most relays specify the switched current for a purely resistive load. Always consider the total switched power when considering switched current

Maximum Carry Current -- This is the maximum amount of current that the contacts are rated to handle once the relay is closed. It is typically about twice the limit of switched current. Carry current is typically only limited by how low the closed contact resistance is (R1) and the physical size of the relay contacts and wiring.

Maximum Switched Power -- The total amount of power the relay contacts can handle as they are opened and closed. It is important to recognize this spec because the switched voltage and switched current specs are usually much larger than the total switched power spec allows. For example: A standard reed relay will usually hot switch 400 volts and can hot switch 1 amp. But the total switched power is typically 10 watts. So if you are switching 400 volts, you would be limited to 25 ma of current. And if you are switching 1 amp, you would be limited to 10 Volts. Once again, this is usually listed as the specification for a purely resistive load. Both capacitance and inductance must be considered when calculating this specification.

Minimum Voltage and Minimum Current -- Some relays will not even list this specification. Other relays will list a recommended range. This spec. is usually included if the relays are not intended to switch very low levels. Many relays intended to switch a lot of current have unpredictable contact resistance when very little current is switched. Some relays will use different metals on the contacts to handle more hot switched power and this makes them horrible for measuring low voltage levels. Many of the specifications for a relay are dependent on certain voltages or currents being switched so they will list the minimum to avoid confusion.

As a general rule, reed switches will handle signals in the micro volt levels, and currents down to nano amps. Small armature relays designed for instrumentation applications will also handle low levels. Relays designed for very high power levels or current levels are usually the worst for dealing with low level signals. Once again, solid state switches will usually be marketed and sold for the specific application, so the question will not usually come up. There will be a spec such as leakage current, max voltage level or max current level that won't lead you believe it might be used at both ends of the spectrum.

Contact Resistance -- This is the resistance measured across the closed contacts. In the schematic, this is R1 on the closed relay. For mechanical relays this is typically a very low number such as 0.05 ohms which is what you would expect across metal contacts. For solid state switches this specification can vary anywhere from 0.01 ohms, to 650 ohms, depending on what the relay is intended to do.

For mechanical relays, this spec is often given with the measurement conditions such as:

Resistance = 0.1 ohms @ 10 volts and 200 ma, 3 ms after contact closure.

It is important to pay attention to this, especially when choosing armature relays. Many armature relays will have a very low contact resistance as long as there is some current flowing across the contacts. But the contact resistance can go up as the current goes down. This is due to current flow actually holding the contacts together and used to be know in the telephone cabling world as "sealing current". Typically this is only an issue on relays that are intended to carry large amounts of current and is due to the large physical size of the contacts.

Stating the amount of time after the contacts close is needed to account for contact bounce. Often they will state two separate resistance measurements such as "Initial Resistance" vs "Stable Resistance". This can be an important consideration if measurement timing is critical and basically tells you how long you need to wait for stable relay contact resistance.

Solid state relays do not have issues with contact resistance vs load and have no contact bounce, but the contact resistance can be related to the drive voltage. Solid state relays usually specify the contact resistance at different drive voltages if this is the case.

Isolation Resistance -- This is the resistance measured across open contacts. In the open relay schematic this is R1. This spec is usually very high and usually is directly related to breakdown voltage. This spec is important because it determines how high a resistance you can measure or, more likely, how low a current you can measure.

For a single relay circuit almost any relay will have a high enough isolation resistance for the task required. But because resistors divide in value when in parallel, the isolation resistance gets divided by the number of relays you have in parallel. So if you have a 256x1 multiplexer used for taking leakage current measurements, the resistance across all the open relays is 1/256th of what a single relay would be. This is assuming that all of the relays are of equal isolation resistance value.

There are tricks you can do to minimize this effect, and we'll get to that later in the book.

Resistance to coil and resistance to ground -- These are the stray resistance values R2 through R4 on the schematic. It is the resistance from the contact to either the coil or to ground. Typically these values are so much higher than contact Isolation resistance R1 that they are not any issue. Often they will not even be specified. If they are specified, it is most likely because they are close enough to R1 in value to be of concern. These can add up in systems that are run at high voltage levels adding to stray leakage currents.

Capacitance across open contacts -- This is the value for C1 in the schematic for the open relay. Usually this value is small (0.1 to 2 pF) but it can have an effect since capacitance adds in parallel. This parallel stray capacitance can effect the settling time for measurements as you wait for all the capacitance to charge. It can also effect high frequency measurements since it adds the C component of an RLC filter circuit, eventually contributing to the frequency limit of the system.

Capacitance to coil and ground -- These are the stray capacitance values C2 through C4 on the schematic. It is the capacitance from the contact to either the coil or to ground. Typically these values are smaller than C1 but often high enough that they need to be taken into account. On relays intended for high frequencies, they design the relays to have a characteristic impedance matching the type of signal you are switching such as 50 or 75 ohms. For those relay types, this spec is typically not mentioned since it contributes to the impedance.

MBB and BBM -- The acronyms refer to Make-Before-Break and Break-Before-Make and are always in reference to multi-throw relays such as Form C, Form A/B or switches configured as 1xN. It basically just refers to whether the first contact separates before the second contact closes. Most normal Form C relays are assumed to be Break-Before-Make unless otherwise specified. It is by far the most common configuration. Armature relays may be made to Make-Before-Break by constructing the contacts in a way that forces the the Normally Open contact to close before the Normally Closed contact opens. For reed relays, a normal Form C is always BBM, but Form A/B relays can be made to operate as MBB by timing the drives or adding a magnet to the Form B reed to slow down the opening. MBB relays are usually only used in situations where they always have to have a connection and can not allow a signal to be broken. This can be required in communication or power applications where interrupting whatever is happening can be disastrous.

If you need a MBB relay you will need to specifically look for one. They tend to be so infrequently used that many relays will not list this feature unless they are being built for that purpose.

Relay Drive Specifications

Drive types:

Non-latching, Single-Side Stable -- This is the most common drive with defined + and - drive pins. You complete the circuit through the relay coil and it energizes an electromagnet moving the contacts into the "ON" position. You disconnect the voltage and it returns to the "OFF" position. Relays like this either have a voltage applied to one terminal all the time, and the connection to ground is completed by the circuitry (current sink), or one terminal is at ground all the time, and the connection to voltage is completed by the circuitry (current source). It is simple and reliable, but the only problem is that you have to maintain power to the relay all the time for it to stay on. In applications where losing power could cause a serious issue you may need to use latching relays. If power consumption is a serious issue then latching relays may also be a better choice since you can turn off the drive as soon as the relay changes positions.

Single Coil Latching -- This is used with relays that latch into their position after switching so they will stay that way until you tell them to switch into the other position, even if you lose power. This type of relay requires a more complicated drive circuit that reverses the polarity of the drive to make the relay switch between positions.

Dual Coil Latching -- This relay has two separate drive coils for each position. It's a simpler drive circuit, but requires more physical space in the relay.

One thing to keep in mind with latching relays is that if you take advantage of the ability to turn off the drive to save power, you may lose your ability to tell what position it is in since many status indicator circuits are based on power being applied to the relay drive circuit.

Pulse Latching -- This latching circuit automatically disconnects the drive voltage after the relay has changed position. This can save power and depending on how the drive circuit is configured often allows you to retain the status indicators.

Timer Circuits -- Some relays have built in timer circuits to delay activation or automatically change back to a previous position after a specified increment of time but these are not normally used in programmable switching systems which can simply be programmed to do these functions via software.

Something to keep in mind with all relay drive circuits is that they almost all use a wound coil to generate the electro-magnetic force needed to move the relay contacts between positions. This means that relay drives are basically inductors and like any inductor they may generate a inductive kickback voltage spike when turned off. Many relays and solenoids have kickback diodes built into them to prevent this but if they do not, it is a good idea to include one in your drive circuit. The larger the drive coil, the more important this can be. It is also important to note that since they do generate a magnetic field you may have to pay attention to how closely they are speced since the field from one relay may effect the performance of relays next to them. Some relays will have a metal case or surround the coil with foil that can be grounded to eliminate this possibility.

Drive Voltage:

Most modern relays are driven using DC voltage. While AC driven relays are still available they have become less much less common except very large relays requiring a lot of power to activate. All solid state relays are driven using DC.

Electromechanical relays use an electro magnet so the power required to drive them is a simple V=IR calculation based on the resistance of the coil in the electro-magnet. Typically the choices are 5, 12 or 28 volts and the decision on what voltage to use is based upon the amount of current available for the number of relays you need to drive at once. For general applications such as automotive or appliances where the number of relays is low, the choice is dictated by the voltage that is readily available. For switching systems, the choice is usually based on the relay type and amount of relays being driven. The most common DC voltages used are:

+5 volts -- Solid state and systems with a low number of electro-mechanical relays.
+12 volts -- Typical in reed and armature relay systems with a large number of relays being driven.
+28 volts -- Systems using large relays such as microwave, high current, high power or high voltage.

These voltages are the levels that all of the relay specs are based upon and not the exact levels needed for the relay to operate. When you look at a relays drive voltage specs it will also specify:
Pull-In voltage -- The minimum amount of voltage that will activate the relay. Typically about 70% of the specified drive voltage but it can vary between 20 to 80%
Drop-out voltage -- The voltage level drop that will make a single side stable relay drive turn off the relay. Once again this is typically about 70% of the specified drive voltage but it to can vary a lot.

This worth noting because some relays such as power or microwave will specify a voltage range for the drive instead of a fixed level. Many large relays are specified as 28 volts but will work at any voltage between 24 and 32 volts.

Drive Current:

This is simply a function of the drive voltage divided by the relay coil resistance. For most small reed and armature relays driven with +12 volts this is typically between 10 and 20 ma. As relays increase in size this tends to go up to anywhere from 50 to 300 ma. Part of the motivation to use higher voltages on the drives is to keep the amount of current required lower. This spec is most important when deciding on power supplies in systems that may have a lot of relays turned on at the same time. The amount of power needed for a switching system is often just a function of V*I8N where N = the max number of relays that will be turned on at one time. Obviously as the power goes up you may need to add fans or some type of cooling to dissipate the heat that will build up.

Life Expectancy

Electro-mechanical Relays

This one gets complicated because it ends up being completely dependent on what signal levels are switched. The specification is usually given in two terms for mechanical relays:

Mechanical Operation Life -- This is the number of times the relay can be switched ON/OFF with no signal going through it. Often referred to as **"Cold Switching"**. They cycle the relay ON/OFF as fast as is realistic and then check it every now and then to see if it still meets specifications. This is an easy test to run and the numbers are typically pretty high. They will often tell you in the spec how fast they were cycling the relay in cpm (closures per minute).

Reed Relays -- Typically 500 Million to 1 Billion operations. Despite their moving parts, there isn't a lot to go wrong in a reed relay so they tend to live a long time with no signals going across the contacts.

Armature Relays -- This usually varies according to the size of the relay. Small instrumentation relays may be 100 million operations. Small power relays are typically around 10 Million cycles and larger clunky power or microwave relays or DC contactors are typically around 1 million cycles or less.

Electrical Operation Life -- This spec takes into account that you will be turning the relay ON/OFF with a signal going through it. Often referred to as **"Hot Switching"**. Sometimes it will just be specified based on the max switched power level, and sometimes it will have a very specific switched signal level. Sometimes it will list the expected life with a number of different signal levels. No matter what it says it almost always assumes a purely resistive load. This is because capacitance and inductance can drastically effect relay performance so they always assume you have made an effort to minimize that already. The thing that should be obvious here is that hot switching is always going to reduce the life expectancy. So if you know you are going to hot switch you can ignore the mechanical life expectancy and look for this specification. If you are cold switching then things like breakdown voltage and carry current are the specs you should be concerned with and assume the mechanical life expectancy.

Reed Relays -- Typically just listed at rated load and usually around 10% of mechanical life. So a relay with a mechanical life of 100 million operations is probably good for 10 million cycles under rated load. For high voltage reed relays this spec may be much lower at rated load. They will normally list what load was applied to get that test result they list.

Armature Relays -- This usually varies according to the size of the relay. Small instrumentation relays may be 1 million operations at rated load. Small power relays are typically around 100 thousand cycles and larger clunky power relays or DC contactors may decrease to 10 thousand cycles.

Here is a listing pulled from a common armature relay data sheet:

Expected life	Mechanical Min.	10^8 (at 180 cpm)
	Electrical Min.	10^5 (2 A 30 V DC resistive), 2×10^5 (1 A 30 V DC resistive), 10^5 (0.5 A 125 V AC resistive) (at 20 cpm)

Life Expectancy for Specific Other Relay Types

Solid State Relays -- Since they have no moving parts, the life expectancy of solid state relays is pretty infinite. They are much more likely to be destroyed by heat, electrostatic shock or some other environmental damage than they are to wear out. They usually have some ridiculous spec such as “estimated to be 10^{13} operations” since that is as long as they were willing to test them.

Electro-mechanical Microwave Relays -- Microwave relays normally have a fairly low mechanical life expectancy of 1 million to 10 million operations and the vendors will tell you to never hot switch them. If pushed they may tell you that a relay that can safely carry 100 Watts at 3 GHz can hot switch 0.25 watt at 1 GHz but even that will probably decrease the life expectancy. If you have to hot switch high frequency signals you will need to look at options such as pin diodes and then see if you can find one that suits your needs. A lot of work has been done in the last 10 years in this area due to the proliferation of cellular, wireless and satellite communication so there are many more options.

Translating life expectancy -- What do the numbers mean in time?

Hours per year = 8,760
Minutes per year = 525,600
Seconds per year = 31, 536, 000
These numbers give you a good idea of how long you can expect relays to last if you ran them 24/7/365 which very few people do. In real life the majority of projects end before the relays fail. But it’s a good idea to do the calculations so you are not surprised.

When I first entered this field the relay manufacturers would provide a lot of statistical data about relay failures usually in the form of Weibull Distributions gathered from testing batches of relays. The graph would look like a fairly spiked bell curve and the life expectancy number would be taken from the peak of the bell. They stopped providing this level of detail a long time ago and now just tell you to trust them based on previous experience. The reason to keep this in mind is that while the peak of the bell may be at 100 million operations, that is not a hard number but more like an average value. This means if you have a system with 500 relays you may see your first failure at 50 million operations and some relays may last 200 million operations. But if the system is critical you may not be able to tolerate even low failure rates so it would be a good idea to plan accordingly and think about replacing all the relays as soon as you begin to see failures.

The most common long term failure is the relay contacts simply deteriorate. This usually shows up as a rise in contact resistance across the relay contacts and is fairly easy to measure. Measuring a percentage of contacts can give you a good idea as to whether the whole system is wearing out, or if you simply had a random failure due to some other issue (did that short just trip the over current circuit on my power supply?). We will discuss these types of issues in another chapter which covers common problems and how to deal with them.