Part 1: Basic Electrical Components and How They Work

The purpose of Part 1 is to explain how these parts function using a simple mechanical analogy (specifically, comparing electrical parts to the water plumbing system you have in your house). Then, once basic component understanding is achieved, in Part 2 we will see how some of these simple parts can be connected together to form a battery-based ignition system for an outboard motor.

I strongly advise you to take your time with the Inductor and Transformer sections because without clearly absorbing that information, how Spark Coils work won't make any sense to you.

So, without further delay, let's look at the basic electrical components you are going to run into, and how they work! (See figure 1-1.)

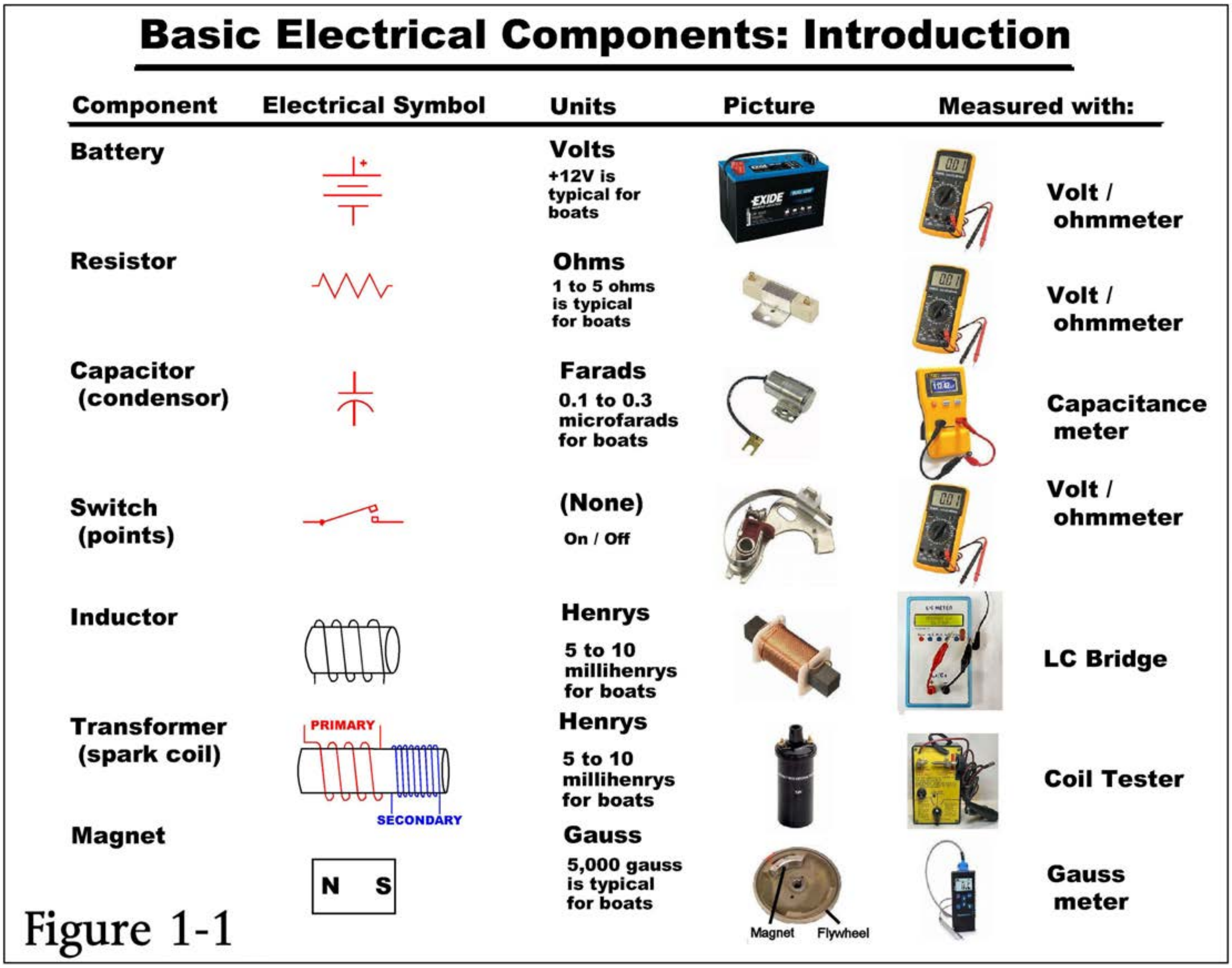


Figure 1-1

Batteries and Switches

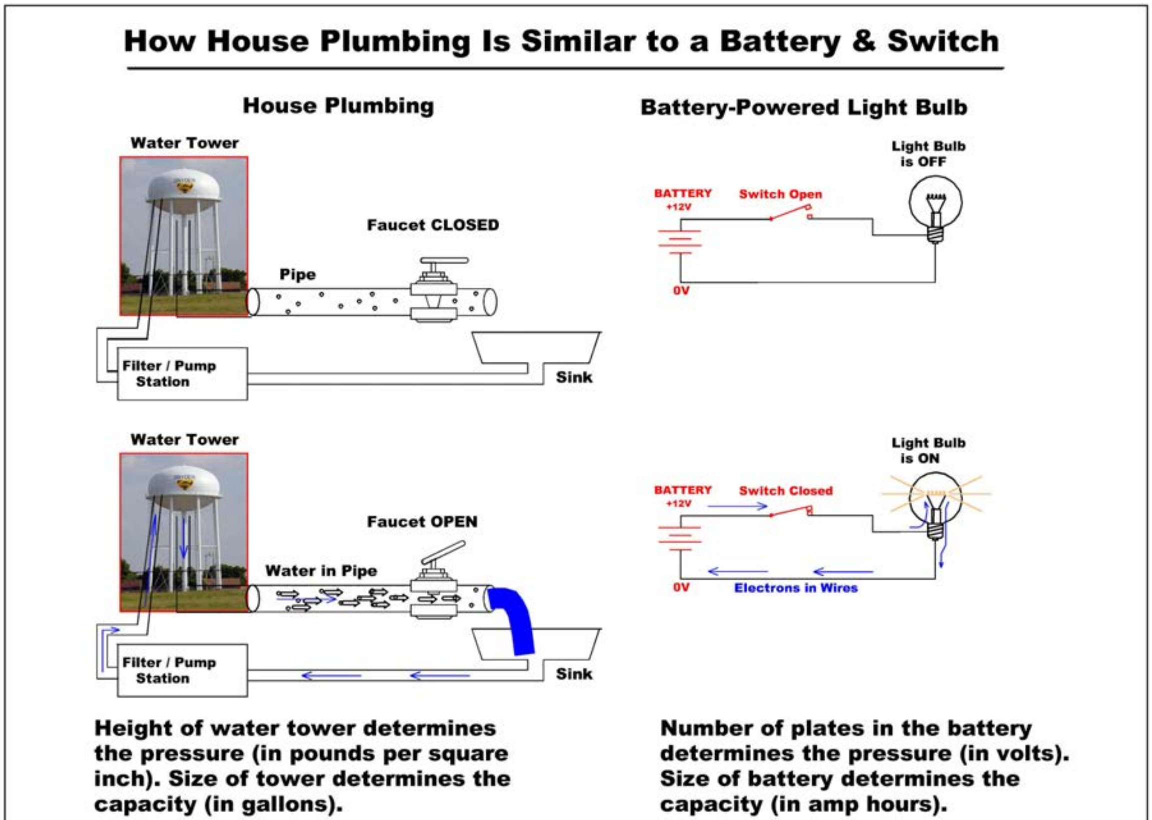


Figure 1-2

The water plumbing system in your house is connected to a water source (typically a water tower) (figure 1-2). The water tower contains hundreds of thousands of gallons of water (its capacity in gallons). The weight of the water located that high in the air creates a lot of pressure at ground level. The height of the water tower determines the water pressure (measured in pounds per square inch). As long as your faucet is closed, this pressure is held back, and no water flows in your plumbing system. When the faucet is opened, this water pressure forces water through the pipes, out through the faucet, into your sink and sewage system, and eventually back to the source.

In a similar fashion, a battery is a source of electrical power (electrons). Electrons flowing in a wire (called “current”) is similar to the flow of water molecules in a water pipe. The number of cells in the battery determines the “pressure” of the electricity, measured in volts, and the number of plates and physical size of the battery determine its capacity (measured in ampere hours). As long as your electrical switch is open (the contacts are not touching), no current can flow, and your light bulb will be off. If you close the contacts in the switch and electrical current can flow, and your light bulb will light up.

CRITICAL DETAIL: In electrical circuits, all electrons must flow in a loop, from the source (in this example, the battery), through the device being powered, and then back to the battery. Any break in any wire will cause an electrical circuit to NOT WORK. Don't ever forget this!

Resistors

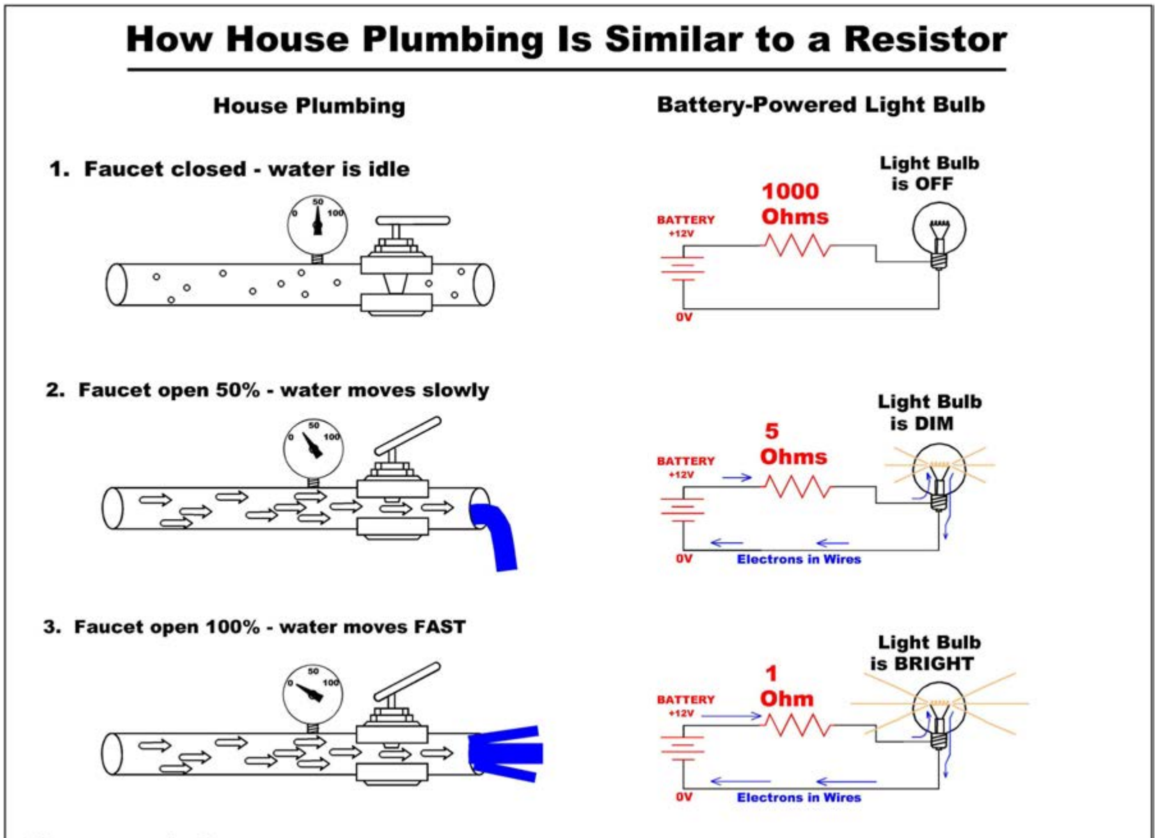


Figure 1-3

If a switch works like a faucet, turning a light on or off, then a resistor is like a faucet that is only partially open (figure 1-3). A partially open water faucet resists the flow of water, limiting the flow to something less than 100%. Putting a resistor into an electrical circuit does the same thing: it cuts back the flow of electrons to something less than 100% flow. Depending on the value of the resistor (rated in ohms), you can either slow down the electricity flow by a little, or a lot.

In battery-powered ignition systems, you will often find a "ballast resistor" near the spark coil. (Figure 1-1 shows a ballast resistor as an example of a resistor.) Most ballast resistors are rated at 1 to 5 ohms, and this cuts the power to the spark coil just about in half. (I'll explain why later).

If you take an ohmmeter and measure across a ballast resistor that has been disconnected, you should see about 1 to 5 ohms. If you read more than 5 ohms, it's suspiciously high, and should probably be replaced. (Compare it to a new ballast resistor to be sure). If you measure more than 100 ohms, there's no doubt about it; your ballast resistor has failed and absolutely must be replaced.

Inductors
(Spend some time here, as this topic takes a bit of effort to understand!)

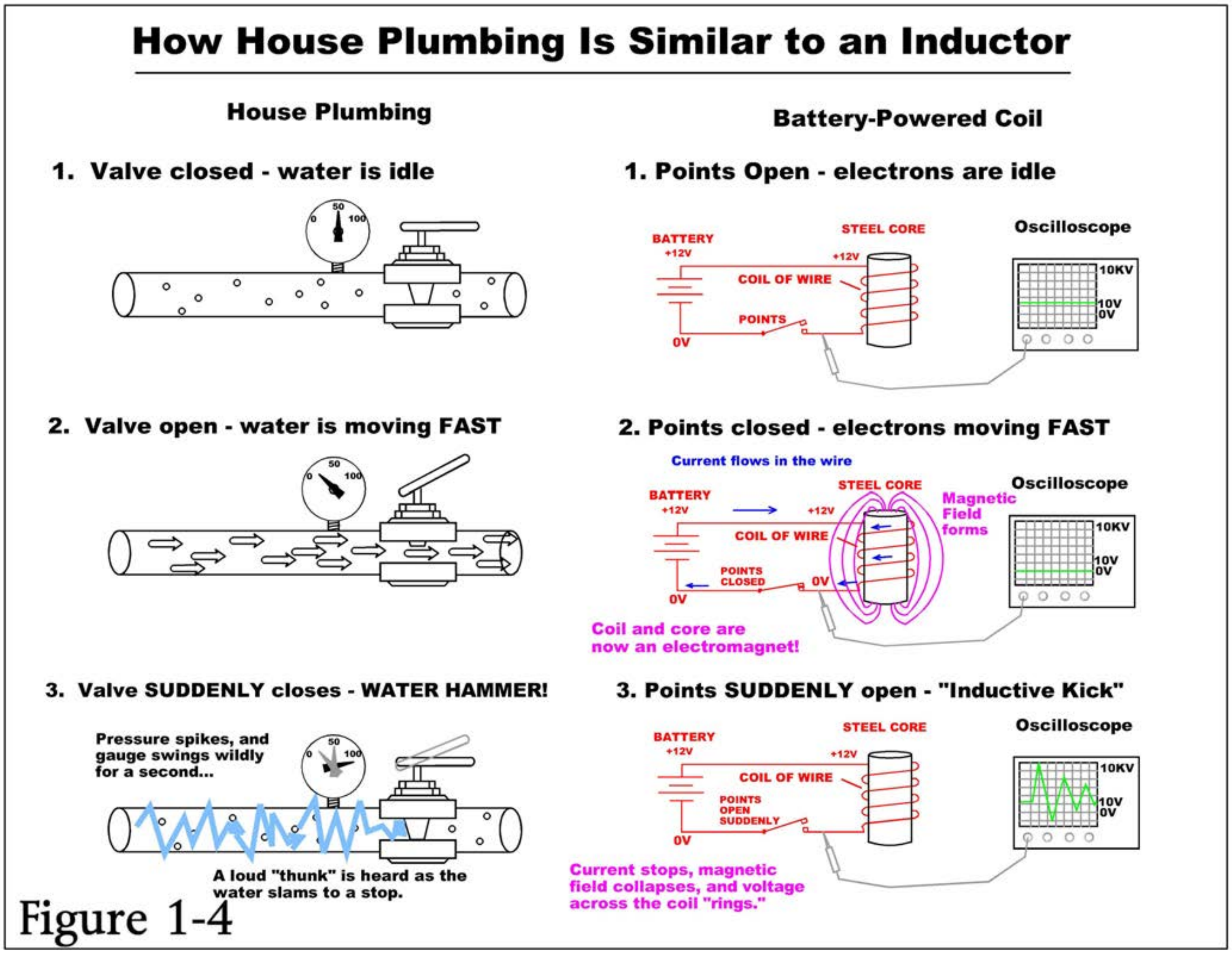


Figure 1-4

(See figure 1-4) Water is heavy…and once it gets flowing fast in a pipe, it does NOT like to be stopped quickly. (It’s like driving your car into a wall!) If the water is only flowing slowly, and you abruptly stop it by turning the faucet off fast, there won't be much of a problem, but if you have the water flowing very fast, and you abruptly stop it by turning the faucet off fast, you are going to hear a “thump” or “bang” in the pipes in your house. This is known as the “water hammer” effect. It is most often heard when appliances like washing machines are filling, then suddenly the valves close.

NOTE: If you have a water pressure gauge on your pipes and you suddenly shut off the faucet, the gauge will swing wildly when the "water hammer" is heard, as this is measuring the shock wave caused by the sudden stopping of the flow of water. The peak pressure of this shock wave can be many times greater than your average water pressure, enough to split your pipes in some cases.

In the electrical world, this is very similar to what you see with inductors. An inductor is just a bunch of insulated wire, wound around a steel rod. The main characteristic of an inductor is that it opposes a **change** in electrical current flow. If current is flowing through an inductor, and you suddenly stop the current flow (for example, by opening a switch) you are going to get a “bang,” just like in the water pipes in your house. The split second the switch contacts open, the current flow is forced to go to zero in nearly zero time, creating a huge voltage spike. The “inertia” of the electrons flowing will cause a shock wave when the current is stopped. This shock wave can’t be heard, but it can be “seen” with an instrument called an oscilloscope (lower right, figure 1-4). Just like the water gauge swinging wildly during a water hammer event, the oscilloscope is showing that the voltage across the inductor will swing wildly if you try to stop the current flow too quickly.

Now, the “shock wave” that is created in an inductor creates voltages many times greater than the voltage that was originally connected to the inductor. This greatly increased voltage can easily be more than 1000 times greater than the initial voltage from your battery. This is enough voltage to jump across the contacts in your switch, just like the static electricity “zap” you get when you touch a doorknob in the winter months! This tremendous magnification of voltage when you suddenly stop current flow in an inductor is known as **inductive kick**.

In a battery-powered ignition system, when the points open this same inductive kick is generated in your spark coil – but this is not the high voltage that you want to jump across your spark plug. It's on the WRONG SIDE (electrically) of your spark coil. It’s generated on the battery/points side of your coil, and it will cause sparks to arc across your points that will destroy them in a short length of time if you don’t cut that voltage back to a safer level.

You do need some of the inductive kick for the spark coil to work correctly. Specifically, to keep your points from being destroyed you want the 12 volt battery voltage kicked up to about 50 to 200 volts, but not up to thousands of volts. To limit this inductive kick to a lower voltage, you need some kind of “shock absorber,” and in the electrical world that component is known as a condenser (also called a capacitor).

Condensers

To extend our water plumbing analogy, we will describe a condenser (it is called a “hammer arrestor” in plumbing terms) that is often seen in home plumbing systems.
It looks like this (figure 1-5):

Fig. 1-5

A plumbing hammer arrestor is just a closed container filled with air that is connected at one end to the home plumbing pipes. The piston moves up and down with changes in water pressure, allowing water to enter or leave the arrestor. When the water pressure increases, water flows into the bottom of the hammer arrestor, raising the piston, until the air pressure matches the pressure of the water. If the water pressure suddenly increases sharply due to a water hammer event, water will flow rapidly into the arrestor, which will greatly decrease the maximum pressure spike of the hammer event and prevent pipe damage. Hammer arrestors are often installed near washing machines in homes, as washing machines are a major cause of hammer events.

In electrical circuits, a condenser is the electrical equivalent of the hammer arrestor in your home plumbing. The hammer arrestor damps out sharp changes in water pressure. A condenser limits sharp changes in voltage in an electrical circuit. Let's see how this is done.

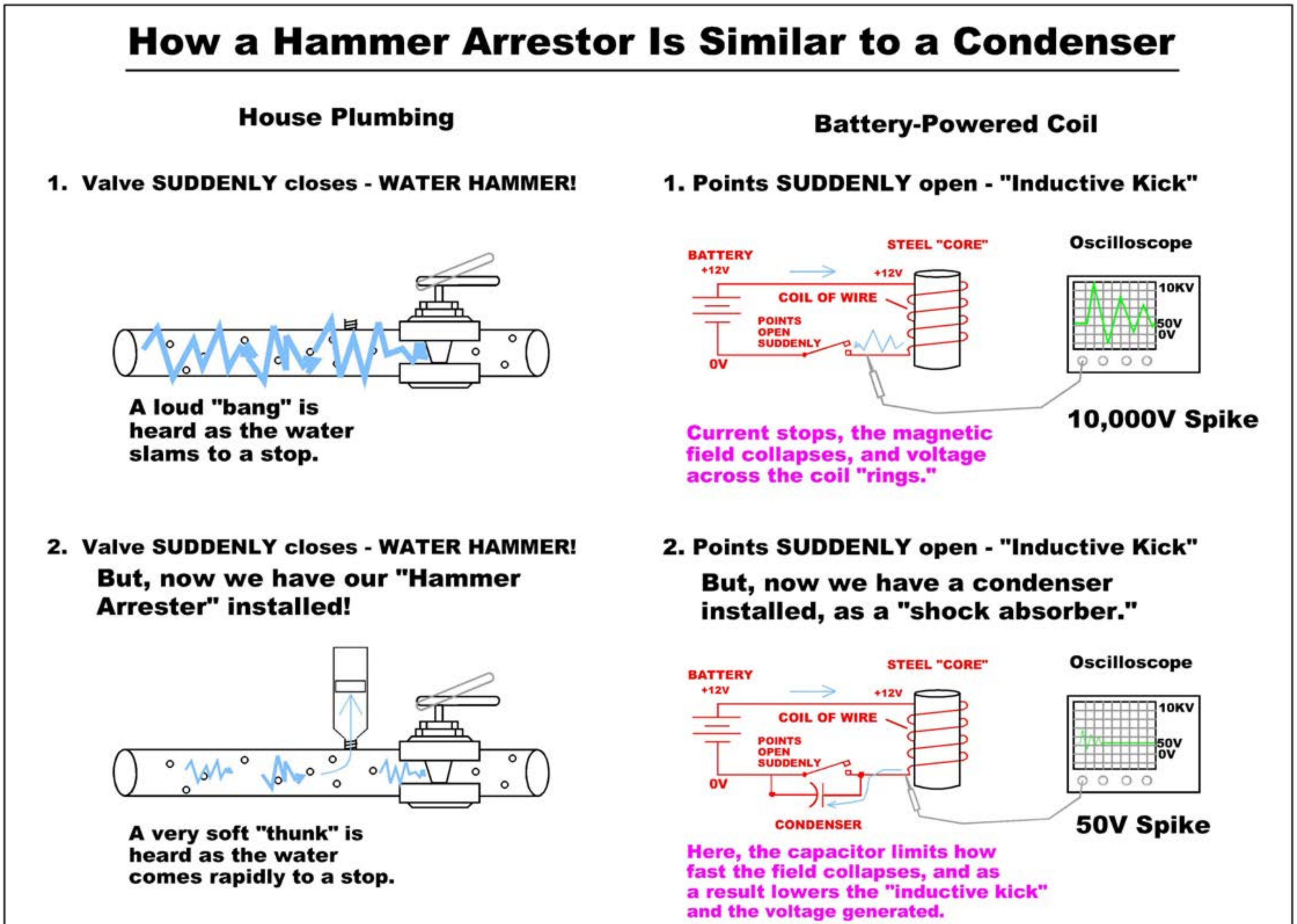


Figure 1-6

As you can see in figure 1-6, in the house plumbing case, adding a hammer arrestor to the pipes will greatly reduce the shock wave “bang” you hear when a faucet or valve is suddenly shut. In the electrical “inductive kick” example, adding the condenser cuts this big voltage spike down from 10,000 volts to about 50 to 200 volts. This protects the switch contacts from damage while allowing the spark coil to work correctly.

Transformers

Unfortunately, our home water plumbing analogy has its limits. There really isn't any way to describe how transformers work, using a mechanical analogy.

A transformer is a steel core with two (or more) coils of wire on it (figure 1-7). Electrical power is transformed (transferred) between these two (or more) coils by means of the shared magnetic field.

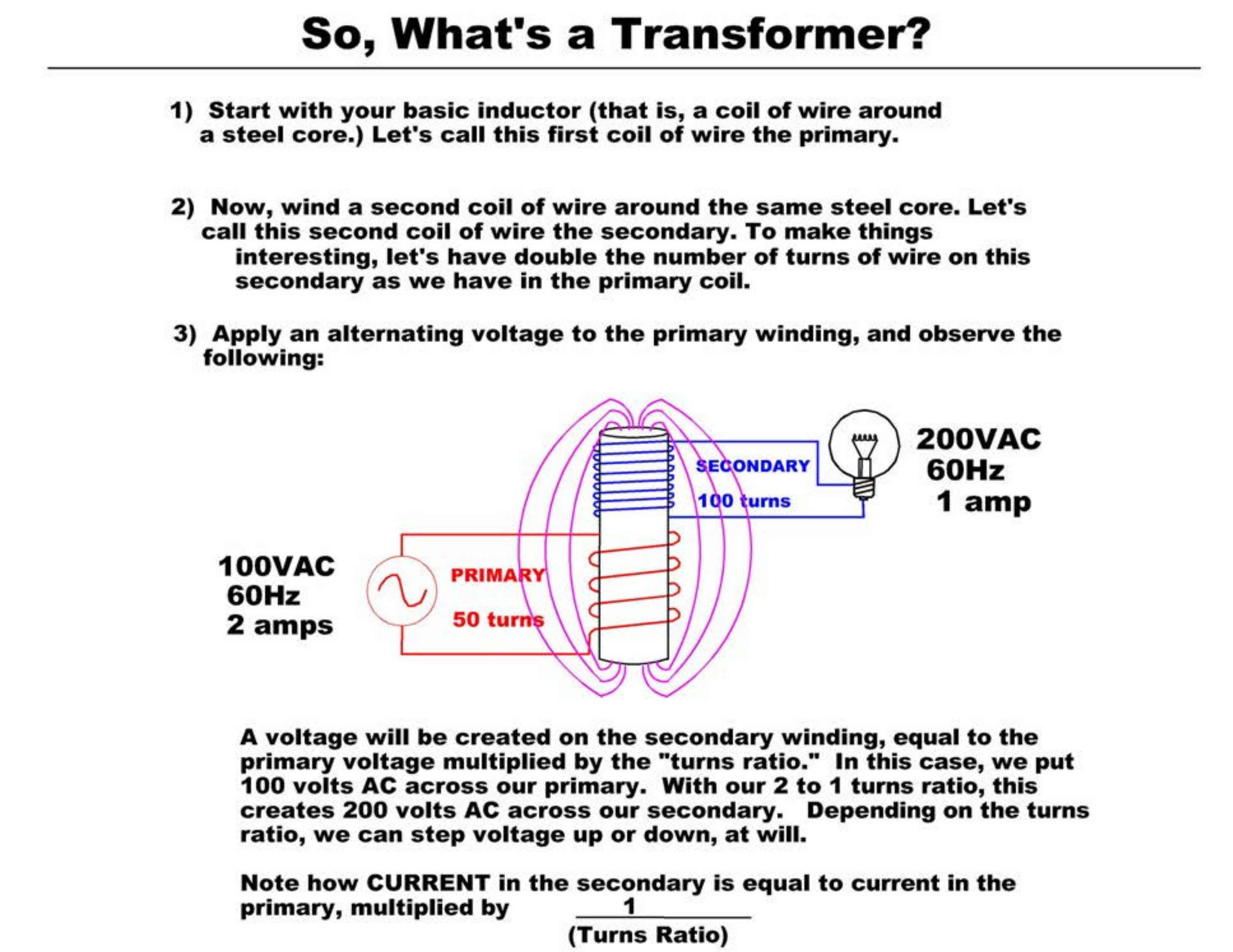


Figure 1-7

A transformer CANNOT transfer DC power (like the +12 volts from your boat battery) because power is transferred only when the magnetic field is growing or shrinking. As a result, alternating current (AC, like the 120 volt, 60 Hz power in your wall outlets) must be used with transformers. However, switching a DC power source on and off gives the same effect as using AC current! If you continually connect, then disconnect a DC power source to the primary of a transformer, it will create the changing magnetic field that is necessary to generate a voltage in the secondary winding, as shown in figure 1-7.

Spark Coils

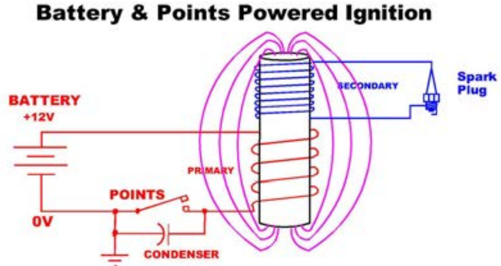
The spark coil in your battery-powered ignition system is a transformer. However, unlike most power transformers that use alternating current to power their primary coil,
in an outboard motor spark coil the primary windings are powered by the +12 volt battery, "chopped" (repeatedly turned on and off) by the points, which are operated by a cam on the crankshaft. See figure 1-8.

What's a Spark Coil, and How Does It Work?

1) A "spark coil" IS a transformer. It's built to handle high voltages. The turns ratios are typically between 60 to 1 and 500 to 1.

2) Note: transformers cannot work with DC (direct current, as supplied by a battery.) They must work with a CHANGE in input voltage. So, either an alternating current (AC) voltage must be applied to the primary, or you must convert your DC battery voltage to AC somehow. This is done with "points" (a simple electrical switch) in this ignition system.

Battery & Points Powered Ignition



3) In your outboard motor, the points (a simple electrical switch) are opened and closed by a cam on your motor's crankshaft. As the piston starts to go up (compression cycle,) the points close, allowing the battery to force current through the primary coil. This quickly creates a strong electrical current in the primary winding of the spark coil.

When the piston is all the way up to "top dead center", the points open up, stopping the current. This causes the "inductive kick", which multiplies the 12 volt battery voltage to 100 volts or more across the primary.

Because of the "turns ratio" being about 100 to 1, this 100 volts will get multiplied by the turns ratio (100,) producing a 10,000 volt charge across the secondary. This voltage will jump across the spark plug easily!

Figure 1-8

As you can see in Figure 1-8, when the points open up, the spark coil first behaves like a simple inductor. The “inductive kick” caused by the attempt to instantly stop the flow of current in the primary winding causes the 12V batter voltage to be multiplied up to 100 volts or more. However, because the spark coil has more than just the primary winding (it also has a “secondary winding”,) the spark coil is also a transformer. And, acting as a transformer, it multiplies the primary voltage by the turns rato, creating the 10,000 volts or more to jump the gap in your spark plug. Both of these voltage multiplying effects occur at the same time, but you have to look at them separately to understand what’s going on here!

SCOTT: Note: Power supply designers refer to the points and primary section as being a **“Flyback Boost Converter”.** The multiplication of the primary to secondary voltages is a simple transformer function. But, I don’t know that we need to describe Flyback Boost Converters, or even mention the name here.

Part 2: Battery, Ballast Resistor, Spark Coil, Points and Condenser Ignition System

Figure 2-1 puts it all together, including the ballast resistor. The purpose of the ballast resistor is to limit the power to the primary winding in the spark coil when the ignition switch is turned on but the motor is not running. In this condition, the points could be either open or closed for a long period of time. If the points are closed, without a ballast resistor the spark coil will get uninterrupted full voltage for a long period of time, which could cause the spark coil to get very hot (and perhaps burn up).

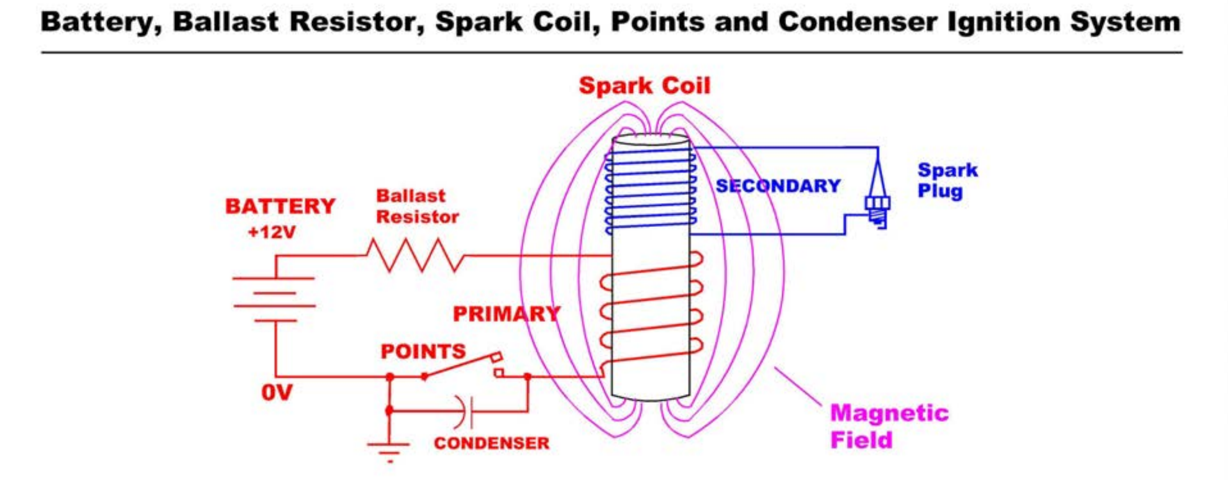


Figure 2-1

BATTERY-POWERED IGNITION DETAILS

In your battery-powered ignition system, voltage is applied to the primary winding with a 12 volt battery. When the points are closed, this voltage creates a large current (and hence a strong magnetic field) in the spark coil primary. However, this field increases slowly (over about 5 milliseconds, slow by electrical standards), so that the voltage induced in the secondary is equal to the primary voltage multiplied by the turns ratio. In battery powered ignition systems, the turns ratio is typically 100 or 200 to 1, so only about 1,200 to 2,400 volts of electricity will be produced across the spark plug when 12 volts is applied across the primary. This is not enough voltage to jump across the spark plug gap. (See figure 2-2. The coil current is shown at the bottom of the figure).

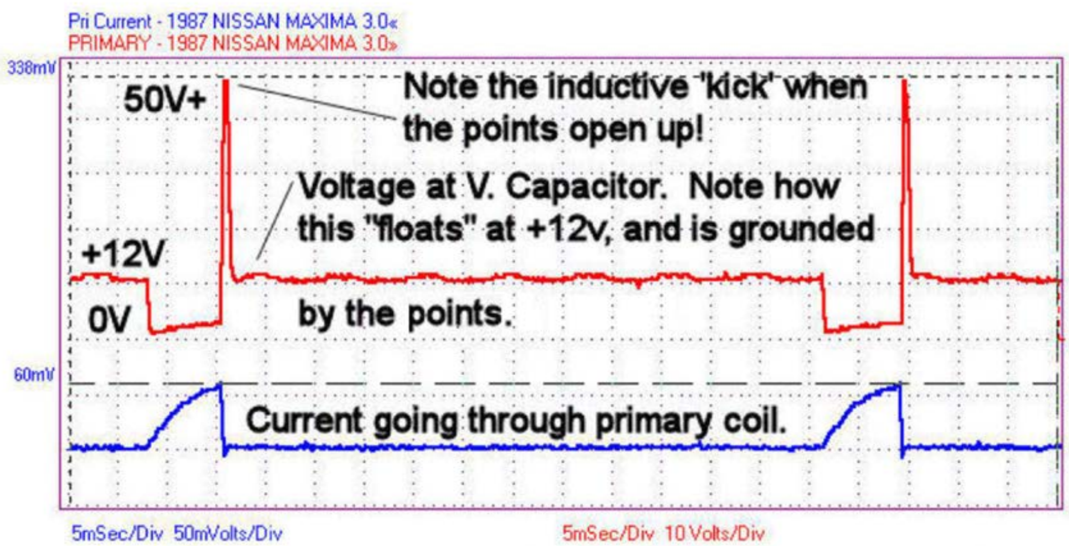


Figure 2-2

However, when the points open, something very interesting happens. The instant the points separate, the current is interrupted, and it attempts to go to ZERO in almost zero time. This causes the magnetic field in the primary to attempt to change from some large value to zero, in near-zero time as well. Per Faraday's law, the faster you try to change a magnetic field, the larger a voltage will be created in any conductor that's in that field while it changes. This rapidly collapsing field creates a voltage in the primary that is much larger than the +12 volts that created the magnetic field initially. If it were not for the presence of the condenser in the circuit, this induced voltage (the inductive kick) would skyrocket to thousands of volts – whatever voltage was necessary to allow the current to continue to flow while the field was collapsing. However, the condenser does allow some small amount of current to flow, which cuts back the induced voltage to only about 50 to 100 volts in the primary. This keeps your points from melting!

Remember that a spark coil is not just an inductor, it is also a transformer, you say several times that a spark coil is a transformer, but not that it is also an inductor (except briefly in the Introduction). Perhaps clarify somewhere in the text and/or in figure 1-8 so whatever voltage you see across the primary, the secondary will see that same voltage multiplied by the turns ratio. If the primary voltage jumps to 50 volts, and if the turns ratio is 200:1, then you will see 10,000 volts across the secondary winding. 10,000 volts is way more than necessary to fire a spark plug, so a spark is created across the spark plug gap.

Here are a couple of interesting notes that you might not be aware of:

1. The turns ratio in most battery-powered coils is typically about 100:1 to 200:1. It really does not take 25,000 volts to fire a spark plug. At a .035" gap, about 2,000 volts is enough to jump across the spark gap in open air. In a cylinder, the presence of fuel and the higher pressure caused by the compression ratio increases the amount of voltage needed to jump this .035" gap, but typically about 5,000 or 6,000 volts is still more than adequate. The "25,000 volt" and "50,000 volt" coils you see are more marketing hype than actual needed voltage potential.

2. Typically, most battery-powered spark coils run around 8 milliHenrys of inductance. The coils run about 5 amperes of primary current (peak), creating about 100 milliJoules of energy, which will get discharged across the spark plug. (A Joule is the same as a watt-second, so we are producing about 10 watts of power over a 0.00005 second period of time.) That's actually a fairly small amount of energy, packed into a high voltage discharge over a very tiny period of time. To use a different example, the battery in your cell phone holds about 50,000 Joules of energy, and could power your ignition system for about 500,000 sparks, or about 2 hours of operation.

3. This spark discharge is powered ONLY from the collapsing primary magnetic field, and this doesn't take long. Spark duration in conventional ignition systems is very short, typically around 50 microseconds. As we will see in Part 3, magneto-based systems often have very long spark durations, often over 1 millisecond (a 20 times longer time period). which means they will much more reliably ignite the air-fuel mixture.

Why is this? Ideally, a carburetor will atomize the gasoline, and mix it perfectly with air to create the fuel mixture for the engine to burn. If perfectly atomized and mixed with air, the fuel will be easy to ignite and will burn quickly, creating maximum power. However, carburetors don't atomize the fuel perfectly and mix it perfectly with the air. As a result, there are spaces in the fuel mix where you have air but no gasoline, and if a short duration spark passes through this space, you won't get ignition, and the engine will misfire.

Also, consider that the air/fuel mixture is moving VERY VERY FAST in the cylinder, and igniting it is kind of like trying to light a cigarette with a candle, in the middle of a tornado. A magneto is a much hotter and longer duration ignition source. It's still like trying to light a cigarette in a tornado, but this time you are using an acetylene torch. It just does a better job under extreme conditions.

4. In general, the higher the RPM, the lower the energy a battery and coil ignition system can create to jump the spark gap. In contrast, with magneto-based systems, the higher the RPM, the greater the energy created to jump the spark gap, making magnetos better for higher-RPM operation. (This is true for motorcycles and racing cars; way up at >10,000 RPM you'll sometimes hear those engines misfire a bit with standard ignitions, but they won't if they are using magnetos. Most outboards rarely cross 5,000 RPM, so it's not as critical, but this is why you see magnetos still used in many racing applications.)