I. INTRODUCTION

This laboratory exercise (1) explores the physics of automotive ignition systems used on vehicles for about half a century until the 1980's and, (2) introduces more modern transistorized systems. The main job of the ignition system is to supply electricity to the spark plugs so that they can ignite the fuel-air mixture in the cylinder. In our experiment we will apply concepts such as Faraday induction, *RL* circuits (current build-up and decay), back *emf*, step-up (low-voltage to high-voltage) transformers, *RLC* circuits (resonance), and transistors (for switching currents). Keep in mind that whenever we speak of *voltage*, we are talking about a *potential difference* — the difference in potential between two points of interest in the circuit, one of which is usually what we call *ground*. In the process of understanding the underlying physics principles, you should also get an appreciation for what's going on under the hood of your car and answer the question, "How do you get a 30,000-volt spark from a battery that supplies only 12 volts?"

The diagram in Figure 1 depicts the elements of a very basic ignition circuit that provides the high voltage necessary to produce a spark in the spark plug. It consists of 1) a battery, 2) a series resistor, 3) the ignition coil, 4) points (switch contacts), and a capacitor (called a *condenser* in old automotive repair manuals). Notice the symbol for *ground* in the circuit diagrams — most voltage measurements are with respect to ground.

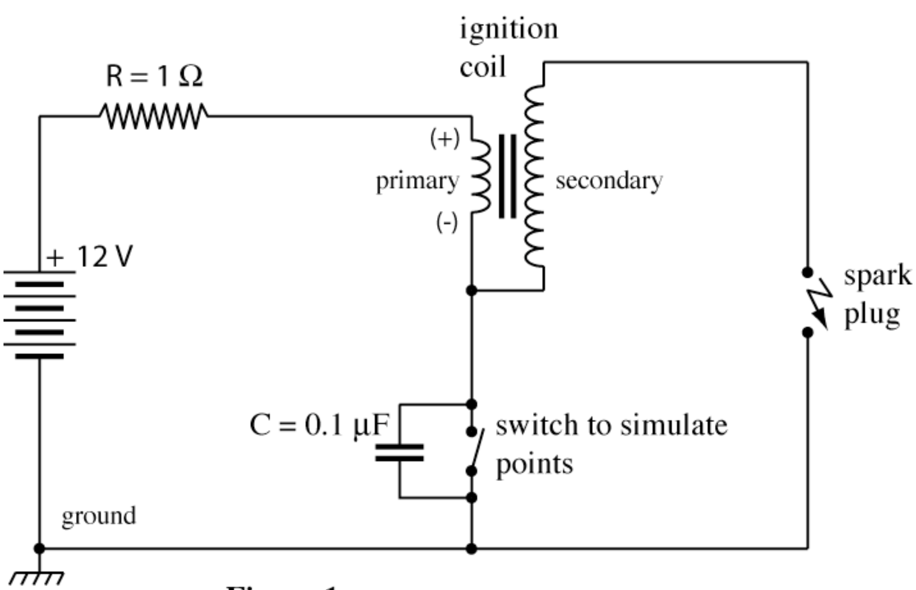


Figure 1

☞ **To complete this laboratory, carry out all the bold-faced steps. Answer any questions on a sheet of paper and turn that sheet in at the end of the lab.**

II. PRELIMINARIES — DETERMINING THE ELECTRICAL CHARACTERISTICS OF THE CIRCUIT COMPONENTS

We'll begin with a closer look at the ignition coil, which is nothing more than a step-up transformer [see Giancoli, section 21-7]. When a current passes through a coil of wire wound around a soft iron core, a magnetic field is produced. In the ignition coil, a few hundred turns of relatively heavy wire are wound around an iron core; this becomes the primary coil of the transformer. Thousands of turns are wound over the primary coil with much finer wire; this becomes the secondary of the coil. There will be more resistance in the secondary coil than the primary coil because it contains so much more wire [Giancoli, section 18-4]. Note that the actual geometry differs from that shown schematically in Figure 1, which uses the generic symbol for a transformer. The primary and secondary coils are concentrically wound, cylindrical coils.

1. **Measure and record the resistances of the primary and secondary coil windings of the ignition coil.**

2. **If a 12-V battery is connected to the primary coil, calculate the current through the coil?**

That's a considerable current to draw continuously from the battery. It not only drains the battery quickly, but also heats up the coil [Giancoli 18-5].

3. **Now that you know the relevant parameters, calculate the electrical power lost in the coil.**

One way to lessen this power loss is to decrease the current through the coil; for this purpose a resistor is added to the primary circuit. In your car it is a discrete component mounted on the firewall behind the engine or, more often, a resistive wire in the wiring harness. In the experiment we shall use a 1-Ω discrete resistor in series with the battery and primary coil.

Being made of many turns of wire, the primary and secondary coil windings have an appreciable inductance [Giancoli 21-9]. Inductors have the property that an *emf* is induced across the inductor when there is a change in the magnetic flux inside the inductor. A change in current produces a change in magnetic field and thus the *emf* can be expressed by $V = -L\ (\Delta I/\Delta t)$. The minus sign indicates a "back" *emf* because it opposes the voltage of the battery pushing the current through the coil. The back *emf* thus acts to oppose changes in current, the net result being that you can't instantaneously change the current in a coil; the time it takes to increase (or decrease) the current depends on the inductance. In an *RL* circuit [Giancoli 21-11], the solution to the previous equation shows that the current increases exponentially as $I(t) = I_{max}(1 - e^{-(R/L)t})$, or decreases exponentially as $I(t) = I_{max}e^{-(R/L)t}$. The amount of time it takes to increase to 63% of its maximum value is called the "time constant" and is given by $\tau = L/R$. The time it takes to decrease to 37% of its value (1/*e* value) is also given by τ. You can observe this exponential build-up and decay of the current in the next exercise, and thereby determine the inductance of the primary coil from the time constant.

Set up the PASCO function generator as in Figure 2 to give you an "on/off step" voltage (square wave output) and apply this to the primary of the coil with a 4 Ω resistor in series. Measuring the voltage across the resistor will give you the current through the resistor (Ohm's law) and thus the current through the coil. Monitor this voltage as a function of time on the oscilloscope.

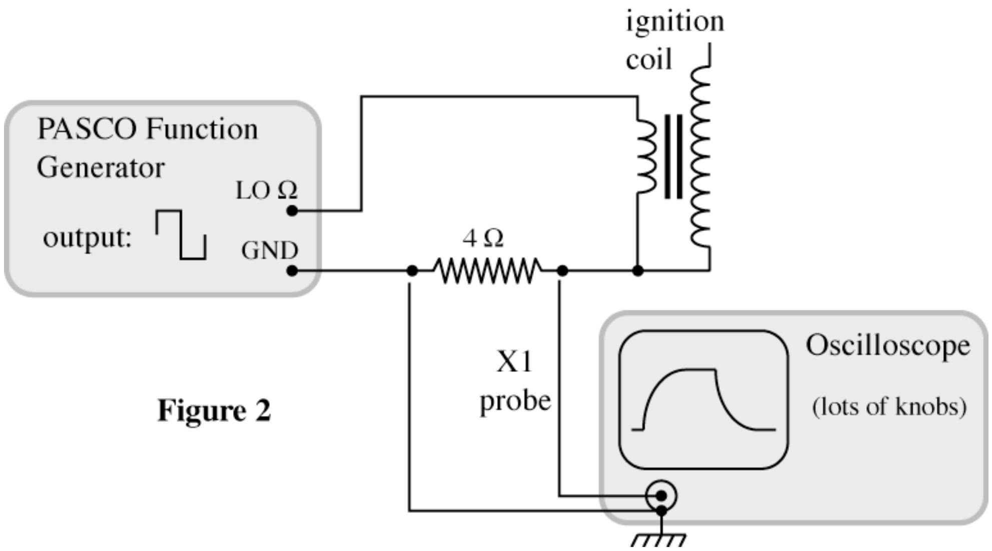


Figure 2

4. **How long does it take for the current to build up to close to its maximum value? To 63% of the maximum? How long does it take to decay to 37% of the maximum? To zero?**

5. **Calculate the inductance of the coil from the observed time constant.**

Don't forget that the time constant depends on the total resistance of the circuit. Now change the 4 Ω resistor to a 1 Ω resistor in the set-up above and repeat the measurements.

6. **How does less resistance in the circuit affect the time it takes the current to build up and decay? Does the change in time constant change the inductance?**

Because it takes a finite amount of time for the current to build up (and decay) in the coil, it also takes a finite amount of time for the energy in the magnetic field to build up to a maximum (and decay). Ultimately, it's the energy stored in the magnetic field of the coil [Giancoli 21-10] that provides the energy for the spark in the spark plug. If the engine runs too fast, there won't be enough time between revolutions to build up the magnetic field in the coil. Carry out a rough calculation to see if the coil can meet our requirements. Suppose you have a 6-cylinder engine running fast, say 3000 RPM (revolutions per minute). Being a 4-cycle engine (never mind what that means, if you don't know), each spark plug only needs to fire every other revolution of the engine.

7. **How many times (per second) must the magnetic field build up and decay to provide sufficient energy for all six spark plugs?**

8. **Using your answer to the previous question, what must be the time interval between successive magnetic field decays? Is this time interval long enough, given the value you measured in exercises 4) and 6)? Do you see a potential problem using this coil in racing cars engines, which have more cylinders and run at higher RPMs?**

Now that you've measured some of the electrical characteristics of the circuit components, you're ready to learn how they behave as part of the real ignition system whose purpose is to provide a high voltage to the spark plug at just the right time.

III. INVESTIGATING THE PRIMARY CIRCUIT OF THE IGNITION SYSTEM

In your automobile, the source of voltage is the battery. A DC voltage applied to the primary windings of the coil drives a current through the windings which, in turn, produce a magnetic field inside both the primary and the secondary coil. A *change* in this magnetic field *induces* a voltage across the primary (and secondary) coil. This induced voltage is determined by (*a*) the number of turns in the primary winding, (*b*) the strength of the magnetic field, and (*c*) the rate of change in the current (and therefore a change in the magnetic field). The number of turns in the primary has been fixed by the manufacturer of the coil and the strength of the magnetic field (determined by the current) is fixed by the resistance in the circuit and the battery's voltage. We are left with trying to optimize (*c*). The simplest scheme to change the magnetic field rapidly is to just switch off the current to the coil. But you have already learned that the current in an inductive coil does not die down to zero instantaneously. Suppose that you wanted to *force* it to do so. For example, suppose you try and make the switch contacts open (and break the circuit) in, say, 0.1 millisecond.

9. **From your measured value of inductance, calculate the induced back *emf*.**

What do you suppose actually happens if you open a switch that is providing a lot of current to an inductor? To answer this question, you have to appreciate that the expression for the induced *emf* tells us it is not possible to switch off the current instantaneously: as $\Delta t \rightarrow 0$, *emf* $\rightarrow \infty$! What happens in practice is that, when the voltage gets high enough, the air breaks down (ionizes) in the strong electric field near the point where the current is interrupted, and a spark is produced that allows the current to continue through the air for a bit longer.

To actually measure the induced back *emf* across the primary, set up the circuit shown in Figure 3. Since we expect to measure relatively high voltages, we shall use a X10 probe (which attenuates the signal by a factor of 10).

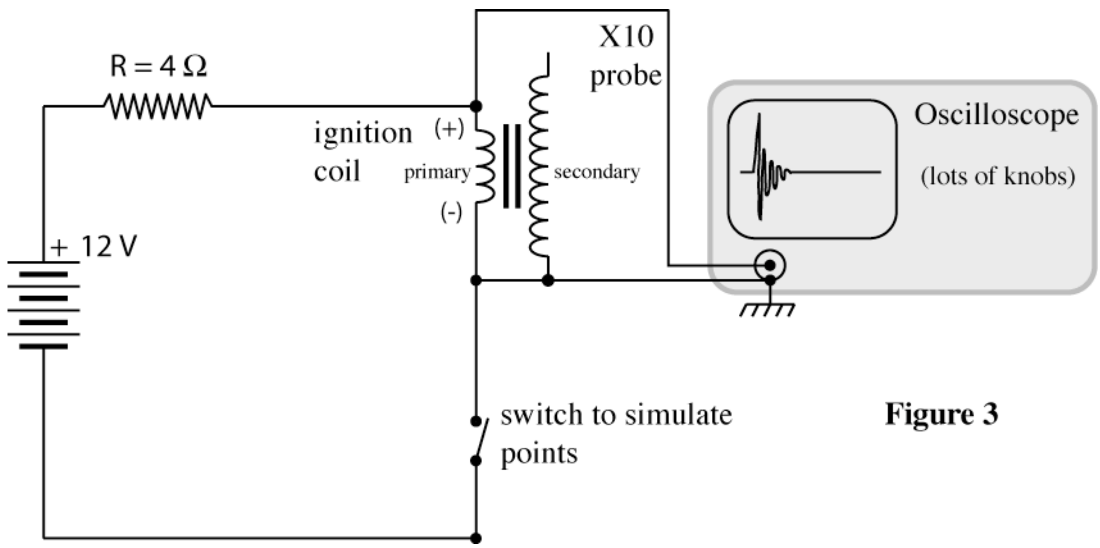


Figure 3

<u>Cautionary Note</u>: You have already calculated how much current can flow in the primary circuit and should appreciate that it would be prudent not to leave the switch closed for very long — you will quickly drain the battery if you do. Unlike a large car battery, the battery you are using stores a rather limited amount of energy. Therefore, ***when you close the switch, do so only <u>momentarily</u>***. As you've already learned, a fraction of a second in the closed position is more than enough time to build up the current to its maximum.

10. **Using a X10 probe with the oscilloscope, measure the voltage spike across the primary of the ignition coil. After the voltage spike you should also observe a decay of the voltage with an oscillatory behavior. These oscillations have to do with resonant behavior and will be investigated later.**

In older cars, the switching of the primary coil circuit was accomplished by mechanically opening and closing contacts, called "points." A shaft, rotating in sync with the engine, would momentarily open the points at the "right" time (when a spark was needed). Not only did these points require timing adjustment every few months (part of the "tune-up"), but they also deteriorated from the constant arcing of the current. To minimize the arcing, **a capacitor is put across the points, as shown in Figure 1**. This increase in capacitance across the points prevents the voltage from building up too high ($V = Q/C$, see Giancoli 17-7) resulting in less ionization and arcing through the air. Less energy lost in heating the air means more energy is available for the spark plug, and that's a good thing. One would think that the larger the value of C, the better off one is, but that is not the case here. Notice (Figure 1) that when the points are closed, the primary of the ignition coil is part of an *RL* circuit. When the points are open, the circuit components form an *RLC* circuit. *RLC* circuits have many interesting behavior characteristics, *resonance* [Giancoli 21-13, 21-14] being the predominant and important one in this application. If the *RLC* circuit oscillates at its resonant frequency, large voltages can build up across the inductor (coil). Thus, even though the battery supplies only 12 V across the entire *RLC* circuit, typically a couple hundred volts can appear across the coil.

The inductance of the primary coil is fixed, but the capacitance can be chosen. Its value will determine the resonance frequency of the *RLC* circuit: $f_0 = \dfrac{1}{2\pi\sqrt{LC}}$. It turns out that the secondary of the ignition coil naturally resonates at a particular frequency, and one can maximize the energy transfer from the primary to the secondary by driving the secondary at its resonance. We thus wish to adjust the primary coil resonance frequency to match that of the secondary. This is not unlike pushing a mechanical oscillator at its resonance frequency and getting a huge amplitude. The primary and secondary coils have a significant mutual inductance and you could see evidence of the resonating secondary coil in the oscillatory behavior of the primary coil voltage (exercise 10) and even in the primary coil current (exercise 4). Next we will look at this resonant behavior in detail

IV. INVESTIGATING THE SECONDARY CIRCUIT OF THE IGNITION SYSTEM

As shown in the circuit diagrams, the primary and secondary windings of the ignition coil are connected at one end, so that the secondary is automatically grounded (internal to the housing) through the primary circuit. In other words, the two windings have a common ground connection. In a car, the ground connection is the metal chassis of the car; it's actually insulated from the *real* ground by the rubber tires, but we still call it ground and connect the negative end of the battery to this common connection. Ignition coils typically have a primary-to-secondary turns ratio around 1:80. To determine the turns ratio for your particular coil, set up the circuit shown in figure 4.

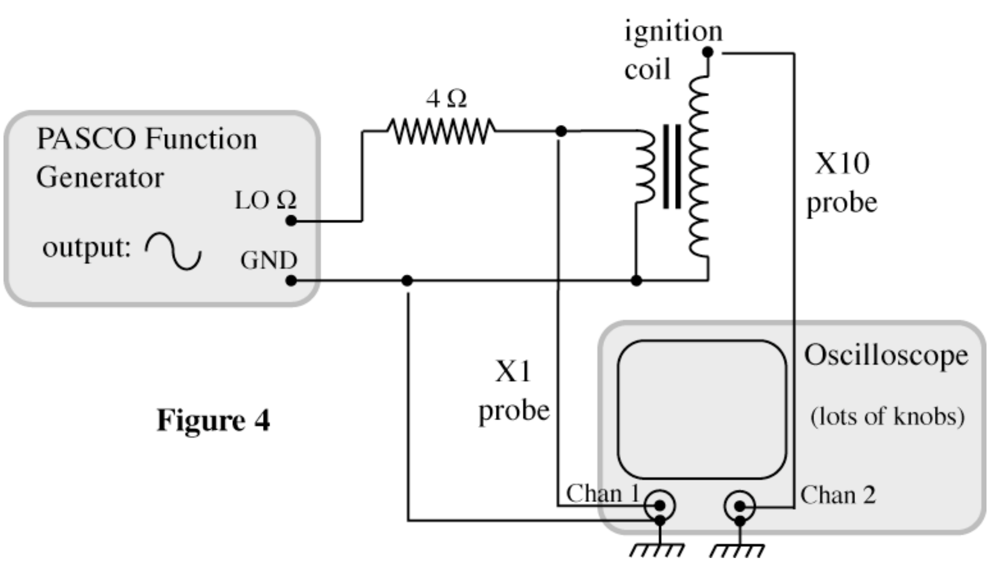


Figure 4

11. **How could you determine the turns ratio for your particular coil? Briefly describe what you would do to measure the turns ratio. Proceed with your measurement after checking with your instructor. What is the turns ratio?**

12. **With voltage spikes of 100-200 V across the primary, how much voltage could be generated across the secondary, given this turns ratio?**

Use the same set-up as in Figure 4 to investigate the resonance of the coil. Keeping the input voltage to the primary fixed, say at ½ $V_{p\text{-}p}$ (peak-to-peak voltage) or less, measure the output voltage of the secondary as a function of frequency. To get a quick picture, take measurements every kHz up to about 10 kHz. Then take a few extra measurements every 500 Hz around the region of interest (where there are rapid changes in voltage). Make a plot of the secondary coil voltage versus frequency.

13. **What is the resonance frequency? What is the voltage gain from input to output at resonance? Notice the phase shift between the input and output voltages as a function of frequency. How does it vary?**

It turns out that all resonant oscillating systems in nature, be they electrical, mechanical, or otherwise, have in common this phase relationship between the input stimulus and the output response. To take advantage of this resonance phenomenon and huge voltage gain, we choose the capacitor across the points so that the primary RLC circuit of the coil has a resonance frequency close to that of the secondary coil.

14. **Calculate what the capacitance should be, using your values of primary inductance and secondary resonance frequency. Is the capacitor provided for this experiment close to your calculated value?**

Now that we have investigated the important details, let's go back to the basic ignition circuit depicted in Figure 1 and see how it behaves.

15. **Wire the circuit to include the spark plug in the secondary circuit, as shown in Figure 1. Momentarily close and open the switch — do you get a spark at the spark plug? If you remove the capacitor across the switch, do you still get a spark? Is the spark stronger or weaker? Why?**

In an automobile engine, the momentary high voltage needs to be passed on to the appropriate cylinder spark plug. In older cars this is accomplished by the "distributor," which mechanically switches the output of the ignition coil to the spark plugs. In modern automobiles, the mechanical switching in the primary circuit and secondary circuits has been replaced by electronic circuits and is much more trouble free, with no mechanical parts to wear out. You will next work with a very simple electronic switching circuit.

V. ELECTRONIC IGNITION SYSTEMS

The points have been replaced by a solid state switching device called a transistor [Giancoli 29-7 through 29-9]. We shall use an IRF640 power MOSFET (it's an n-channel enhancement mode silicon gate power field effect transistor, in case you want to impress your friends). The MOSFET switch needs a control signal to turn it on and off. Most automobile manufactures generate that control signal with some sort of magnetic pick-up system. One way to do this is to have a permanent magnet on a shaft rotate past a small coil of wire so that an *emf* is generated in that "pick-up" coil (Faraday induction at work again!). The resulting voltage can be used as a signal to electrically gate the transistor switch on and off.

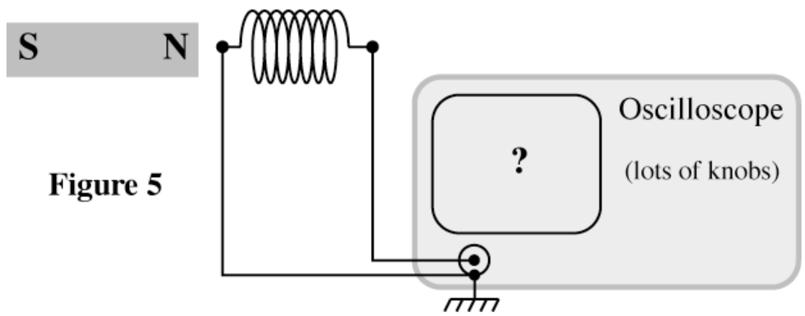


Figure 5

16. **Connect the oscilloscope X1 probe to your pick-up coil as shown in Figure 5 to measure the voltage across the coil. Quickly pass the small magnet across the coil and observe the induced voltage on the oscilloscope. Draw the shape of the signal and explain why there is a positive as well as negative part to the signal. Approximately how large is your signal?**

17. **Vary the speed with which you swipe the magnet across the coil. Does the induced voltage vary with speed? How? Why?**

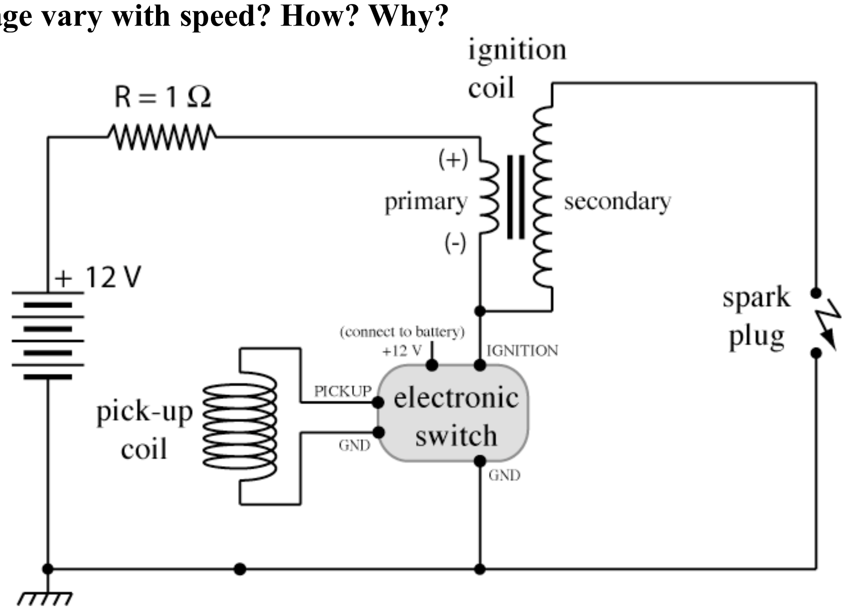


Figure 6

Connect the pick-up coil and electronic switch (the green circuit board) to the rest of the ignition circuit as shown in Figure 6. Often not all wires are shown in a circuit diagram to help make the functionality of the circuit more clear; in this case the wire that connects the battery to the electronic switch (the electronic switch needs battery power to operate) is not drawn in. All ground (GND) connections on the circuit board are in common (are connected together).

18. Swipe the magnet across the pick-up coil. Do you get a spark at the spark plug? How does the quality of the present spark compare with that generated using the mechanical switch. What do you suppose causes the difference?

When you first try to start up the engine in your car, one of the (several) things the ignition switch does is to turn on the electric starter motor that rotates the engine. The large current required to run the starter motor causes the battery voltage to drop well below 12 volts.

19. Explain why the battery voltage drops significantly.

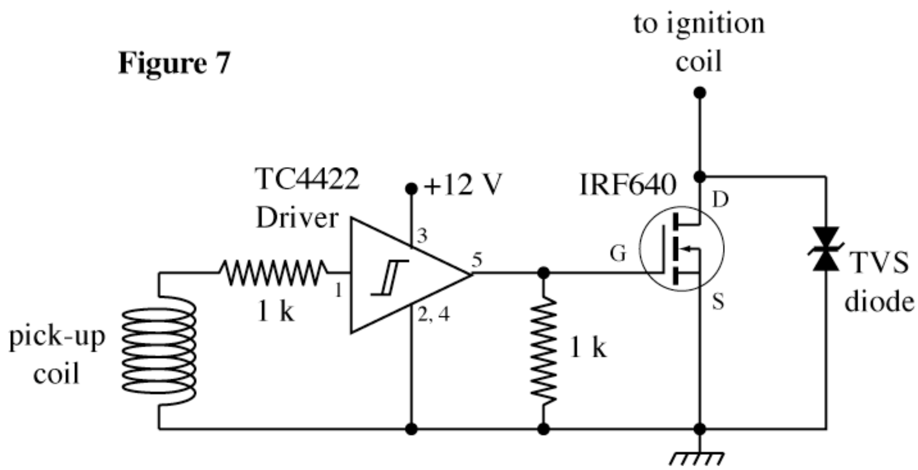
At the same time, the combustion chambers and spark plugs are cold and require a higher voltage to spark than when the engine is warmed up. In order to provide adequate ignition voltage when the car is being started, the series resistor (shown in figures 1, 3, and 6) is momentarily bypassed when the ignition switch is engaged and the battery becomes directly connected to the primary of the coil.

20. By-passing the series resistor is accomplished by the wiring of the ignition switch. Describe <u>two</u> ways you can do the same thing in your circuit (fig 6). Check out your ideas with your TF and then proceed to by-pass your series resistor.

21. Having by-passed the series resistor, describe the difference in the quality of the resulting spark at the spark plug. Explain how this is possible even though the voltage of your battery has decreased.

In case you are interested, the details of the electronic switch are shown in Figure 7. You can identify the components on the circuit board by following the diagram. As stated above, the transistor that switches the primary current on-and-off is the IRF640 power MOSFET. When its gate is at ground, the transistor is off. A positive voltage on the gate turns it on. That gate voltage is provided by the TC4422 driver, which has the following virtues. First, it transforms the relatively low voltage generated by the pick-up coil (≈ 4 V) to its own supply voltage (12 V); when the gate of the IRF640 is raised this high, the power MOSFET turns on completely. Second, the TC4422 driver switches between ground and 12 V in fractions of a microsecond — much faster than the voltage transitions generated by the pick-up coil, and it is a rapid change in current in the primary of the ignition coil that induces a large *emf* in the secondary.

Figure 7



To help you navigate around the circuit board, Figure 8 shows the pinout configurations of the components. Although the IRF640 has an internal protection diode, the TVS diode has been added for double protection and is intended to shunt any transients over 200 V to ground.

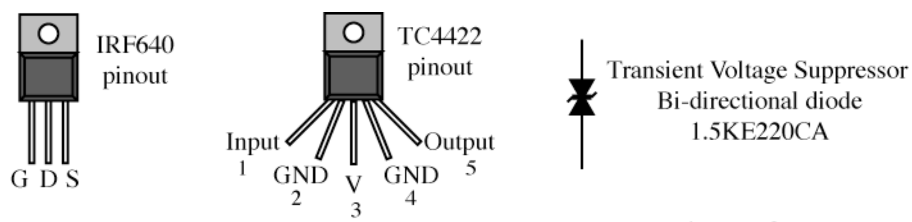


Figure 8

In today's cars, each spark plug has its own dedicated ignition coil right at the cylinder, so there is no longer any need to distribute the high voltage from one ignition coil to the various spark plugs. (Distributors were always a problem.) Furthermore, with a dedicated ignition coil, high engine speeds are no longer an issue in terms of there not being enough time to completely build up and collapse magnetic fields. Modern ignition systems have been refined even more with all kinds of sensors and microprocessor controls, but the basic physics has not changed!

VI. SUBMISSION CHECKLIST

1. Answer all the questions in this handout.
2. Turn in a sheet of paper with your work.