Lesson Plan – Capacitors, Inductors, and Oscillating Circuits

Georgia Institute of Technology STEP-UP Summer 2018

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Subject: Physics – Electricity & Magnetism
Grade: 9-11
Suggested Time: Two 50 minute periods

Topics
- Review of Solenoids/Inductors
- Introduction to Capacitors
- Application of both in an Oscillating Circuit (LC Circuit)

Problem / Essential Questions
- How does a coil of wire (an electromagnet) behave in an electric circuit?
- What is a capacitor and what properties affect capacitance?
- How are oscillations produced in an electric circuit?
- What are some applications of inductors and capacitors?

Abstract

Standard honors-level physics curriculum covers electricity and circuit elements up to combination circuits using resistors only. This lesson serves as an extension to this curriculum by introducing capacitors and inductors at a non-mathematical level. The lesson involves students investigating the properties that cause capacitance by making their own capacitor out of two sheets of aluminum foil and two sheets of an insulating layer. The lesson introduces the application of inductors and capacitors by showing how both are used together to produce oscillations. Finally, the lesson concludes with a lab assessment where students use an online circuit simulator to build and analyze their own LC circuits.
Alignment with State and Local Standards

**Georgia Standards of Excellence**

SP5. Obtain, evaluate, and communicate information about electrical and magnetic force interactions
   d. Plan and carry out an investigation of the relationship between voltage, current, and power for direct current circuits
   e. Plan and carry out investigations to clarify the relationship between electric currents and magnetic fields.

**Gwinnett County Schools Physics AKS**

D – Electricity and Magnetism
   Analyze (via laboratory analysis) the properties of magnetic fields and their relationship to electric fields.

Objectives

- To introduce parallel-plate capacitors to students for the first time. Students need **not** analyze the mathematical behavior of capacitors in series and parallel.
- To expose students to Capacitors and Inductors before they see these devices in AP Physics
- To have students build their own capacitor and investigate properties
- To show how an LC circuit creates oscillations and is used in modern electronics

Anticipated Learner Outcomes

Students will be able to
1. Describe that a capacitor is made of two conducting parallel plates separated by an insulating layer
2. Investigate how surface area of the plates and distance of separation affects the total capacitance of a device
3. Draw electrical schematics using capacitors and inductors
4. Calculate the frequency of oscillation of an LC circuit

Background

**Prior Knowledge** – before beginning the lesson, students should already be familiar with
- Series and Parallel electric circuits
- Electromagnetic induction
- Solenoids and electromagnet coils
- The definition of frequency and measurement of frequency in **Hertz (Hz)**
**Lesson Info**

This lesson begins with a *review* of solenoids and the creation of a magnetic field around a coil of current-carrying wire.

As seen above, a coil of wire carrying current $I$ will create a magnetic field inside of and around the coil. Students learn this as an *electromagnet* in their earlier science education. For this lesson, introduce to students that this device is also called an *inductor* in electric circuit diagrams. While both words refer to essentially the same basic device in physics, there are key differences between the two in the field of engineering. The main difference between the two words is that an electromagnet is specifically used to create a strong magnet or magnetic field whereas an inductor is used to control the *rate of change of current* in an electric circuit. Inductance is represented by the symbol $L$ and is measured in the unit of *Henries*. The voltage across an inductor is given by:

$$V = -L \frac{dl}{dt}$$

meaning that a potential difference only exists when the current in the coil is *changing*. When powered on in a DC circuit, the inductor will store increasing energy in its magnetic field until reaching maximum current. Once the current is steady and unchanging, the inductor’s magnetic field will be constant. If the DC power is switched off, then the current begins decreasing negatively. This means that the inductor will continue to supply positive voltage to the circuit, even after the power is turned off! The energy is stored in the magnetic field, and the current will *slowly* decrease as this energy is released.

In the Georgia Standards of Excellence for high school Physics, studying circuit elements such as inductors and capacitors is not required. However, in AP Physics students will need to do analysis and calculation of circuits with $L$ and $C$. Therefore, the function of this lesson’s content is a “first look” into what an inductor or capacitor is for an on-level Physics student, so that they will have seen these devices at least once before taking an advanced Physics course.

A capacitor is a pair of conducting plates or sheets of area $A$ offset by some gap of distance $d$. Between the two conductors is an insulator. In most simple diagrams this insulator is drawn as air, but in actual devices the insulator is any solid insulating material and is called the *dielectric*. A diagram of a capacitor is shown on the next page.
Because the two conducting plates do not make contact, a capacitor will block sustained current flow in a DC circuit. The function of a capacitor is to store a large quantity of electric charges. A capacitor can do this because of the large surface area of the two plates. The amount of charge that a capacitor can hold is related to its capacitance, $C$, measured in Farads, which is determined by its geometry and the properties of the dielectric:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

Where $\varepsilon_r$ is the dielectric constant of the material, and $\varepsilon_0$ is the electric permittivity of free space $8.854 \times 10^{-12} \text{ F/m}$. In this lesson students will NOT be using the electric constants to calculate capacitance, but will rather be building a capacitor out of aluminum foil and an insulating layer of their choice to investigate how to make a more effective capacitor with a larger value of $C$. Students should attempt to maximize two-dimensional Area of the conductive sheets while minimizing the distance between them.

It is critical that students understand that even though a capacitor seems like an open circuit, in DC a current will flow briefly while the capacitor is charging or discharging. Positive “charges” (in actuality: a lack of negative electrons) flow onto the positive terminal, while negative charges flow onto the negative terminal, until the potential difference across the two plates is equal to the voltage of the battery:
The first part of the lesson introduces the concept of capacitance and how capacitors can store electric charge. The second part of the lesson shows how combining a capacitor and an inductor in a circuit (an **LC Circuit**) produces sinusoidal oscillations.

Pictured is the simplest possible LC circuit. Note, it is important that the capacitor begins in a fully-charged state. The capacitor will discharge through the inductor, which will allow the current to slowly rise. Once the current is maximum, the capacitor is discharged and the inductor’s magnetic field is at maximum. The inductor will now *keep the current flowing* which will re-charge the capacitor in the opposite direction. Once the current reaches zero, the capacitor will now *discharge in the opposite direction* which repeats the cycle all over again. The result is an *I vs t* chart which looks like:

![I vs t chart](https://i.imgur.com/xFNC2k7.gifv)

The oscillation frequency is given by

\[
f = \frac{1}{2\pi\sqrt{LC}}
\]

The above chart is only possible if the capacitor, inductor, and wires have a perfectly zero resistance. Of course, for real objects the electrical resistance will be non-zero, meaning the oscillations will decrease in amplitude over time due to loss of energy. In engineering practice, an oscillating circuit will have an input source of energy, the LC circuit will be used to produce oscillations, and this frequency will be fed to a resistive load like an antenna.
Building a homemade capacitor
A capacitor can be made of simple household materials, for students to investigate what capacitance is and how it works. Check the Materials section below for a list of needed materials, seen here:

Step 1 – Lay out a few feet of insulator (in these pictures, wax paper is used, though plastic wrap or regular paper will also work as an insulating layer. Lay out the same length of aluminum foil, and place the foil on top of the insulator.

Step 2 – Make sure that the aluminum sheet is about 1 inch smaller in all dimensions than the wax paper sheet. The conducting layers of a capacitor must NOT TOUCH and it is critical that the aluminum does not overhang the paper.
Step 3 – Lay out a second sheet of wax paper on top of the first sheet of aluminum, then lay a second sheet of aluminum atop of the stack. You should have a stack alternating between insulating and conducting layers, making sure that the CONDUCTING LAYERS DO NOT TOUCH.

Step 4 – Lift up the layers a bit and tape a paperclip to the bottom conductor so that it overhangs the edges. Tape a second paperclip to the top conductor. These will be the terminals of the capacitor.

Step 5 – Use a paper towel tube or other circular tube to roll the 4 layers into a cylinder. As always, while rolling, take care that the conducting layers do not slip and touch.
Step 6 – Use a multimeter to measure the capacitance of your capacitor. You will need to use a high-quality multimeter that has the capacitance (\(\frac{1}{\mu F}\)) feature. This particular capacitor is about 150\(nF\).

Sadly, the homemade capacitor will most likely be on the order of a few hundred \(nF\), which means it won’t hold enough energy to produce any easily observable effects in a classroom setting.

If you want to build an LC circuit that can demonstrate some visible oscillation you can use or order some commercial circuit elements (for example from [www.sparkfun.com](http://www.sparkfun.com)).

The spiral roll is how most large capacitors are made, because it maximizes surface area while minimizing total volume.
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Materials – At least one per group of

- Aluminum Foil
- Wax Paper
- Plastic wrap
- Paper clips
- Paper towel tube
- Paper
- Alligator clips
- Tape (any kind)
- Multimeter WITH capacitance meter

Plan

This lesson is split into two parts. It can be taught as one 90 minute lesson or two shorter lessons.

The table below lays out a “schedule” for the two-lesson sequence:

Part 1:

<table>
<thead>
<tr>
<th>Teacher is doing:</th>
<th>Time</th>
<th>Students are doing:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin lesson with a review of electromagnets. A current-carrying coil creates a magnetic field. Ask student questions to activate background knowledge</td>
<td>5 min</td>
<td>Reviewing with their notes and with a discussion with the class and teacher</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Answering review questions posed by teacher</td>
</tr>
<tr>
<td>Go through lecture on attached slides on Capacitors (see appendix)</td>
<td>20 mins</td>
<td>Listening and making notes</td>
</tr>
<tr>
<td>Introduce “Make your own capacitor” materials and instructions. Hand out necessary tools and materials</td>
<td>5 min</td>
<td>Listening to instructions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Preparing materials</td>
</tr>
<tr>
<td>Circulate and assist students building their capacitor</td>
<td>15 min</td>
<td>Building a capacitor using the required materials, either alone or in a small group</td>
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<td></td>
<td></td>
<td>Discussing and observing with each other</td>
</tr>
<tr>
<td>Test! Go to each student (or student group’s) capacitor, and use a multimeter to measure their capacitance</td>
<td>5 min</td>
<td>Observing and recording the effectiveness of their capacitor</td>
</tr>
</tbody>
</table>
Part 2:

<table>
<thead>
<tr>
<th>Teacher is doing:</th>
<th>Time</th>
<th>Students are doing:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin Lesson 2 by reviewing Lesson 1</td>
<td>5 mins</td>
<td>Listening and answering teacher questions</td>
</tr>
<tr>
<td>Lecture and show the operation of an</td>
<td>15 min</td>
<td>Listening and making notes</td>
</tr>
<tr>
<td>oscillating LC circuit (see appendix)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assisting students with online lab</td>
<td>25 min</td>
<td>Going through the “LC Circuit Simulator Lab and Activity”</td>
</tr>
<tr>
<td>activity</td>
<td></td>
<td>Students are online at phet.colorado.edu, interacting with the online AC/DC circuit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>builder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Students are writing answers to question prompts on the attached activity sheet</td>
</tr>
<tr>
<td>End the two day lesson with a discussion</td>
<td>5 mins</td>
<td>Discussing their observations and conclusions</td>
</tr>
<tr>
<td>on what properties affected their</td>
<td></td>
<td></td>
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<tr>
<td>capacitors, and what kinds of uses an LC</td>
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<td></td>
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<tr>
<td>circuit might have</td>
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</tbody>
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Assessment

Assessment
The assessment is an online lab with a student-guided worksheet (see appendix). This assessment involves students constructing a circuit in an online circuit-builder environment, and then adjusting and measuring parameters and properties, recording calculations and observations. Instructions and files are attached below.

Summary

This lesson is designed to be a “first look” at two electronic devices that are normally not covered in intro-level high school Physics courses. Inductors and Capacitors are both covered in an AP Physics course, but students are often seeing those devices for the first time in that course. This lesson gives a purely conceptual look at what inductors and capacitors are and the basics of how they work. The lesson does not cover how L and C are used in most electrical engineering designs because that would require a knowledge of AC circuits.

The lesson is roughly 100 minutes of classroom content which can be split into multiple days if needed. The lesson begins with the attached slides and content for lecture. Next, students will use aluminum sheets and insulating sheets to build and investigate their own capacitors. The lesson includes a second set of slides on how L and C are used together to produce oscillations. Finally, the lesson concludes with a lab assessment where students use an online circuit simulator to build and analyze their own circuits with L and C.
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Bibliography


APPENDIX

I. LC Circuits Lab Simulator and Activity (Handout for students)

II. Selected Presentation Slides
LC Circuit – Lesson Lab and Circuit Simulator Activity

Purpose-
In this lab/activity, we will model a circuit with 1 Inductor (L) and one Capacitor (C) and observe its behavior.

Setup-
Go to http://phet.colorado.edu/new/simulations/sims.php?sim=Circuit_Construction_Kit_ACDC.
Test the simulator’s functions, such as adding components and connecting wires.

Instructions-

Step 1 – Construct the circuit as shown:

\[ V = 10 \text{ volts} \]
\[ R = 5 \text{ ohms} \]
\[ C = 0.05 \text{ Farads} \]
\[ L = 10 \text{ Henries} \]

Step 2 – Close Switch 1. What happens to the current after a few seconds pass?

Answer: ____________________________________________

_____________________________________

Step 3 – The capacitor is now fully charged. Open Switch 1 and close Switch 2.

Describe the motion of the current:

____________________________________________________________________________________

____________________________________________________________________________________

Step 4 – Use \( f = \frac{1}{2\pi \sqrt{LC}} \) and the values of L and C above, to find the frequency of the circuit

\[ f = \__________________________ \]

Does this match the frequency you observe? Why or why not?

____________________________________________________________________________________
Step 5 – Suppose you are a circuit designer and you want to design an oscillating circuit operating at a frequency of 20,000 Hz. Select values of L and C that will produce this frequency. Design and build your circuit in the AC/DC simulator. Test your circuit, and refine it until you get the result you want!

Sketch your 20 kHz circuit below:

Step 6 – One of the major problems that Electrical Engineers are trying to solve today is called the “Terahertz Gap.” There are no electronic devices that reliably produce frequencies above 1.0 Terahertz (THz). That’s 1,000,000,000,000 Hz!

Using the formula above, select two values of L and C that would produce 1.0 THz:

L =

C =

Why do you think it is so hard to make an oscillating circuit above 1.0 THz?
Review! A Solenoid

- We've already learned that a coil of wire with current running through it will create a magnetic field!
- We've called this a coil, or a solenoid.
- In an electrical circuit diagram this is called an Inductor.

- An Inductor has the letter $L$ and the symbol.
Now let's introduce a new circuit element: the **Capacitor**

- Two metal plates separated by a gap or insulator called the "dielectric"
- The middle part of a capacitor **DOES NOT** conduct electricity!
- Symbol for a Capacitor:
Capacitor in a Circuit

- Suppose I make this circuit:

  **How Capacitors Work** Basic Configuration

  - At first, a capacitor seems like an open circuit, it is a GAP between two conductors that don't touch!
  - But remember, unlike a wire, a capacitor can HOLD charge because it has a large surface area!
  - The voltage pushes positive charges on one plate, and negative charges onto the other plate
A capacitor creates an electric field

- **Remember**: E-field lines point away from positive charges and towards negative charges.

- **Meaning**: this circuit creates an Electric field! (In the capacitor)
To sum up:

An inductor $L$ makes a magnetic field.

A capacitor $C$ makes an electric field.
Let's make our own capacitor!

Materials:
• Aluminum Foil
• Wax Paper
• Plastic wrap
• Paper clips
• Paper towel tube
• Paper
• Alligator clips
• Tape (any kind)
• Multimeter
Ideas!

Keep your sheets of aluminum smaller than sheets of your insulator.

Your two conducting sheets can't touch!

Use 4 layers, alternate between conductor and insulator.

Tape a paperclip to each conducting sheet to connect to.

Roll the layers up into a tube!
Test!

We will hook a multimeter up to your capacitor, and measure the "capacitance" in Farads, (F).

Formula for capacitance:

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

A is the area of your conductive sheet
d is the distance between the sheets
\( \varepsilon \) is a constant (called the dielectric constant)
(Don't worry about this right now)

Who can build the capacitor with the highest capacitance?
Discuss!

Capacitance, what worked, what didn't?

What kind of designs do we see in class?

Who had the highest capacitance? Why did their design work?
Lesson 2 - Oscillating Circuit!

Review:
A capacitor can store charge!

This means it can also **discharge**
LC Circuit

Suppose we start with the capacitor charged like this!
LC Circuit

The capacitor will discharge, current will flow through the inductor, creating a magnetic field
LC Circuit

The inductor keeps the current going, slowly recharging the capacitor in the opposite direction.
LC Circuit

Until the current goes to zero, now the E-field is at maximum again!
LC Circuit

Now the capacitor discharges in the opposite direction and the cycle repeats!

Oscillation happens at a frequency \( f = \frac{1}{2\pi\sqrt{LC}} \)
LC Circuit simulator lab and activity

Go to
http://phet.colorado.edu/new/simulations/sims.php?
sim=Circuit_Construction_Kit_ACDC