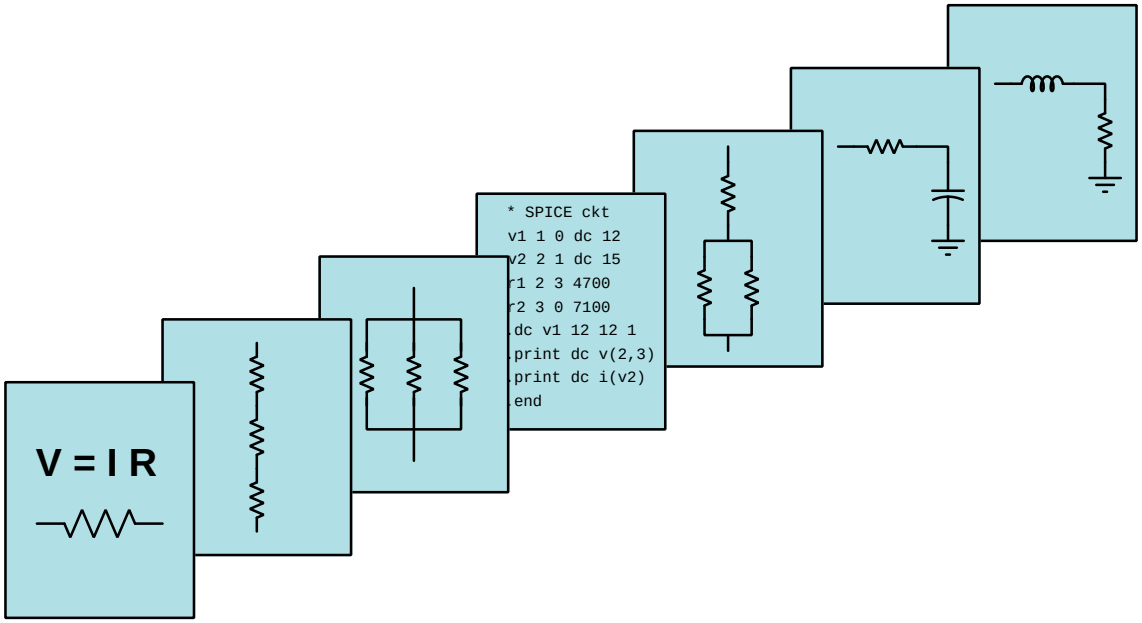
Modular Electronics Learning (ModEL) project



Resonance

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Chapter 1

Introduction

1.1 Recommendations for students

Resonance is a general phenomenon in physics, not limited to electric circuits, whereby complementary modes of energy storage in a system support oscillations. In an electric circuit, those complementary energy-storage modes are *capacitance* and *inductance*. Resonance may be intentional, as in circuits where we include inductance and capacitance for the express purpose of sustaining such oscillations, or it may be accidental where stray ("parasitic") inductance and capacitance gives rise to oscillations we don't actually want.

In addition to exploring the phenomenon of resonance, this learning module will also review series and parallel RLC networks at or near resonant-frequency conditions.

Important concepts related to resonance include the **Conservation of Energy**, **Conservation of Electric Charge**, **inductance**, **capacitance**, **reactance**, **impedance**, **phasors**, **sources** versus **loads**, **parasitic** effects, **oscillation** and **ringing**, **quality factor**, properties of **series** networks, properties of **parallel** networks, **Ohm's Law**, **Kirchhoff's Voltage Law**, and **Kirchhoff's Current Law**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to demonstrate the phenomenon of resonance? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of resonance?
- What does it mean to say that energy is always *conserved?*
- How does an electrical load behave?
- How does an electrical source behave?
- What are some examples of electrical components capable of being either sources or loads?
- What physical systems exhibit capacitance?

- What physical systems exhibit inductance?
- Is it voltage or current that resists change in a capacitor, and why?
- Is it voltage or current that resists change in an inductor, and why?
- What are some examples of complementary properties for inductance versus capacitance?
- Does inductance obey Ohm's Law like resistance does?
- Why does the combination of capacitance and inductance naturally support *oscillation*?
- What mechanical phenomenon is analogous to capacitance?
- What mechanical phenomenon is analogous to inductance?
- What is an *analog computer* and how does it work?
- What is the purpose of modeling a mechanical system using an analog computer?
- Why does the insertion of resistance tend to dampen oscillations in a circuit?
- What practical benefit do complex numbers lend to the analysis of AC circuits?
- How does reactance differ from resistance?
- How does impedance relate to resistance and reactance?
- Do the properties of series networks still hold true for AC as they do for DC?
- Do the properties of parallel networks still hold true for AC as they do for DC?
- Does Kirchhoff's Voltage Law still hold true for AC as it does for DC?
- Does Kirchhoff's Current Law still hold true for AC as it does for DC?
- When might we prefer an LC network with a high quality factor (Q)?
- When might we prefer an LC network with a low quality factor (Q)?

1.2 Challenging concepts related to resonance

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Phase shift** – like voltage, phase shift is a relative quantity. A single AC waveform, without another waveform to compare to, cannot have a phase value at all. Only when two waves of the same frequency are compared against one another may we intelligently state a phase shift, or time displacement, between the two. Properly reading phase shifts from an oscillograph can also be challenging for students, and requires reminding that time goes from left to right on an oscillograph: i.e. the wave reaching its peak first (left) compared to the other is leading, while the other is lagging. Another confusing aspect of phase shift is that it may be expressed in multiple ways: e.g. $+90^o$ phase shift is equivalent to -270^o phase shift, since waves repeat their patterns every 360 degrees.

- **Resistance versus Reactance versus Impedance** – these three terms represent different forms of opposition to electric current. Despite the fact that they are measured in the same unit (ohms: Ω), they are not the same concept. Resistance is best thought of as electrical *friction*, whereas reactance is best thought of as electrical *inertia*. Whereas resistance creates a voltage drop by dissipating energy, reactance creates a voltage drop by *storing* and *releasing* energy. Impedance is a term encompassing both resistance and reactance, usually a combination of both.

- **Parasitic effects** – phenomena such as resistance, capacitance, and inductance don't just exist where we want them to, but in fact always exist everywhere they can. All conductors (except for superconductors) have some amount of resistance, all conductors separated by an insulating gap exhibit capacitance, and all conductors possess inductance by virtue of their ability to produce a magnetic field with the passage of current. Often these "parasitic" effects are small enough to ignore, but in some applications they may be severe.

- **Impedance at resonance** – the fact that series-connected LC networks act like shorts at resonance and parallel-connected LC networks act like opens at resonance is not intuitive at all. Either one may be proven through quantitative analysis of individual component versus network (total) impedances, or by analyzing them conceptually from the perspective of equal energy-transfer rates at resonance.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter's examples.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Apply phasor quantities to the solution of voltages and currents in an AC circuit

  Assessment – Calculate voltages and currents in AC networks containing both capacitance and inductance; e.g. pose problems in the form of the "Series LC circuit calculations" Quantitative Reasoning question.

- **Outcome** – Calculate resonant frequency for a simple LC network

  Assessment – Given inductance and capacitance, calculate the expected resonant frequency of a simple LC network.

Chapter 2

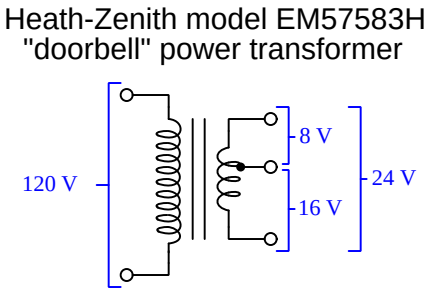
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: measuring transformer winding inductance

A *transformer* is a device with multiple coils of wire wrapped around a common core, designed to exploit the principle of *mutual inductance*[1]. We may use each coil (called a "winding") individually, though, which makes transformers useful as multiple inductors packaged as one component. The following schematic symbol represents a common transformer used to power electric doorbells in homes, stepping down 120 Volt AC line power to either 8, 16, or 24 Volts AC to energize the doorbell.



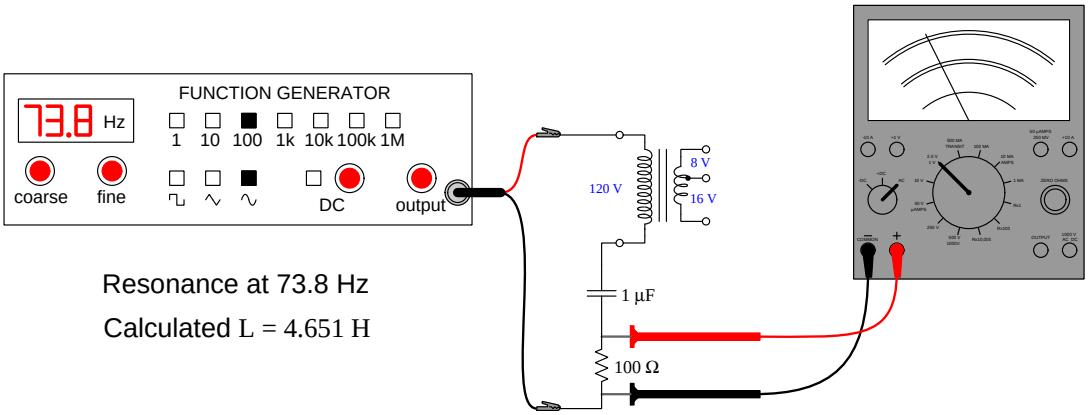
We may measure the inductance of an inductor by connecting it in series with a capacitor and a resistor, then measuring AC voltage across the resistor as we vary the frequency of an energizing AC source (e.g. signal generator configured to output a sinusoidal waveform). At resonance the resistor's voltage drop will be at its maximum. Measuring the source frequency necessary to achieve resonance allows us to calculate inductance based on a known capacitance value:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$L = \frac{1}{4\pi^2 f_r^2 C}$$

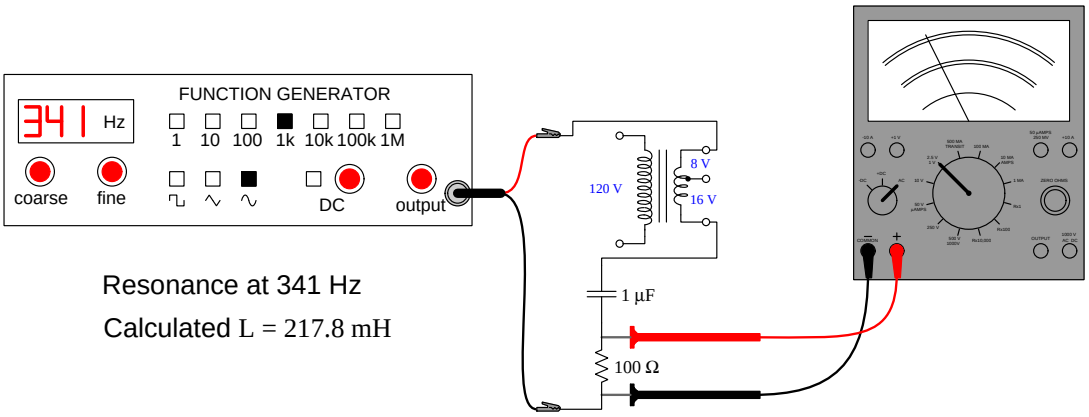
[1] Whereas inductance is the storage of energy in a magnetic field caused by a current through a conductor, mutual inductance is the *transfer* of energy from one conductor to another through a shared magnetic field. Likewise, whereas inductance manifests a voltage resulting from a rate-of-change of current through a conductor ($V = L\frac{dI}{dt}$), mutual inductance is where a voltage results across one conductor resulting from a rate-of-change of current through another conductor, once again by the action of a shared magnetic field.

The following measurements were taken on the Heath-Zenith model EM57583H transformer using a signal generator as the AC source, a 100 Ω resistor to measure voltage across (using either a multimeter with a wide frequency range or an oscilloscope), and a 1 μF mylar capacitor:



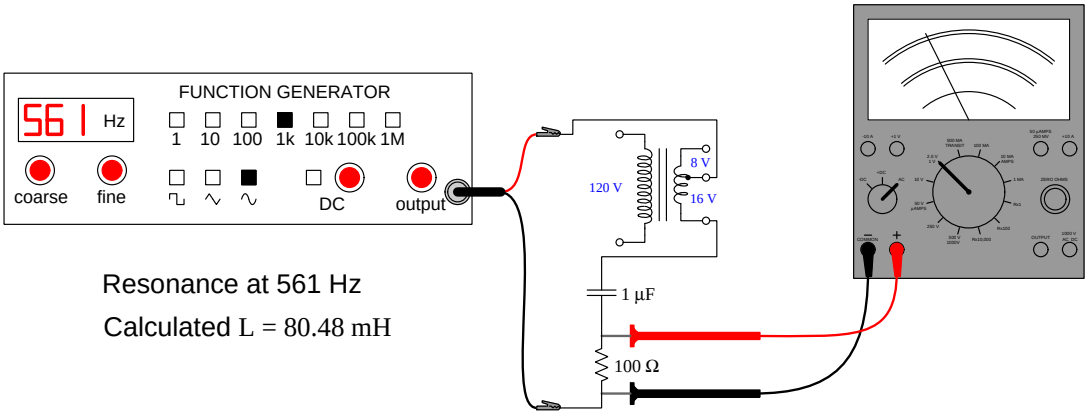
Resonance at 73.8 Hz

Calculated L = 4.651 H



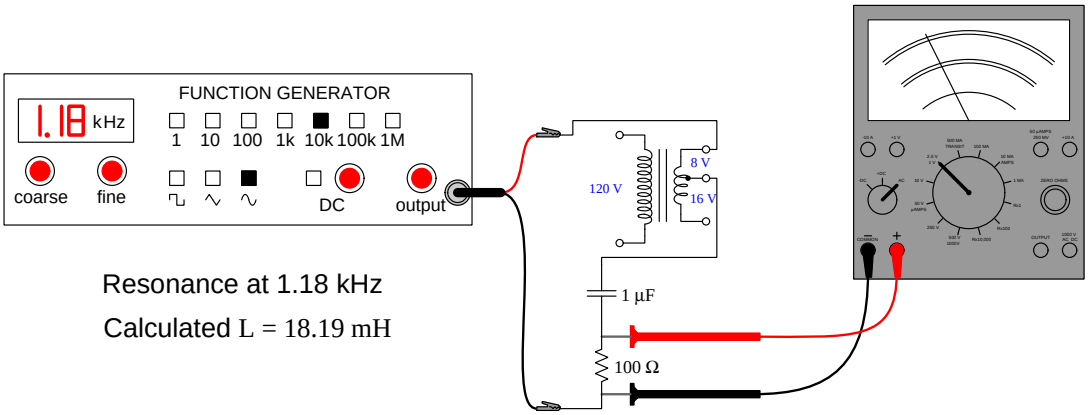
Resonance at 341 Hz

Calculated L = 217.8 mH



Resonance at 561 Hz

Calculated L = 80.48 mH

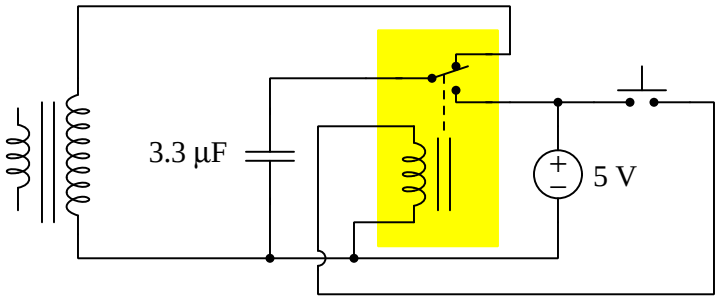


Resonance at 1.18 kHz

Calculated L = 18.19 mH

2.2 Example: low-frequency resonant circuit

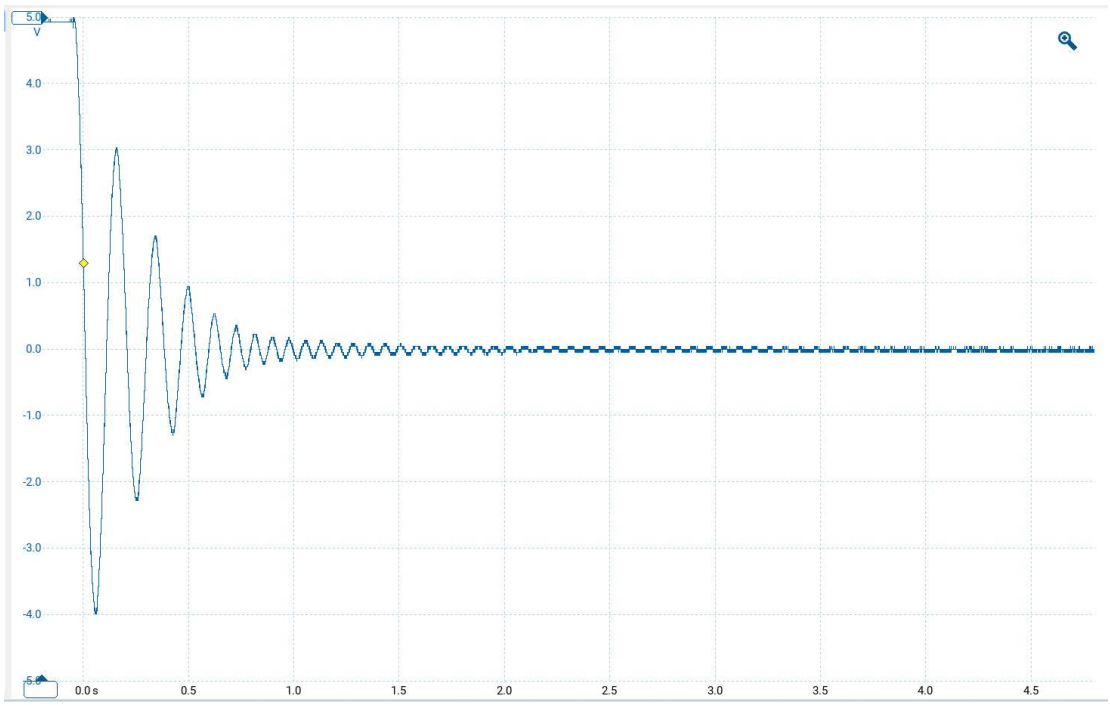
The following circuit oscillates at a remarkably low frequency because the inductor has an enormous value, bring the primary winding of an electrical utility power transformer (rated for 7.2 kV at 60 Hz):



When the pushbutton switch is pressed, the relay coil energizes and the capacitor is connected across the 5 Volt DC source to charge up with energy. Upon releasing the pushbutton, the relay coil de-energizes and its SPDT contacts disconnect the capacitor from the 5 Volt source and connect it in parallel with the transformer's massive primary winding. The result of this switching is a damped oscillation of voltage across the capacitor and transformer winding (inductor) as energy is exchanged between each.

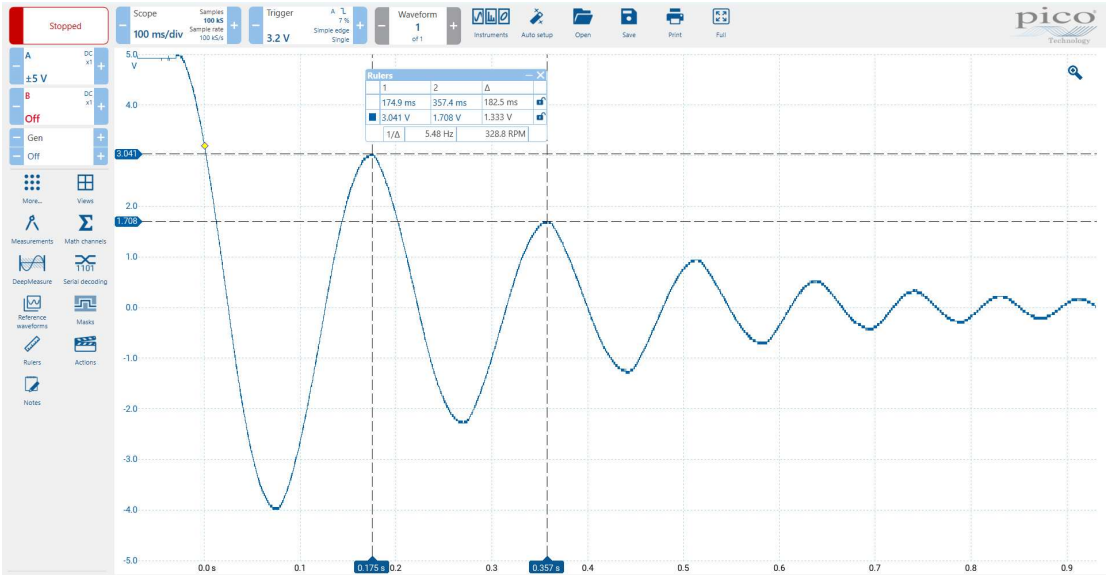
Given that energy is conserved, and the initial store of energy is contained solely within the capacitor at a voltage of 5 Volts, at no time in the oscillation will the peak voltage ever reach (let alone exceed) 5 Volts.

Below we see an oscillograph of the resulting damped oscillation:



Note the time scale of this oscillograph, in whole *seconds*! This oscillation is so slow you can actually watch it oscillate in real time as the oscilloscope sweeps the trace across its display from left to right. Even four and a half seconds after releasing the pushbutton we still see tiny oscillations occurring.

Below we see another oscillograph taken on the same circuit, this one captured at a faster sweep rate (i.e. shorter timebase setting) and using the oscilloscope's cursors to measure peak-to-peak period and frequency of the oscillations:



Given this measured frequency of 5.48 Hz, we may manipulate the LC resonant frequency formula to calculate the inductance of the transformer's winding:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$2\pi f = \frac{1}{\sqrt{LC}}$$

$$4\pi^2 f^2 = \frac{1}{LC}$$

$$L = \frac{1}{4\pi^2 f^2 C}$$

$$L = \frac{1}{4\pi^2 (5.48 \text{ Hz})^2 (3.3\ \mu\text{F})}$$

$$L = 255.6 \text{ H}$$

255.6 Henrys is indeed an enormous amount of inductance!

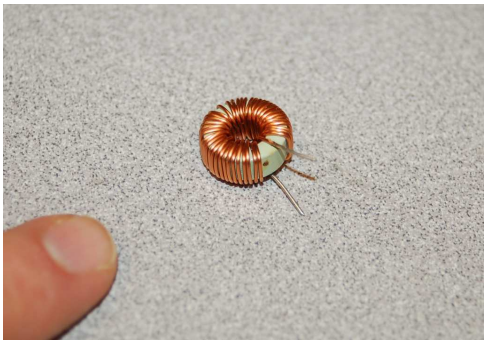
Chapter 3

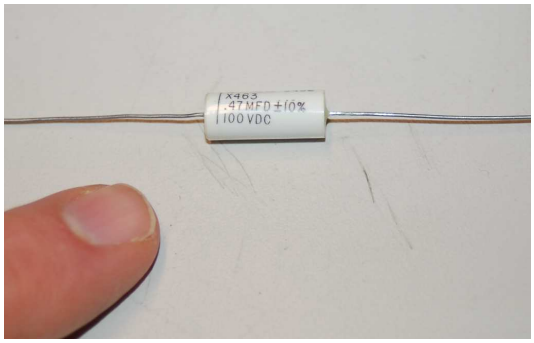
Tutorial

3.1 Review of inductance and capacitance

Inductance and *capacitance* refer to modes of electrical energy storage: inductance being the storage of energy in a magnetic field associated with current passing through a conductor, and capacitance being the storage of energy in an electric field associated with voltage existing between two distinct conductors. These phenomena take purposeful form in the construction of *inductors* and *capacitors*, respectively. Inductors typically consist of coils of wire wrapped around a magnetic core material, while capacitors consist of metal surfaces[1] separated by an electrical insulator called a *dielectric*.

A small inductor (left) and small capacitor (right) appear in the photographs below:



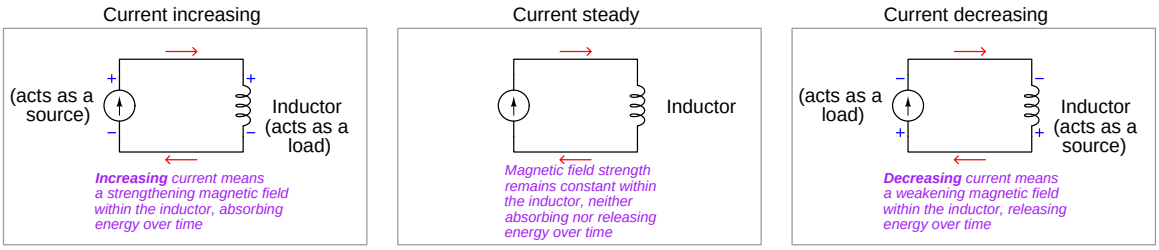


The amount of energy stored in any inductor's magnetic field is a function of current through the inductor's coil, since the strength of that magnetic field varies directly with current. Similarly, the amount of energy stored in any capacitor's electric field is a function of voltage between the capacitor's plates, since the strength of that electric field varies directly with voltage. Energy, as we know, is always conserved, which means it cannot simply appear or vanish without being transferred *from* or *to* somewhere. It follows logically, then, that neither the amount of current through an inductor nor the amount of voltage across a capacitor may vary without energy transfer from or to some other portion of an electric circuit.

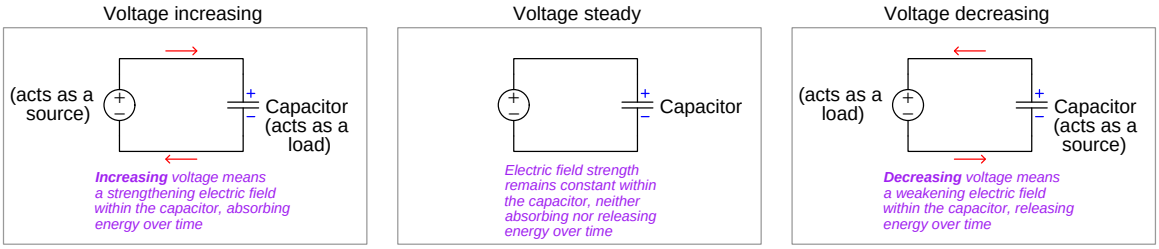
[1] Typically the "plates" of a capacitor are sheets of thin metal foil wrapped into cylinders to conserve space.

Energy transfer to or from any electrical component requires that component act as either a *source* or a *load*, and these roles are defined by the relationship between voltage polarity and current direction for that component.

Inductors store energy in magnetic fields, and these fields relate directly to current. Therefore, in order for an inductor to absorb energy from the circuit it must function as a load (i.e. electric charge carriers entering at higher energy and leaving at lower energy, from + to −), and in order to release energy it must function as a source (i.e. charge carriers entering at lower energy and leaving at higher energy, from − to +). Zero voltage across an ideal[2] inductor means a condition of stasis where the magnetic field (and therefore stored energy) neither accumulates nor depletes:



Capacitors store energy in electric fields, and these fields relate directly to voltage. Therefore, in order for a capacitor to absorb energy from the circuit it must function as a load (i.e. electric charge carriers entering at higher energy and leaving at lower energy, from + to −), and in order to release energy it must function as a source (i.e. charge carriers entering at lower energy and leaving at higher energy, from − to +). Zero current through an ideal[3] capacitor means a condition of stasis where the electric field (and therefore stored energy) neither accumulates nor depletes:

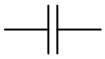
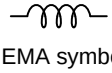
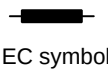


Note which parameters reverse and which maintain the same orientation for each of these energy-storing components. For inductors, current remains flowing in the same direction and voltage polarities reverse as the inductor switches roles as source versus load; for capacitors, voltage remains in the same polarity and current reverses direction as the capacitor switches roles as source versus load. *In each case, the parameter directly related to the amount of energy stored in the component is the one conserved – precisely because energy must be conserved – while the other parameter reverses as needed to facilitate energy transfer into or out of the component.*

[2] An ideal inductor being made of superconducting wire having no resistance to create its own voltage drop.

[3] An ideal capacitor being one with no "leakage" resistance through its dielectric to pass current.

When we compare and contrast the properties of inductance versus capacitance, we see a consistent symmetry between the two, and from this we may see how inductance and capacitance are *complementary properties* of electric circuits:

Capacitance (C)	**Inductance** (L)
 NEMA symbol IEC symbol	 NEMA symbol  IEC symbol
An *electric field* is created by a *voltage* existing between two conductors	A *magnetic field* is created by a *current* passing through a conductor
Capacitance is enhanced by the area of the conductors, and a narrow spacing between them	Inductance is enhanced by the length of the conductor, and forming a coil shape with multiple turns
An electric field stores energy as a function of voltage: $E_C = \frac{1}{2}CV^2$	A magnetic field stores energy as a function of current: $E_L = \frac{1}{2}LI^2$
Acts as a *load* when *voltage increases* over time ; current flows into + terminal and out of − terminal	Acts as a *load* when *current increases* over time ; voltage drop + where current enters and − where current exits
Maintains a constant voltage when passively storing energy	Maintains a constant current when passively storing energy
Acts as a *source* when *voltage decreases* over time ; current flows out of + terminal and into − terminal	Acts as a *source* when *current decreases* over time ; voltage rise − where current enters and + where current exits
Current is able to *instantly* cease or reverse direction while voltage cannot; current switches direction when capacitor transitions between source and load	Voltage is able to *instantly* cease or reverse polarity while current cannot; voltage switches polarity when inductor transitions between source and load
The amount of current is proportional to the *rate* (speed) at which energy is being absorbed by or released from the electric field	The amount of voltage is proportional to the *rate* (speed) at which energy is being absorbed by or released from the magnetic field
Current is equal to the capacitance times the *rate-of-change* (speed) that voltage varies over time: $I = C\frac{dV}{dt}$	Voltage is equal to the inductance times the *rate-of-change* (speed) that current varies over time: $V = L\frac{dI}{dt}$

3.2 Combining inductance with capacitance

A fascinating phenomenon associated with combinations of capacitance and inductance is *resonance*, where energy exchanges back and forth between these two modes. This has a close analogy in the mechanical world to springs and masses: just as capacitors store energy in electric fields and inductors in magnetic fields, springs store potential energy in the form of tension and displacement while masses store kinetic energy in the form of motion. Any mass connected to a spring will exhibit resonance: an ability to sustain alternating motion for sometime after being stimulated. A spring-loaded mass moves to and fro because the spring and mass exchange energy back and forth with each other.

A cart with mass stores energy in kinetic form, while a spring with elasticity stores energy in potential form. Similarly, an inductor stores energy in its magnetic field as a function of current (kinetic charge carriers), while a capacitor stores energy in its electric field as a function of voltage (potential energy per charge). Coupling these complementary devices together means they now have the ability to exchange energy back and forth, and will do so if initially energized by some external source. For the spring-coupled cart it means the assembly will tend to move back and forth cyclicly; for the capacitor-inductor network it means the circuit will *oscillate* (i.e. produce alternating current, or AC).

The rate at which systems like this will oscillate depends on the characteristics of its elements. A stiffer spring will cause the cart to move back and forth more rapidly. A more massive cart will cause the cart to alternate more slowly. With capacitors and inductors it is even simpler: increasing the size of either component will slow down the rate of oscillation.

The resonant frequency for any simple capacitor-inductor network is predicted by the following formula:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

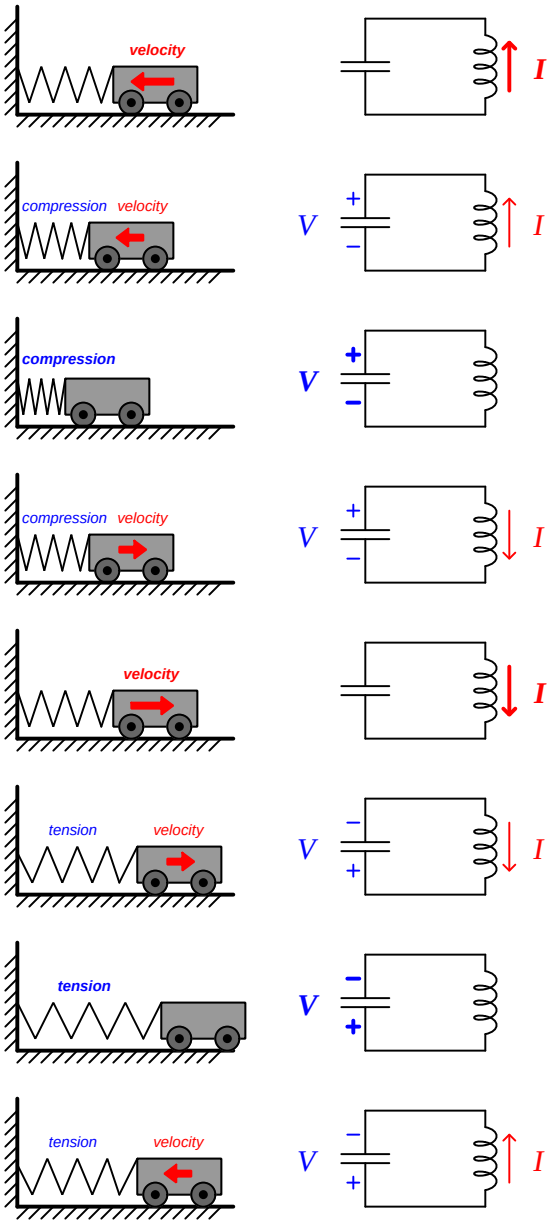
Where,

f_r = the frequency of oscillation in cycles per second or Hertz
L = inductance in Henrys
C = capacitance in Farads

For example, if we were to connect a 0.15 μF capacitor to a 22 mH inductor, the resonant frequency of this simple LC network would be:

$$\frac{1}{2\pi\sqrt{(22 \times 10^{-3}\ \text{H})(0.15 \times 10^{-6}\ \text{F})}} = 2770.53\ \text{Hz}$$

The following series of illustrations show a step-by-step sequence of events for an oscillating spring-and-cart mechanism alongside an oscillating capacitor-inductor circuit:



The spring's ability to store potential energy is analogous to the capacitor's ability to store energy in an electric field. The cart's ability to store kinetic energy is analogous to the inductor's ability to store energy in a magnetic field. Compression and tension within the mechanical spring is analogous to voltage across the capacitor; velocity of the cart is analogous to current through the inductor.

Even the mathematical formulae describing resonant frequency is similar between these mechanical and electrical systems. On the left we see the resonant frequency formula for the mass-and-spring system while on the right we see the resonant frequency formula for an inductor-capacitor network:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad\qquad f_r = \frac{1}{2\pi\sqrt{LC}}$$

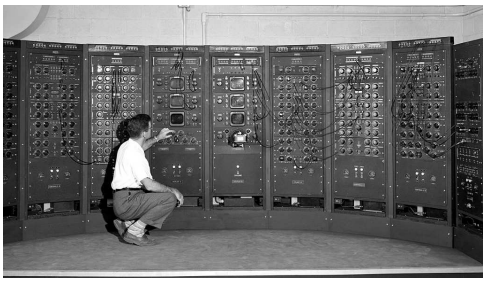
Where,

f_r = the frequency of oscillation in cycles per second or Hertz
k = spring constant of the spring in Newtons per meter
m = mass in kilograms
L = inductance in Henrys
C = capacitance in Farads

In the absence of any friction (resistance), both systems will oscillate ceaselessly as they exchange energy back and forth without losses. Mechanical systems made of springs and masses are used to create vibrations, an example being the string of a musical instrument such as a guitar: the elasticity and mass of the spring serves both roles in one component, so that the assembly *resonates* at a desired pitch. Capacitor-inductor circuits (often called *tank circuits*) are similarly used to create alternating current (AC) signals of a specific frequency.

The similarity we observe between mechanical and electrical resonant systems is so precise that in fact it is possible to use LC electrical networks to *model* mechanical systems. This is an example of an electrical *analog computer*, where electrical components having characteristics analogous to mechanical elements are used to simulate mechanical systems, the result of these simulations being voltages and/or currents that may be measured as predictive of mechanical stresses and velocities.

In the photograph[4] below we see an early example of an electronic analog computer used for engine simulations at the Lewis Flight Propulsion Laboratory in the late 1940's, long "patch" cables used to connect various circuitry sections together to form an analog network simulating some aspect of a mechanical engine. Cathode Ray-Tube (CRT) monitors provide oscillographic displays for the resulting voltage signals representing vibratory movement of the engine components:



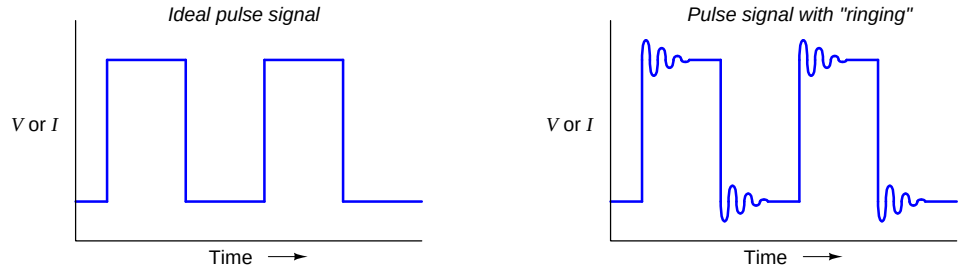
Modern simulations utilize digital electronic computers rather than analog, but the purpose is the same: inexpensive models simulating the real behavior of an expensive system allows engineers and technicians to make design refinements prior to constructing real prototypes.

[4]This public-domain photograph is courtesy of NASA.

3.3 Parasitic inductance and capacitance

Capacitance and inductance, like elasticity and mass in mechanical systems, are intrinsic phenomena and therefore exist in *every* circuit whether desired or not. If any circuit component happens to exhibit an unintended phenomenon, we refer to that phenomenon as being *parasitic* to the component. For example, a wire-wound resistor that happens to exhibit some inductance due to the shape of its wire coil may be said to have *parasitic inductance* in addition to its (intended) resistance. Inductors and transformers, similarly, suffer from *parasitic resistance* (from the length of thin wire used to form the windings) as well as *parasitic capacitance* (from different turns of wire separated by insulation, as well as between the insulated wire and the ferrous core).

The existence of such "parasitic" capacitance and inductance in circuits means resonance may occur where it is unintended, just as unintended resonance may occur in mechanical assemblies[5]. An example of unintended electrical resonance called *ringing* is often encountered in *pulse* circuits where voltage or current is suddenly switched on and off to some load: instead of the graph of this voltage or current over time resembling a square-edge as desired, some oscillations will be seen at the leading edges of the pulse.



Whether the unintended resonance is electrical or mechanical, the insertion of energy-dissipating elements into the system helps dampen any oscillations that may otherwise occur. For mechanical systems this means incorporating sufficient *friction*[6]; for electrical circuits it means incorporating sufficient resistance.

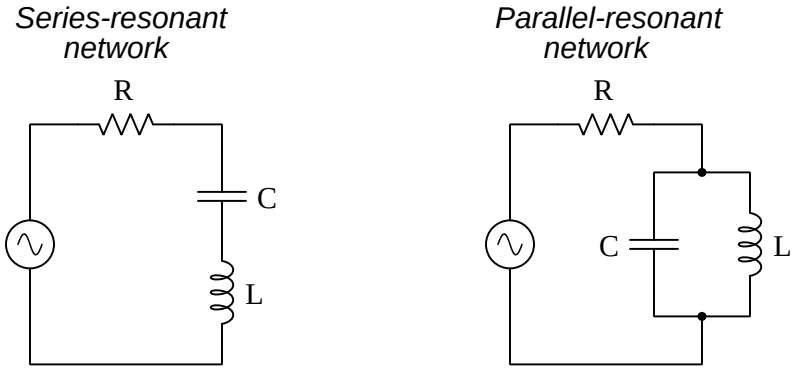
For most electric circuits lacking capacitors and inductors, the amount of capacitance present between wires and the amount of inductance along the length of wires is so small compared to the energy-dissipating elements that these effects are negligible, and unintended resonance is simply impossible. However, for some specific types of circuits, especially those dealing with extremely high-frequency (fast-alternating) AC signals such as *radio* circuits, special care must be taken positioning all conductors to mitigate parasitic capacitance and inductance.

[5] Excessive "bouncing" in a vehicle's suspension system is one common example, but in fact nearly every mechanical assembly is capable of resonance. Rotating machines exhibit *critical speeds* where the shaft rotation period matches the resonance period of the rotating element, causing vibration to naturally occur at these speeds. Struts and other supporting members for some mass will tend to oscillate at a natural frequency, the mass acting to store kinetic energy and the strut's elasticity acting to store potential energy. The infamous Tacoma Narrows bridge was a spectacular example of unintended resonance in a mechanical structure, earning it the nickname "Galloping Gertie" by motorists due to wind-induced oscillations prior to its catastrophic collapse on 7 November 1940.

[6] The so-called *shock absorber* is a component designed to do exactly this in vehicle suspension systems, to prevent bouncing (oscillations) that would otherwise result as a consequence of the vehicle's elastic suspension system and its mass.

3.4 Series versus parallel resonance

When inductance and capacitance exists in a circuit with other components and not just with each other, we have the possibilities of series resonance and parallel resonance, both illustrated in the following schematic diagrams:



In either network, resonance occurs when the reactances of the capacitor and inductor (X_C and X_L) are precisely equal, and for this reason the resonant frequency is calculated the same way: $f_r = \frac{1}{2\pi\sqrt{LC}}$. However, the effects in each of the circuits at this resonant frequency are very different.

For any series-connected network of components, total impedance is the sum of the individual impedances. Since the complex (i.e. *phasor*) impedance of an inductor is $0 + jX_L$ and the complex impedance of a capacitor is $0 - jX_C$, in series their combined impedance must be:

$$Z_{series} = (0 + jX_L) + (0 - jX_C) = jX_L - jX_C$$

If we know $X_L = X_C$ at resonance, then this series equivalent impedance must be zero which means the inductor and capacitor in series act as a short circuit!

For any parallel-connected pair of components, total impedances is the product of the individual impedances divided by the sum of the individual impedances[7]. Since the complex impedance of an inductor is $0 + jX_L$ and the complex impedance of a capacitor is $0 - jX_C$, in parallel their combined impedance must be:

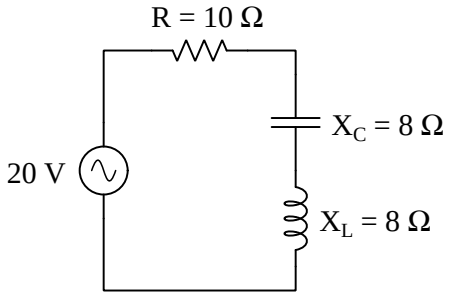
$$Z_{parallel} = \frac{(0 + jX_L)(0 - jX_C)}{(0 + jX_L) + (0 - jX_C)} = \frac{X_L X_C}{jX_L - jX_C}$$

From the series example we already know the sum is equal to zero at resonance, and in this equation that zero sum lies in the denominator of the fraction, resulting in infinite[8] parallel impedance, which means the inductor and capacitor in parallel act as an open circuit!

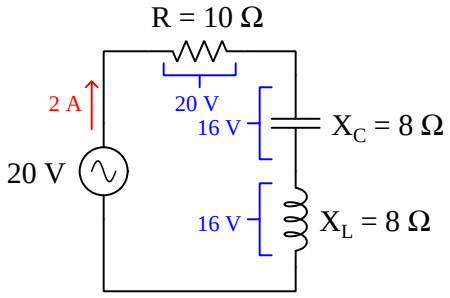
[7] Either $Z_{parallel} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}$ or $Z_{parallel} = \frac{Z_1 Z_2}{Z_1 + Z_2}$ will suffice for calculating the parallel equivalent of two impedances, but the product-over-sum formula is less clumsy here than the reciprocal-of-reciprocals formula.

[8] Strictly speaking, dividing by zero results in an *undefined* quantity, but for practical purposes here it means infinite impedance.

As non-intuitive as it may be to contemplate a total series impedance of zero, even stranger are the voltages and currents that result. First we will analyze the series resonant network, assigning simple resistance and reactance values to each component:



Knowing that the equivalent series impedance of the capacitor and inductor will be zero at resonance (where their reactance values are equal), total impedance for the entire circuit must be solely due to the resistor: 10 Ohms. With a 20 Volt source and 10 Ohms of total impedance, Ohm's Law ($I = \frac{V}{Z}$) predicts a current of 2 Amperes. Using Ohm's Law ($V = IZ$) once again to calculate voltage across each component based on this known current value, we obtain 20 Volts across the resistor, 16 Volts across the capacitor, and 16 Volts across the inductor:



At first this seems like a violation of Kirchhoff's Voltage Law: how can 20 Volts, 16 Volts, and 16 Volts add up to the source voltage of 20 Volts? If we show all the calculations for circuit current and voltage drops using complex numbers, the answer becomes clearer:

$$I = \frac{V_{source}}{Z_{total}} = \frac{20 + j0}{10 + j0} = 2 + j0 \text{ Amperes}$$

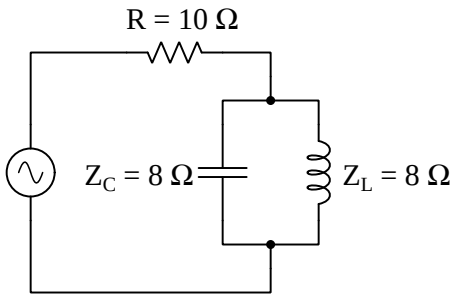
$$V_R = IZ_R = (2 + j0)(10 + j0) = 20 + j0 \text{ Volts}$$

$$V_C = IZ_C = (2 + j0)(0 - j8) = 0 - j16 \text{ Volts}$$

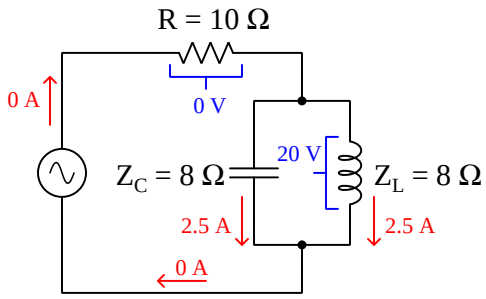
$$V_L = IZ_L = (2 + j0)(0 + j8) = 0 + j16 \text{ Volts}$$

Now it makes sense: V_C and V_L are 180 degrees out of phase with each other, and so in series their combined voltage drops add to zero, leaving just the resistor's voltage to equal the source voltage.

Next, we will analyze the parallel resonant network, assigning the same resistance and reactance values as before:



Knowing that the equivalent parallel impedance of the capacitor and inductor will be infinite at resonance (where their reactance values are equal), total impedance for the entire circuit will be infinite as well. The full 20 Volt source voltage will be dropped across the parallel capacitor-inductor network with the resistor dropping nothing and source current being zero. Ohm's Law ($I = \frac{V}{Z}$) predicts a current of 2.5 Amperes through the capacitor and inductor, though:



This time the apparent violation is with Kirchhoff's Current Law: how can 2.5 Amperes of current flow through both the capacitor and inductor branches of the circuit and yet result in a total current of zero? The answer, once again, lies with the complex phase angles of these calculated branch currents:

$$I_C = \frac{V}{Z_C} = \frac{20 + j0}{0 - j8} = 0 + j2.5 \text{ Amperes}$$

$$I_L = \frac{V}{Z_L} = \frac{20 + j0}{0 + j8} = 0 - j2.5 \text{ Amperes}$$

Once again it makes sense: I_C and I_L are 180 degrees out of phase with each other, and so in parallel their combined currents add to zero.

3.5 Resonance explained conceptually

It is quite non-intuitive for students accustomed to DC series networks to find that a series-connected capacitor and inductor pair exhibit zero Ohms of total impedance at a specific frequency, because the universal experience with DC resistor networks is that resistances in series always add up to form a *greater* total resistance. Likewise, the phenomenon of parallel-connected capacitor and inductor pairs exhibiting infinite impedance also seems implausible, since we learn in DC resistor networks that parallel resistances always diminish to form a *lesser* total resistance. Even after seeing how phasor mathematics proves each case, it is not unreasonable to want resonance to make more *conceptual* sense and to be more congruent with previous conceptual knowledge. In this section we will aim to do just that.

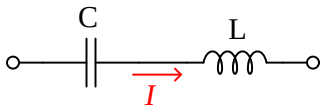
First, let us begin afresh by reviewing the definition of resonance: *a condition where energy exchanges back and forth between two complementary modes.* A mass coupled to a stationary surface by way of an elastic spring will resonate when the mass's kinetic energy and the spring's potential energy exchange back and forth. A pendulum's mass resonates as it exchanges energy between potential (height) and kinetic (velocity) forms, potential reaching its maximum at each end-point of the swing and kinetic reaching its maximum at the lowest point of the swing. Capacitors and inductors resonate when they alternately release and absorb energy to/from each other.

If we consider for a moment the scenario of a mechanism resonating on its own after having been initially bumped, or an inductor/capacitor pair resonating (oscillating) on their own after having been momentarily energized by an outside electrical source, we may draw another conclusion about the energy exchange taking place in a resonating system: for any system in a state of resonance apart from any external energy source or load, the rates of energy release and energy absorption in that system must be perfectly matched at all points in time, due to the Law of Energy Conservation. If energy cannot be created or destroyed, but must always and everywhere be accounted, then whatever energy is released in one portion of a resonating system must be absorbed by another portion so long as there is no external source or load. Thus, a free-swinging pendulum or a vibrating mass-and-spring assembly loses potential energy at the same rate it gains kinetic energy, and vice-versa; a free-oscillating LC network's capacitor loses energy at the same rate its inductor gains energy, and vice-versa. This must be true at every point in time, at every point in the oscillatory cycle, for any free-oscillating resonant system because the Law of Energy Conservation informs us the energy has nowhere else to go.

Capacitance and inductance in a resonant circuit alternately serve as sources and loads to each other, but if they are the *only* sources and loads to each other then their sourcing and loading power must precisely match at every point in time. This is why resonance occurs only at one frequency for all these systems: there is only one frequency at which the power release matches the power absorption at all points in time.

Now that we realize the rate of energy release and absorption matters to resonance, we may apply what we know of series and parallel networks, as well as source and load behavior, to deduce the voltage, current, and impedance characteristics of resonating networks.

It is a fundamental property of series networks that current is the same through all the series-connected components at any point in time, because there is only one path for electric charge carriers to flow in a series network, and because electric charges are conserved (i.e. cannot be created or destroyed). Therefore, in a series network consisting of one capacitor and one inductor there must be the same amount of current through each at any given time:



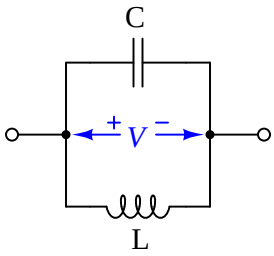
As these two components resonate with each other, one must be a source while the other must be a load at any given point in time. These roles swap of course over time, but at any given time one of these components must be supplying energy to the other, and at the exact same rate.

If we know the capacitor and inductor both share the same current, it means the current magnitude and current direction for each component must be identical. If we know at every point in time that one of them must be acting as a source and the other as a load, we may conclude their voltage polarities must be opposite each other. Furthermore, if we know their rates of energy transfer (i.e. power) must be equal at resonance, we may conclude the amount of voltage dropped by each one must be equal as well because instantaneous power is the product of voltage and current (i.e. Joule's Law).

Therefore, it stands to reason that series-connected capacitors and inductors at resonance must experience equal and opposite-polarity voltages at all times for any amount or direction of current. Since they are connected in series with each other, and we also know series voltages algebraically add to one another (Kirchhoff's Voltage Law), the total (net) voltage of this series network must be zero. Zero voltage dropped with the passage of any finite amount of current means zero Ohms of opposition to that current, and this is why series-resonating capacitor-inductor pairs exhibit zero impedance.

To summarize: resonance is that condition where energy is alternately released and stored at equal rates by different parts of the same system. In order for one of these components to release energy at the same rate that the other absorbs while connected in series, the voltage of one must be equal in magnitude to and opposite in polarity than the other, resulting in a total voltage of zero for the series network and therefore zero impedance.

It is a fundamental property of parallel networks that voltage is the same across all the parallel-connected components at any point in time, because those components share the same pair of electrically-common (and equipotential) points, and because energy is conserved (i.e. cannot be created or destroyed). Therefore, in a parallel network consisting of one capacitor and one inductor there must be the same amount of voltage across each at any given time:



As these two components resonate with each other, one must be a source while the other must be a load at any given point in time. These roles swap of course over time, but at any given time one of these components must be supplying energy to the other, and at the exact same rate.

If we know the capacitor and inductor both share the same voltage, it means the voltage magnitude and voltage polarity for each component must be identical. If we know at every point in time that one of them must be acting as a source and the other as a load, we may conclude their current directions must be opposite each other. Furthermore, if we know their rates of energy transfer (i.e. power) must be equal at resonance, we may conclude the amount of current through each one must be equal as well because instantaneous power is the product of voltage and current (i.e. Joule's Law).

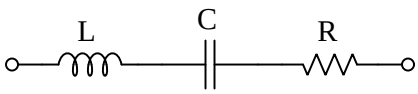
Therefore, it stands to reason that parallel-connected capacitors and inductors at resonance must experience equal and opposite-direction currents at all times for any amount or polarity of voltage. Since they are connected in parallel with each other, and we also know parallel currents algebraically add to one another (Kirchhoff's Current Law), the total (net) current of this parallel network must be zero. Zero current passed for any finite amount of applied voltage means infinite Ohms of opposition, and this is why parallel-resonating capacitor-inductor pairs exhibit infinite impedance.

To summarize: resonance is that condition where energy is alternately released and stored at equal rates by different parts of the same system. In order for one of these components to release energy at the same rate that the other absorbs while connected in parallel, the current of one must be equal in magnitude to and opposite in direction than the other, resulting in a total current of zero for the parallel network and therefore infinite impedance.

3.6 Quality factor (Q)

All practical LC networks exhibit some form of energy loss, whether in the form of conductor resistance or *equivalent* resistance in the forms of inductor core magnetic losses, capacitor dielectric losses, or even radiated energy (electromagnetic radiation) losses. The ratio of energy exchanged back and forth between a network's inductance and capacitance versus energy dissipated away from the network is broadly known as the *quality factor*, mathematically symbolized by the variable Q. As a ratio of energy to energy – i.e. both the numerator and the denominator of the fraction having the same physical units of measurement – quality factor itself is unitless. LC networks with low losses have high Q values. A theoretical "lossless" LC network would have an *infinite* quality factor.

Consider a simple series LC network, with total (real and equivalent) resistance modeled as a resistor in series with the inductor and capacitor:



In a condition of resonance where X_L exactly equals X_C in magnitude, the impedances Z_L and Z_C will cancel out to zero because their phase angles are 180 degrees apart. This leaves only R effective in the network. In a theoretical "lossless" network where $R = 0$ the network's total impedance would also be zero at resonance, and non-zero at any other frequency. In a real series LC network the total resistance of that network sets the minimum impedance possible at resonance. While at resonance, Q for such a series network is simply calculated as reactance[9] divided by resistance:

$$Q = \frac{X_{resonant}}{R}$$

If we multiply both numerator and denominator by I^2, the numerator becomes I^2X which is reactive power while the denominator becomes I^2R which is true power[10]. Since power (in any form) is simply the rate of energy exchange over time, we see that for any given amount of elapsed time the ratio of $X_{resonant}$ to R really is the ratio of energy exchanged between components to energy dissipated.

[9] Either X_L or X_C, as these two quantities are equal at resonance.

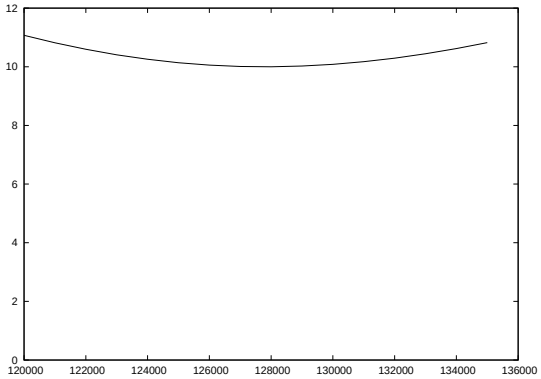
[10] Recall that P is the symbol for true power measured in Watts (W), S the symbol for apparent power measured in Volt-Amperes (VA), and Q the symbol for reactive power measured in Volt-Amperes Reactive (VAR). It is an unfortunate duplication of symbols in electrical theory that we use Q to represent different things: in this case, it could mean quality factor or it could mean reactive power, with context being the only differentiator. It is even more unfortunate that these two different concepts are closely related to each other, which only adds to the potential confusion!

Quality factor is a very important measure of an LC network's behavior not only at resonant frequency but also at frequencies above and below resonance. Consider the following comparison between networks having equal L and equal C values but different R values:

The resonant frequency formula $f_r = \frac{1}{2\pi\sqrt{LC}}$ tells us both networks will resonate at 127.795 kHz, but while the left-hand network has a Q of 3.7739, the right-hand network has a Q value ten times greater (37.739) due to its resistance being a whole order of magnitude less. This difference significantly impacts maximum versus minimum total impedance as frequency sweeps from below resonance to above, as shown in the tables and graphs below:

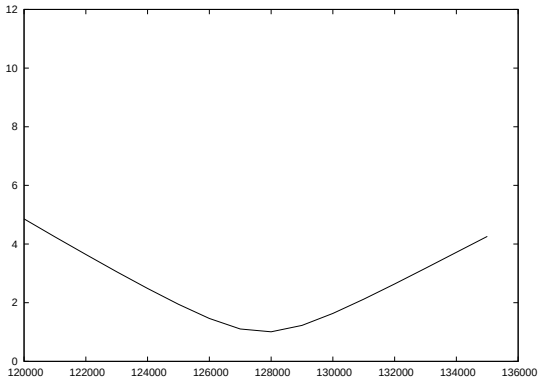
With 10 Ohms of series resistance:

f (Hz)	Ztotal (Ohms)
120000	11.0723
121000	10.8178
122000	10.5961
123000	10.4085
124000	10.2557
125000	10.1384
126000	10.0568
127000	10.0111
128000	10.0007
129000	10.0251
130000	10.083
131000	10.1733
132000	10.2943
133000	10.4443
134000	10.6215
135000	10.8238



With 1 Ohm of series resistance:

f (Hz)	Ztotal (Ohms)
120000	4.85753
121000	4.24547
122000	3.6439
123000	3.05556
124000	2.48578
125000	1.94591
126000	1.46292
127000	1.1054
128000	1.00728
129000	1.22544
130000	1.63316
131000	2.12034
132000	2.64061
133000	3.17552
134000	3.71693
135000	4.26081



Both networks achieve minimum impedance at the same frequency of 127.795 kHz, but the one with greater Q exhibits a much greater impedance *variation* over the same frequency range.

It is also possible to alter Q simply by adjusting L and C values without changing R. Consider the following test, where we increase X_L and X_C by equal measure at resonance by boosting L ten times and shrinking C ten times, achieving the same resonant frequency but with a greater Q due to reactance alone. Making L ten times larger and C ten times smaller results in the same resonant frequency of 127.795 kHz but at greater reactance values, therefore overshadowing the same 10 Ohms of resistance to a greater degree. Note that both graphs have vertical axes scaled from 0 to 49 Ohms, rather than 0 to 12 Ohms as before:

Original network with 47 μH and 33 nF:

```
f (Hz) , Ztotal (Ohms)
120000 , 11.0723
121000 , 10.8178
122000 , 10.5961
123000 , 10.4085
124000 , 10.2557
125000 , 10.1384
126000 , 10.0568
127000 , 10.0111
128000 , 10.0007
129000 , 10.0251
130000 , 10.083
131000 , 10.1733
132000 , 10.2943
133000 , 10.4443
134000 , 10.6215
135000 , 10.8238
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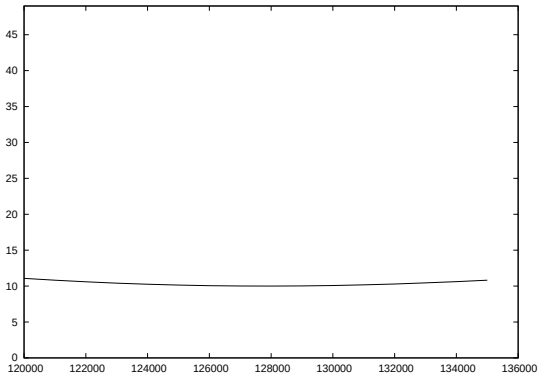
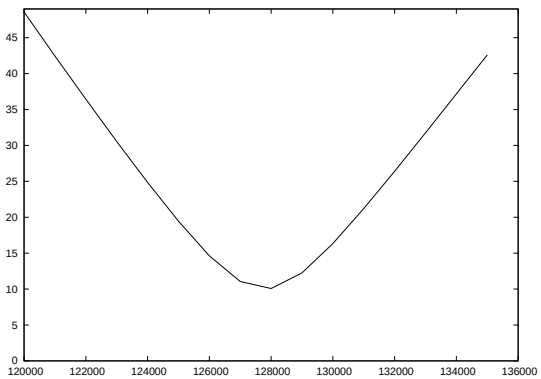


New network with 470 μH and 3.3 nF:

```
f (Hz) , Ztotal (Ohms)
120000 , 48.5752
121000 , 42.4547
122000 , 36.439
123000 , 30.5556
124000 , 24.8578
125000 , 19.4591
126000 , 14.6292
127000 , 11.054
128000 , 10.0728
129000 , 12.2544
130000 , 16.3316
131000 , 21.2034
132000 , 26.4061
133000 , 31.7552
134000 , 37.1693
135000 , 42.6081
```



Both networks still achieve the exact same minimum impedance of 10 Ohms at 127.795 kHz, but the one with greater Q stemming from more reactance clearly exhibits a greater impedance *variation* over the same frequency range.

The term *quality* factor implies greater Q values are better than lower Q values, but this depends actually on the intended application. Here are some different scenarios, and how quality factor affects each:

- For oscillator circuits where the resonant frequency of an LC tank network determines the stability of the circuit's operating frequency, a higher Q value means a frequency value that is less likely to drift as other circuit parameters vary, and this is generally a good thing.
- For filter circuits where the resonant frequency of an LC network determines which signal frequencies get blocked versus which are able to pass through the circuit, a high-Q LC network means a "sharper" response, screening a narrower band of frequency values. If we wish our filter to screen frequencies as specifically as possible, then a high Q factor is good.
- If we wish an LC network's oscillations to dampen quickly to zero rather than go on and on over time, then a lower Q value is better than a higher Q value. This is due to the fact that lower quality factor means more energy being dissipated from the network as opposed to being exchanged back and forth between the inductor and the capacitor.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

4.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

4.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Conservation of Energy

Electric field

Magnetic field

Capacitance

Inductance

Dielectric

Electrical source

Electrical load

"Ohm's Law" for capacitance

"Ohm's Law" for inductance

Potential energy

Kinetic energy

Resonance

Parasitic effect

Phasor

Phase angle

Properties of series circuits

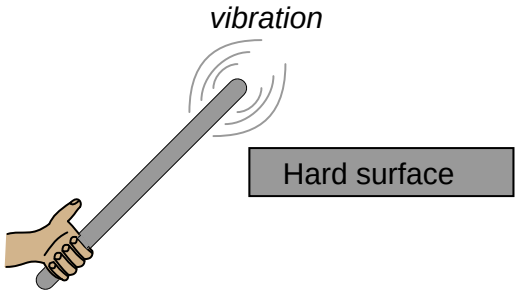
Properties of parallel circuits

Kirchhoff's Voltage Law

Kirchhoff's Current Law

4.1.3 Ringing metal bar

If you strike a metal bar against a hard surface, the bar will "ring" with a characteristic frequency. This is the fundamental principle upon which musical *tuning forks* work:



The ability of any physical object to "ring" like this after being struck is dependent upon two complementary properties: *mass* and *elasticity*. An object must possess both mass and a certain amount of "springiness" in order to physically resonate.

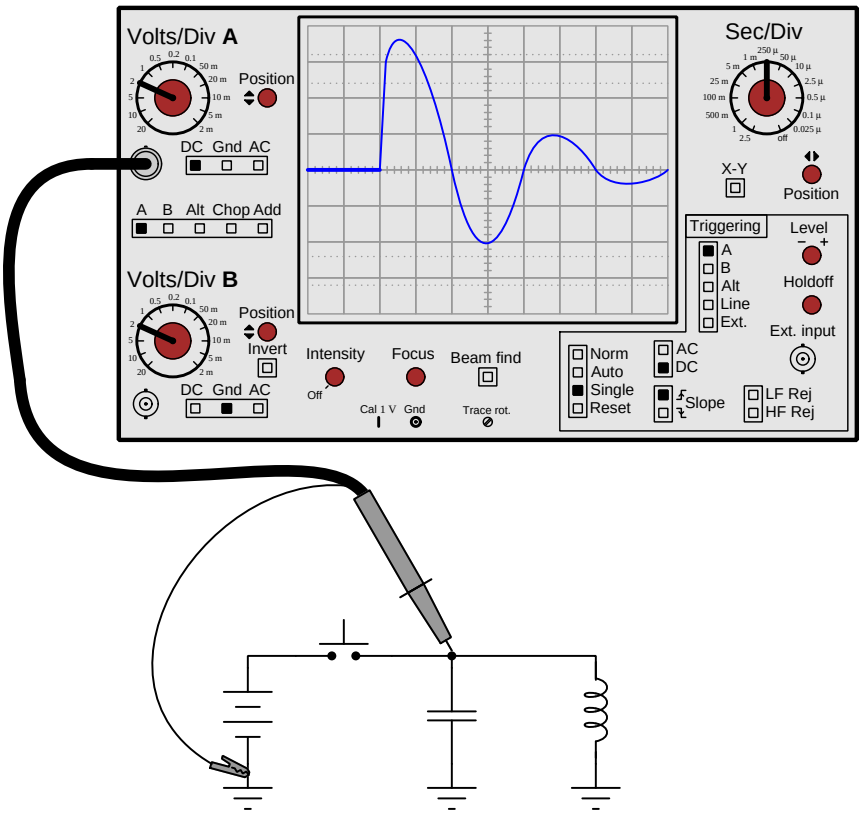
Describe what would happen to the resonant frequency of a metal bar if it were made of a more elastic (less "stiff") metal? What would happen to the resonant frequency if an extra amount of mass were added to the end being struck?

Challenges

- Suppose you wished to make a wind chime out of metal bars. How would you "tune" the pitch of each bar to make them sound harmonious together?

4.1.4 Resonant pulse circuit

If an oscilloscope is set up for "single-sweep" triggering and connected to a DC-excited resonant circuit such as the one shown in the following schematic, the resulting oscillation will last just a short time (after momentarily pressing and releasing the pushbutton switch):



Explain why the oscillations die out, rather than go on forever.

What factor(s) dictate(s) the frequency of these oscillations?

Challenges

- Explain how you might be able to modify the circuit to make the oscillations of this exact same circuit persist for a longer period of time.
- Explain how you could modify the circuit to include a 555 timer repeatedly re-energizing this circuit to sustain oscillations indefinitely.

4.1.5 Tank circuit frequency adjustments

Identify more than one way to increase the resonant frequency of a *tank circuit*.

Challenges

- Identify how your proposed alterations would affect the amount of energy stored in the tank circuit.

4.1.6 Parasitic properties

Not only do reactive components unavoidably possess some parasitic ("stray") resistance, but they also exhibit parasitic reactance of the *opposite* kind. For instance, inductors are bound to have a small amount of capacitance built-in, and capacitors are bound to have a small amount of inductance built-in. These effects are not intentional, but they exist anyway.

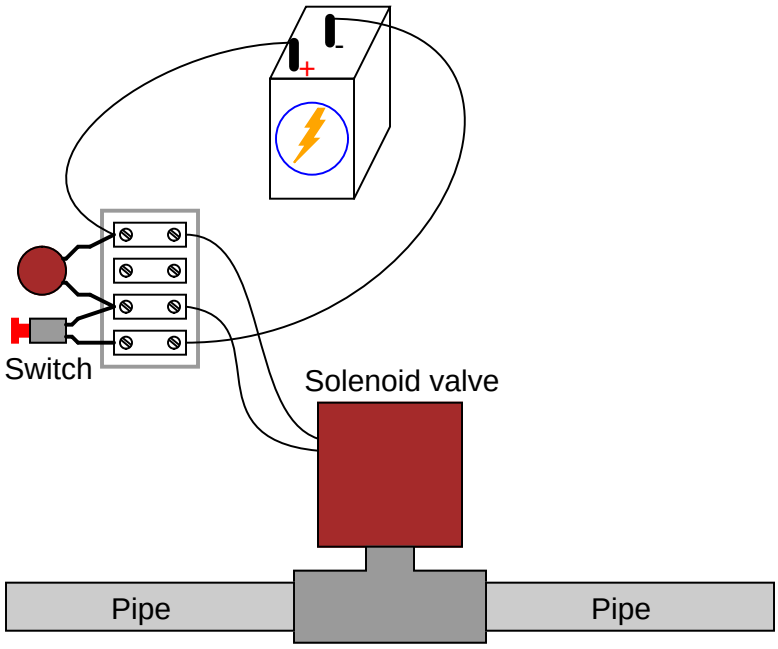
Describe how a small amount of capacitance comes to exist within an inductor, and how a small amount of inductance comes to exist within a capacitor. Explain what it is about the construction of these two reactive components that allows the existence of "opposite" characteristics.

Challenges

- The lengths of leads for through-hole components soldered into printed-circuit boards affects parasitic properties. Explain how.

4.1.7 Anti-arcing capacitor

A capacitor has been connected in parallel with the solenoid coil to minimize arcing of the switch contacts when opened:



The only problem with this solution is, resonance between the capacitor and the solenoid coil's inductance is causing an oscillating voltage (commonly known as *ringing*) to appear across the terminals of each. This high-frequency "ringing" is generating bursts of radio interference whenever the switch contacts open. Radio interference is not good.

You know that the underlying cause of this "ringing" is resonance, yet you cannot simply remove the capacitor from the circuit because you know that will result in decreased operating life for the switch contacts, as the solenoid's inductive "kickback" will cause excessive arcing. How do you overcome this problem without creating another problem?

Challenges

- Other than shortening the life of the switch, what other undesirable effects can switch "arcing" have? Can you think of any scenarios where an arcing switch could pose a safety hazard?

4.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

4.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

4.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

4.2.3 Series LC impedance

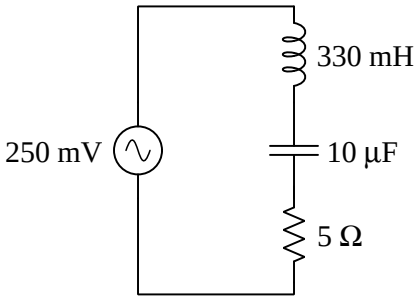
If a capacitor and an inductor are connected in series, and energized by an AC voltage source with such a frequency that the reactances of each component are 125 Ω and 170 Ω, respectively, how much total impedance will this series network exhibit?

Challenges

- Would source frequency need to be increased or decreased to achieve resonance in this circuit?

4.2.4 Series LC circuit calculations

Calculate all voltage drops and the source current in this LC circuit at each of the given frequencies:



- $f = 50$ Hz ;
- $f = 60$ Hz ;
- $f = 70$ Hz ;
- $f = 80$ Hz ;
- $f = 90$ Hz ;
- $f = 100$ Hz ;

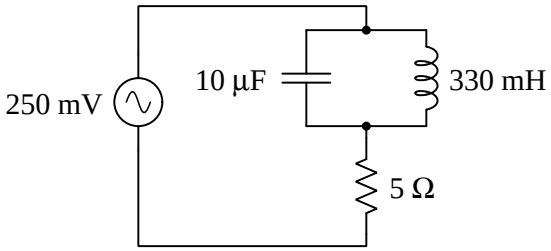
Also, calculate the resonant frequency of this circuit as well as the component voltages and current at this resonant frequency.

Challenges

- How would the operation of this circuit be affected if the resistor had more resistance than it does now?

4.2.5 Parallel LC circuit calculations

Calculate all currents in this LC circuit at each of the given frequencies:



- $f = 50$ Hz ;
- $f = 60$ Hz ;
- $f = 70$ Hz ;
- $f = 80$ Hz ;
- $f = 90$ Hz ;
- $f = 100$ Hz ;

Also, calculate the resonant frequency of this circuit.

Challenges

- How would the operation of this circuit be affected if the resistor had more resistance than it does now?

4.2.6 Deriving the resonant frequency equation

Resonance occurs in a simple inductor-capacitor circuit when the frequency is such that the reactance values of the inductor and capacitor become equal. From this knowledge, develop a single equation solving for this resonant frequency value (f) in terms of L and C.

Challenges

- If C doubles, will f_r double, be cut in half, or change by some other factor?

4.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

4.3.1 Effects of faults in a series resonant circuit

Predict the effects of the following faults on the resonant frequency of a series RLC circuit:

- Inductor fails partially shorted (i.e. some turns of its windings become bypassed)
- Resistor fails partially shorted (i.e. less resistance than it should have)
- Source voltage "sags" due to fault in AC power supply
- Capacitor fails shorted

Challenges

- Which of these faults do you consider most likely to actually occur?

4.3.2 Find the mistake(s)

A student tries to calculate total impedance in a series RLC network, and has the following work to show for their efforts:

$$2\pi \times 75 \times 0.1 = 47.124$$

$$\frac{1}{2\pi \times 75 \times 22 \times 10^{-6}} = 96.457$$

$$47.124 + 96.457 = 143.581$$

$$143.581 + 330 = 473.581$$

Identify the f, R, L, and C values given to this student, identify the mistake(s) in these calculations, and then properly calculate total impedance.

Challenges

- This type of conceptual error is extremely common among new students of electricity and electronics. Describe how you would correct this misconception if you saw someone making the same mistakes.

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

17 February 2026 – corrected a typographical error in a Challenge question, courtesy of Wyatt Gleason.

9 December 2025 – added a new Case Tutorial section showing an extremely low-frequency LC resonant circuit, the experiment done by Wyatt Gleason.

30 November 2025 – minor edit to the Tutorial section on quality factor, regarding the different Q values for networks containing the same R value but different L and C values.

5 August 2025 – added a new section to the Tutorial chapter on quality factor (Q), and also added some references to Q in the Introduction chapter.

30 September 2024 – added content to the Introduction chapter.

10 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

12 February 2024 – added questions to the Introduction chapter.

9-13 February 2023 – minor edits to the Tutorial text and to instructor notes.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

1 July 2022 – edited the Tutorial's explanation of "parasitic" properties to be more general and less specific to resonance.

17 April 2022 – added a new section to the Tutorial explaining the phenomena of series and

parallel resonance in terms of energy exchange, sources and loads, and series versus parallel network properties.

18 October 2021 – divided Tutorial into sections.

8 May 2021 – commented out or deleted empty chapters.

15 February 2021 – additions to the Introduction chapter.

5 November 2020 – minor addition to an instructor note.

25 October 2020 – added a Case Tutorial chapter, with a section showing the measurement of inductance of three transformer windings using series resonance.

13 October 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

9 April 2020 – clarified that the RLC network in the "Find the mistake(s)" Diagnostic Reasoning problem was supposed to be a *series* network.

14 March 2020 – finished Foundational Concepts section.

12 March 2020 – finished writing Tutorial, added problems.

11 March 2020 – document first created.

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