HPHY 3300 Medical Electronics

Spring Semester Class Time: Friday 9:00 - 10:50

Place: TBD

Text: Steward C. Bushong;

<u>Radiologic Science for Technologists, Physics, Biology, and Protection</u>

(use latest edition)

Instructor: Richard R. Brey Ph.D., C.H.P., Chair Dept. Nuclear Engineering and Health Physics

Interim Dean, College of Science and Engineering

Office: CH 234 Telephone: 208-282-4539

Office Hours: Monday through Thursday 10:00 to 11:00 or by appointment. Informal open door policy.

Course Description:

PHYS 3300 Radiologic Physics (2 credits) A lecture-laboratory course covering circuit theory, qualitative theory of active devices and their application to instrumentation. Computer simulations will be done to investigate basic instruments. Primarily for students in the allied health fields.

COREQ: HPHY 3321. S

Tentative Course Schedule

TOPIC

READINGS

(Bushong)

Grading Policy, Testing Format, Homework Policy, Expectations.

Basic Electronics

Electricity

Resistance Series and Parallel Circuits

Class

Notes

Test 1

Magnetism

Electromagnetism

Test 2

The X-ray imaging System

The X-ray Tube

Computer Laboratory Exercisers

Inductive and Capacitive AC and DC Circuits

Killing people with electricity

Test 3 (Cumulative Final) ____________________

HPHY-300 Class Policy

1) Homework will represent 30% of the overall class grade.

a) Homework should be expected frequently.

i) Students are encouraged to work together on homework.

ii) Homework problems can and may be the basis for test questions.

iii) Homework assignments are not considered to be group projects.

* Each student should do their own work, merely consulting with others as appropriate.

- A photocopy of the work of someone else is not acceptable.

** The instructor is a resource during office hours or by appointment.

b) All homework assignments must be completed.

i) Students who don't complete all homework assignments can expect an incomplete grade in the course at the discretion of the instructor.

c) Questions completed correctly will be awarded an appropriate number of points.

Assignments will typically include several multi-part questions or inter-related questions.

* Students are encouraged to write out the assigned questions.

* All work is to be shown.

* The student is encouraged to carry units along with the solution of the problem, and provide a neat easy to follow answer.

- homework which is too difficult to follow will be returned with a zero grade until completed in an acceptable fashion.

* Answers must be given with the appropriate units.

* All answers are to be circled.

2) There will be two full lecture period tests and a cumulative final examination.

a) Tests will cover topics on homework, lectures, and assigned reading.

b) Each test will be worth 20% of the final class grade.

c) The cumulative final examination will be worth 30% of the final class grade.

d) At the discretion of the instructor, any evidence of dishonesty are grounds for failing tests or examinations, and subject to other university disciplinary actions.

3) Final Class grade

a) Grades will be based on:

Homework	30%
Tests	40%
Final	30%

b) Tentatively, grades will be earned based on a straight scale grading policy:

≥ 97% .... +A
≥ 93% .... A
≥ 90% .... –A
≥ 87% .... +B
≥ 83% .... B
≥ 80% .... –B
≥ 77% .... +C
≥ 73% C
≥ 70% .... –C
≥ 67% .... +D
≥ 63% .... D
≥ 60% .... –D
< 60% .... F

c) The instructor reserves the right to change the grading scale, and assignment weighing. Such changes will be:

i) based on profession judgement
ii) applied across the board to all students
iii) in favor of the students

4) Reading assignments should be completed prior to lecture.

a) Students are encouraged to apply the SQ3R study method.

SQ3R:

Survey the literature

Develop **Q**uestions prior to reading and based on the survey

Read the material answering your own questions

Recite what was read

periodically **R**eview the material

6) Lectures:

a) Bring pertinent questions on the literature, personal experiences, and current affairs, which do not have self-evident answers, to lecture.

b) Students can expect to be asked questions about the topics at hand while attending lecture so please be prepared.

i) This lecture style is intended to build student confidence.

- It is not intended to embarrass, intimidate, or belittle, students. It is okay not to have an answer, but not okay to leave it at that.

c) Take advantage of the opportunities available - You have paid for them!

Idaho State University is committed to providing equal opportunity in education for all students. If you have a diagnosed disability or if you believe you have a disability physical, learning, hearing, vision, psychiatric) that might require reasonable accommodation in this course, please contact the Disability Services Center, Rendezvous Building, Room 125 (282-3599) or on the web at http://www.isu.edu/ada4isu. It is the responsibility of students to contact instructors during the first week of each semester to discuss appropriate accommodations.

Academic integrity is expected of all individuals. Behavior beyond reproach must be the norm. Academic dishonesty in any form is unacceptable. Academic dishonesty includes, but is not limited to, cheating and plagiarism. Procedures for determination of academic dishonesty and imposition of penalties for academic misconduct are outlined in the Student Code of Conduct:

Basic Electronics

A. Electricity:

1. In a general sense any device which converts one form of energy into another may be referred to as a transducer.

2. A radiographic x-ray unit fits this description because it converts electrical energy into electromagnetic energy.

3. Usually a study of electricity starts with a description of electrostatics.

    a. This is simply the study of stationary electrical charge.

4. To begin, we know that electrons are said to have a unit negative charge while protons have a unit positive charge.

    a. The unit quantity of charge is measured with a special unit called a coulomb.

    b. One electron has a charge of **1.6×10^{-19} coulombs**

    c. At the risk of confusion this statement may be inverted: One may say that one coulomb is equivalent to 6.25×10^{18} electron charges.

    d. The unit negative charge associated with just one electron is very small. This is why in practice we must use a unit that is so large representing so many individual charge carrying units.

If an object has 400 coulombs of charge how many excess electrons would this electrified object demonstrate?
Since the charge of **one electron = $1.6\text{x}10^{-19}$ coulombs** than

(400 coulombs)(one electron/$1.6\text{x}10^{-19}$ coulombs) = $2.5\text{x}10^{21}$ electrons

5. Do charges move?

a. We know that protons exist in the nucleus of the atom. Protons are stationary objects, in that they are not exchanged between objects that are in contact. The same is not true for electrons.

b. We know that electrons move about the nucleus of an atom at particular energy levels.

i. The mobility of electron about the atom is important. Within some structures this mobility may be extended beyond individual atoms to mobility among groups of atoms in a structural unit.

- The total number of negative charges and positive charges in the universe is equal.

- Matter is electrically neutral. This state of neutrality may be changed if some action is taken on a local scale (within an object) to redistribute the population of electrons.

ii. An object may be said to be electrified if either a net surplus or deficit of electrons. Something that is electrified will have an electric charge.

- Probably all of us have experienced the electrical charges and properties associated with static electricity.

  + Object may become electrified by:

    * the action of friction- rubbing objects together sometimes causes the build-up of electrons in an object.

    * the process of induction - It is possible for the electric field of a charged object to confer charge on another nearby object.

    * the process of conduction - It is possible for the charge of one object in contact with another object to be transferred between the two objects.

6. When an electrified object is brought into contact with a neutral object, there is a tendency for the electrified object to transfer its charge to the neutral object.

a. When considering objects that are electrified due to excessive negative charge, a negative charge is transferred from the electrified object to the neutral object.

b. When considering objects that are electrified due to excessive positive charge, a negative charge is transferred from the neutral object to the electrified object.

Consider lightning: Charges are transferred from cloud to cloud, from cloud to ground, and yes from ground to cloud!

7. Not all objects conduct the flow electrons in exactly the same way.

a. Some objects called conductors allow electrons to easily flow through them.

b. Objects called insulators inhibit the flow electrons.

c. A semi-conductor is an object that under some conditions behaves as a conductor and in other conditions behaves as an insulator.

i. Important semiconductor materials are germanium (Ge) and silicon (Si)
These materials and their properties were used to construct transistors.

8. One neutral object always available to accept electrical charge from an electrified object is the earth.

a. When used in this capacity the earth may be called an <u>electrical ground</u>.

b. In a more general sense, electrical ground is that point in a system which has the capacity to continuously accept charge without noticeable change.

9. There are several important electrostatic principles:

a. When an object is electrified the, the electric charges are distributed throughout the surface of the object.

b. There is a tendency for electric charges to concentrate along the sharpest curvature of the surface of an object.

c. Like charges repel one another

d. Unlike charges attract one another (Opposites attract)

10. The <u>force</u> of repulsion or attraction can be predicted using **<u>Coulomb's Law</u>**:

$$\text{Force} = F = k(q_1 q_2)/r^2$$

<u>where:</u>

F = force: in the MKS system the unit of force is the newton, in the cgs system the unit of force is the dyne.

k = a conversion constant. The value of k depends on the units one chooses to use to express force. When using cgs units the appropriate value of k is 1.0. When using MKS units the appropriate unit of k is:

<u>8.987590×10^9 N-m²/C²</u>

q_1 and q_2 = the charges of two units acting upon one another.

When using the MKS system the unit coulomb is used. The unit coulomb is often abbreviated by the capital letter "C".

If one uses the cgs system the unit referred to as an *esu* or electro static unit (or alternately statcoulombs) is used. For your reference:

1 esu = 3.336×10^{-10} coulombs

r = the distance between the two objects. In cgs units this is expressed in centimeters. While using MKS units this expressed in meters.

11. Potential energy is stored energy

    a. Potential energy has the ability to do work.

    b. an electrical charge represents a form of potential energy.

        i. Remember that work is the application of force across a distance:

        Work = W =Fd

    c. The unit for electric potential energy – electric potential is the **volt**.

        i. Sometimes electric potential is termed the electromagnetic force (EMF)

12. Electrodynamics is the study of electric charge in motion.

a. Electric charge in motion summarizes the concept of electricity.

13. If an electric potential is applied across a conductor it will cause electric charges to move along the wire.

a. The movement of electrons is called electric current.

b. electric current is measured in units called amperes (A) - (often shortened to just amp or amps).

i. The unit ampere is defined as a coulomb of charge per second.

c. <u>by convention</u> *the direction of electric current is always said to be opposite that of electron flow.*

14. When electrons are moving in a system they will experience some degree of resistance to their movement.

a. We measure electrical resistance in units called ohms which are represented by the Greek letter omega (Ω)

15. The relationship between potential energy (voltage), current (amperes) and resistence (ohms) in an electrical circuit is described using <u>Ohms Law</u>:

$V = I\ R$

V = voltage expressed in volts
I = current expressed in amperes
R = resistance in ohms

Example:

16. When describing electrical circuits one usually draws an electrical_ schematic. This special type of drawing used a set of standard symbols to represent various possible aspects of an electrical circuit.

Resistor	Inhibits the flow of electrons offers resistance
Battery	Provides electrical potential
Capacitor	Temporarily stores electrical charge
Ammeter	Measures electric current
Voltmeter	Measures electric potential
Switch	Opens or closes a path for conduction of electrons
Transformer	Increases or decreases voltage by a fixed amount
Rheostat	A variable resistor
Diode	A device which allows electrons to flow in only one direction
Transistor	An electronic switch that can also amplify an electrical signal

There are others...........

17. There are two basic kinds of electrical circuits:

a. Series circuits: all circuit elements are connected in a line along the same conductor.

b. Parallel circuits: circuit elements bridge conductors rather than lie in a line along conductors.

18. The way components of an electrical circuit behave greatly depends on the type of circuit they experience.

Example Series circuit drawing

Example parallel circuit drawing

19. Series circuits

a. Resistance is directly additive in a series circuit.

$$R_T = R_1 + R_2 + R_3 + R_4 + \ldots + R_i + \ldots + R_n$$

A short hand way to write this same expression is:

b. Current through a series circuit is constant.

c. The total voltage (or potential) in a series circuit is equal to the sum of voltages *across* each circuit element.

Examples:

20. Parallel Circuits

a. The total resistance in a series circuit is inversely proportional to the sum of the reciprocals of each individual resistance.

$$1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + ... + 1/R_i + ... + 1/R_n$$

A short hand way to write this same expression is:

b. The total current in a parallel circuit is equal to the sum of the values of current *across* each circuit element.

c. Voltage through a series circuit is constant.

Examples:

21. Direct and Alternating Current

a. Electric current is simply the flow of electrons along a conductor.

b. Electric current is supplied in two different ways; direct current or alternating current.

c. Current flow one-way along the conductor of direct current.

i. A constant potential is expected in direct current applications.

d. Current oscillates in direction along the conductor of alternating current.

i. Domestic and commercial electricity in the United States is supplied as alternating current.

ii. This alternating current continuously alternates from positive to negative and back again.

- Each alternation from positive to negative is called a cycle.
- 60 cycles occur each second. A cycle per second is called a hertz abbreviated hz). Obviously, 60 times each second a wire is positive and 60 times a second it is negative. 120 times a second there is neither current nor voltage.
- hence this 60 cycles/second is referred to as 60-hertz current.
- When plotted this oscillating current would appear as a sine wave.
  + Each complete sine wave takes place in 1/60 of a second.
- Voltage oscillates along with current. Voltage alternates from zero up to +120V back to zero and then to -120V and then back to zero.
- This is referred to as single phase current.

Why don't incandescent lights flicker on and off if the potential voltage and current that powers them is oscillating from zero to a maximum value so frequently?

iii. What about three-phase current.

- Remember, if 120-volt 60-hz current flows in a pair of wires, 120 times every second the wires are dead. There is no voltage at all 120 times every second.

-You may imagine that three-phase current is like three single-phase lines operating in one. Or you may imagine three separate generators on the same shaft positioned at 120° relative to one another. The maximum potential is reached by each generator at different times.

22. Electric power is measured in watts.

a. Remember, Force=Mass x acceleration (F=Ma). Force applied over a distance is work (W = Fd =Mad). Work divided by time is power (W/t =P).

Consider the units:

$F = Ma = kg\text{-}m/s^2$
$W = Mad = kg\text{-}m^2/s^2 = J$
$P = Mad/t = kg\text{-}m^2/s^3 = J/s = watt = w$

b. When describing electrical power(P) we use the expression:

$P =(I)(V)$ ---- units (volts)(amps) = watts

Since V=(I)(R) - ohms law - then substituting this into the expression for power we can see that:

$P = (I)(I)(R) = I^2R$

Examples: If a transducer of some sort uses 40 Amps with 120 volts supplied how much power does it consume?

$P = (I)(V) = (40 \text{ amps})(120 \text{ V}) = 480$ watts

If the resistance of an electrical load is measured to be $2x10^6$ ohms and if a 70-volt potential exists across this load how much current does the load require? How much power does the load consume?

How much current -

$V = IR$ so $V/R = I$

hence $(70 \text{ V})/(2x10^6\Omega) = 3.5x10^{-5} \text{ A} = 35\mu\text{A}$

How much power -

$P = I^2R = (3.5x10^{-5} \text{ A})^2(2x10^6\Omega) = 2.45x10^{-3}$ watts

c. Electricity is sold by the kilowatt-hour (kW-h) used each month.

- how much do you your parents pay per kW-h?
- If you pay $0.06 per kW-h how much does running a 1.2kW x-ray unit cost monthly?

Power consumed:

$(1.2x10^3\text{W})(40\text{h/week})(4 \text{ weeks/month})(\text{kW}/1000\text{W}) = 192$ kW-h/month

Cost:

(192 kW-h/month)($0.06/kW-h) =$11.52/month

B. Magnetism

1) Magnetism has been exploited for centuries.

a. The first magnets were created from magnetite ore and were used as primitive compasses often referred to as loadstones.

b. We describe three different sources of magnetic materials based upon the origin of the magnetic properties:

i. Natural magnetic material such as magnetite.
ii. Artificial magnets - or artificially induced permanent magnets;
These are created when ferromagnetic material is exposed to a strong magnetic field or more simply if a steel bar were rubbed against a natural magnet.

iii. Electromagnets- these are obtained by running an electric current through a coil of conducting wire wrapped around an iron core.

c. We can describe different materials by the way they are affected by magnetic fields:

i. Ferromagnetic- strongly influenced by magnetic fields and can be magnetized.
ii. diamagnetic - Material not affected by magnetic fields
iii. Paramagnetic- slightly influenced by magnets (important paramagnetic materials are the contrast agents used in NMRI)

d. Magnet lines of force can be demonstrated to exist with a magnet and iron filings.

i. By convention magnetic lines of force from the north pole to the south of a magnet.

e. The earth itself demonstrates weak magnetism, this is taken advantage of when using a navigational compass.

i. The magnetic lines of force for the earth seem to run counter to convention when lines of force are drawn for simple magnets.

f. There are two units commonly used to measure magnetic field strength: The Gauss(G) and the Tesla(T)

i. 1.0 Tesla (T) = 10,000 Gauss (G)

ii. The strength of the earth's magnetic field varies from about 50μT at the equator to about 100 μT at the poles.

C. Electricity and Magnetism or Electromagnetism are different aspects of the same fundamental force of nature; the electromagnetic force.

a. The common battery is an example of a source of electromagnetic force.

i. As it happens, when two different metals are brought into contact with
one another a small electric current will flow between them.

ii. Zinc and copper plates are arranged into a voltaic pile. Each set of zinc-and copper in the pile are referred to as a cell of the battery.

iii. Batteries were the first practical way to sustain a current in an electric circuit.

b. Electric magnetic force has the units of Joules/coulomb (J/C) or volts.

c. As an electric current passes through a wire it induces a magnetic field.

i. Such an electric field would appear as concentric lines of force centered on the wire.

ii. The direction of these lines can be determined using the so called right-hand-rule.

- In the right hand rule, the thumb of an individual's right hand is pointed in the direction of the current along a conductor. The individual's fingers in this situation will curl in the direction of the magnetic field lines.

iii. Wrapping a wire in a circular loop creates a geometry of magnetic field lines that overlap. The resulting magnetic field may become very strong. A coil of wire is this type of arrangement may be referred to as a solenoid.

- Placing a ferromagnetic material in the center of the coil of wire further concentrates the magnetic field strength. An electromagnet is a ferromagnetic material wrapped in a coil of wire.

d. We have stated that a magnetic field can be induced by a moving current, it turns out that a moving magnetic field can alternately induce the movement of electrons in a circuit.

i. The changing magnetic field can be experienced by:

- moving a magnet past a conductor
- moving a conductor past a magnet
- by increasing or decreasing the current in an electromagnet near a conductor.

ii. The magnitude of the induced current depends on:

- the strength of the magnetic field
- the velocity of the magnetic field as it moves past the conductor
- the angel of the conductor to the magnetic field
- the number of turns in the conductor

iii. The induced current in a circuit flows in a direction that opposes the action which initially induced the current.

e. There are two basic types of induction: self-induction and mutual induction.

i. The induction of an opposing EMF in a single coil by its own changing magnetic field is called self-induction.

- self-induction occurs in a coil when an alternating current is applied to the coil.

ii. An electric current is expected in a coil that is experiencing a changing magnetic field. If the coil is part of an electromagnet to which an alternating current is applied, we expect the creation of a varying magnetic field.

- If we place a second coil near the first (or primary coil) we expect that the varying magnetic field will induce an electric current - and subsequent magnetic field into the second (or secondary coil).

iii. The process of inducing a current in a secondary coil by passing a varying current through a primary coil is called mutual induction.

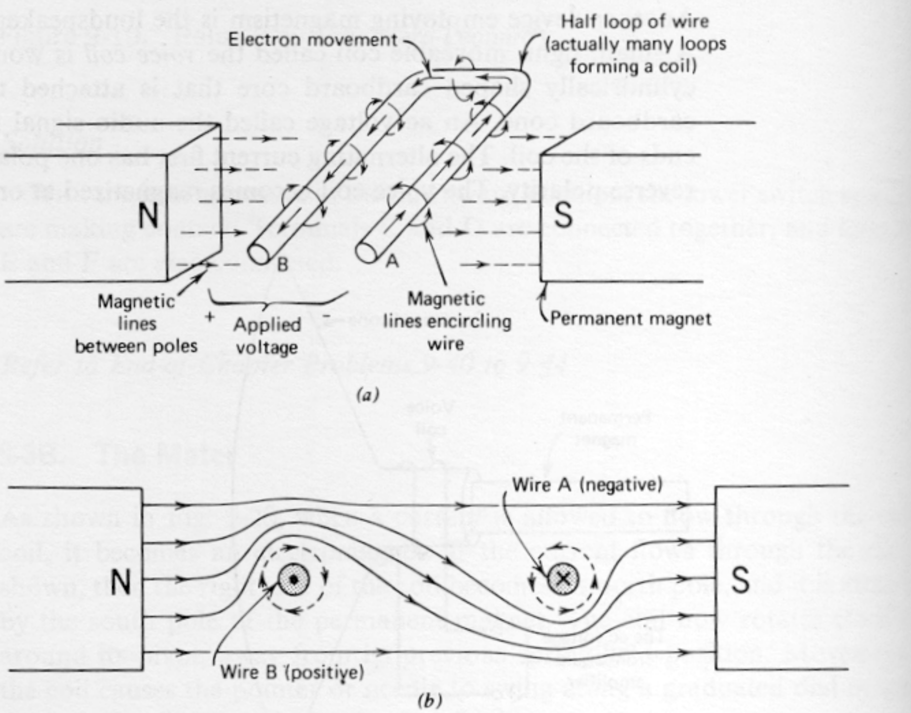


Figure 9-22. Electric motor principle. (*b*) End view of wires *A* and *B* of loop, with their encircling fields. Electrons flowing into *A* (going away from viewer), and out of *B* (coming toward viewer). *A* moves up; *B* moves down.

f. An electric generator takes advantage of induction.

i. The simplest electrical generator can be created by mechanically rotating an electric coil that is positioned the north end and south end of bar magnets.

- the induced current in this coil will oscillate between negative and positive and from its maximum to minimum magnitude as the coil is rotated, and the position or orientation of the wires of the coil are changed with respect to the orientation of the magnetic field of the magnets.

- a direct current generator can be developed in the same way with the addition of a simple device called a commutator ring. The direct current generator's current varies from a maximum to zero potential as the coil rotates within the magnetic field of the magnets but its polarity <u>does not</u> oscillate from negative to positive and back to negative.

- The commutator ring acts as a switch changing the polarity of the contact on the coil at the exact moments when due to its position in the magnetic field the flow of electrons would change direction.

- Electrical generators are examples of traducers as they change mechanical energy (rotation of the coil) into electrical energy.

g. Another type of transducer is an electric motor. An electrical motor converts electrical energy into mechanical energy.

- Imagine the same set up we discussed for the electric generator. A coil of wire is positioned between the north pole and south pole of two bar magnets. An alternating electric-current is connected to the coil. We expect in this situation that the magnetic field of the conductor will either:

+ Be attracted to the external magnets-magnetic field or

+ Be repulsed by the external magnets-magnetic field.

Whatever the case the result is that the conductor will be pushed or pulled by the influence of the two interacting magnetic fields. This causes the motor to spin.

- when describing electric motors, the coil is generally referred to as the armature.
  + A particular type of electric motor commonly used in x-ray tubes is called an induction motor.

  + The armature of an induction motor is called a rotor. The external magnetic field of an induction motor is supplied by a series of stationary electromagnets referred to as stators.

  + No current is supplied to the rotor of an induction magnet, instead an induced field is created in the rotor by the oscillating the sequential current sent through the electromagnets.

  + The induced current creates a magnetic field that is influenced by the magnetic field of the stators- the interaction of these fields results in motion of the rotor.

D. Transformers

a. An electrical transformer changes the magnitude of a magnetic field or of an electric current.

i. The action of a transformer depends on mutual induction.

ii. The action of a transformer also is influenced when a magnetic material serves as the core for the coils of conducting wires comprising the transformer.

iii. Since transformers depend on a constantly changing magnetic field they are only important in alternating current applications. A transformer will not have an impact of a direct current is applied.

iv. When a transformer is used to change the magnitude of current and voltage in an AC circuit the change in magnitude possible is:

- directly proportional to the number of loops (or windings) in the secondary coil to the number of loops (or windings) in the primary coil.

v. The transformer relationships are as follows:

+ For Voltage:

Sometimes this is referred to as the autotransformer law.

+ For Current:

It may be seen by substitution that:

Where: V_s, I_s, and N_s are equal to properties of the secondary windings and V_p, I_p, and N_p are properties of the primary windings. N is the number of windings.

vi. What can observe that voltage and current our inversely proportional to one another. As current is doubled, voltage is halved.

vii. The ratio of N_s to N_p (i.e. N_s/N_p) implies some interesting items:

- the N_s/N_p ratio is known as the "turns ratio".
- if the turns ratio is greater than 1.0 we refer to the transformer as a step-up transformer as it will step up the voltage from the primary side to the secondary side. However, this type of transformer will decrease the current.

- if the turns ratio is less than 1.0 the transformer is called a step-down transformer as it will step down the voltage from the primary side to the secondary side. However, this type of transformer will increase the current.

- Like all such devices, a transformer is not 100% efficient during its manipulation of voltage and current. However, unless the transformer is malfunctioning, the transformer loss should be negligible. Transformer energy loss occurs as:

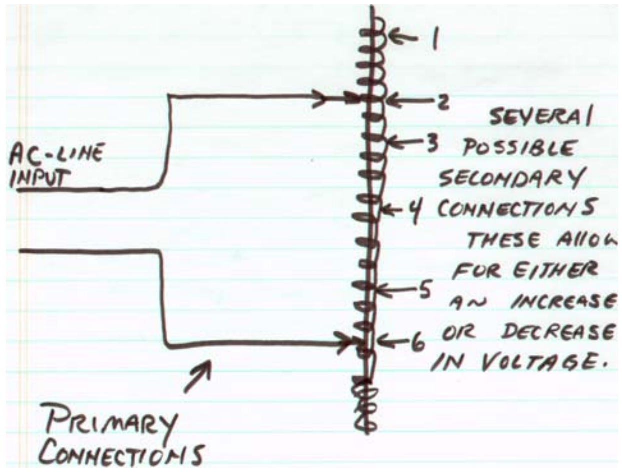
+ Heat generation due to the electrical resistance in the wires.
+ Hysteresis is associated with the alternate reversals of the magnetic field - this represents an energy loss.
+ Opposing magnetic fields are formed by induction -this opposition represents an energy loss.

- There are several different types of transformers:

+ Closed core transformer - these are usually rectangular or square build up from layers of laminated iron. Layering helps reduce heat loss associated with hysteresis.

+ Auto-transformers - this consists of an iron core with only one winding of wire. This transformer type depends on self-induction rather than mutual induction. These are implied only when small incremental changes in voltage or current or desired.

+ Shell type transformers - Are a transformer variation similar to the closed-core type. These, however, are much more economical with magnetic field lines and thus more efficient in providing vast increases in voltage or current. This type is the most common for high voltage applications and the most frequently applied to x-ray machines.



E. Rectifiers

a. A rectifier is a device which <u>converts</u> Alternating *current* to *Direct Current.*

- This is accomplished by allowing current to flow in only one direction.
- There are two common types of rectifiers:
  + Vacuum-tube rectifiers
  + Solid-state diodes

b. Vacuum tube rectifiers have two essential components a heated element cathode filament and an anode.

- due to heating, thermionic emission occurs at the filament.

-When a high positive potential relative to the cathode, is applied to the anode, electrons released due to the thermionic emission process will migrate across the vacuum tube to the anode.

- Should the relative potential be changed, since there is no heating or thermionic emission at the anode, no electrons would be available to travel in the opposite direction. In this way a vacuum tube diode allows current to flow in one direction only.

c. Solid-state rectifiers

- solid-state devices are composed from semi-conductor materials such as germanium.

  + Unlike conductors which readily allow the flow of electrons (e.g. electric current) or insulators which restrict electric current, semi-conductors conduct electric current under only certain conditions.

- semi-conductor materials are classified into two types:
  + n-type
  + p-type.

-n-type materials have loosely bound electrons which may easily migrate about the material.

-p-type materials have a deficit of electrons. It may be said, because there are a deficit of electrons, that p-type materials, have an abundance of "holes".

- both electrons and holes are mobile about semi-conductor materials.

- when n-type and p-type materials are placed in contact we refer to this arrangement as a p-n junction.

+ When a positive potential is applied to the p-side of the p-n junction electrons will tend to migrate from the n-type material across the junction as holes from the p-type material will tend to migrate toward the n-type material.

* This motion of charge carriers is an electrical current.

+ If a positive potential is applied to the n-side of the junction, referred to as a reverse bias application, electrons will tend to stay within the n-type material and holes will not migrate but stay in the p-type material.

* No current will flow under this circumstance. The p-n junction is referred to as a solid state diode. It only allows current to flow in one direction.

<u>Putting all the electronics together:</u>

A. From the operator's perspective there are three major aspects of the X-ray unit.

1. X-ray tube
2. The High Voltage Power supply
3. The control console

B. It is at the control console or operating console where the operator controls the x-ray tube current and voltage and consequently the characteristics of the radiation produced by the machine.

C. The current is directly related to the intensity of the beam. [the mA or mAs selection]

1. Frequently the intensity of the beam is expressed in mR/(s-mA) or just mR.
2. Your text book author relates this to the quantity of the beam.

D. The voltage controls the energy of the x-ray photons produced. [the kVp selection]

1. The energy of the photons are linked to their penetrating quality.
    a. The x-ray energy although continuously changing is usually described by using the peak voltage or maximum voltage possible i.e. the kVp.
    b. As an alternate to "a." above sometime people describe this using the HVL
2. Your text book author relates this to the quality of the beam.

<u>So How does this thing work?</u>

A. Enter Line power:
    1. A stable supply of line power is required.
        a. Problem: line power is not always stable.
            - The effect of instability is poor quality control.
            - What sort of things effect line power?

    2. Solution: line compensation
        a. Line compensation is the technique that controls the power used in the x-ray unit.

- This is done with high precision so good quality of product (radiographs) can be assured.
- Specifically, precisely controlled power is supplied to the filament circuit and the high voltage circuit.

b. Typically exactly 220 volts must be supplied to the system.
- on newer units this power regulation is automatic.
  +Newer units employ an auto transformer to achieve this necessity.
- on older units the operator monitors line power and compensates appropriately.

<u>About the auto transformer</u>:

A. Preposition A: It is much easier and safer to control low voltage than high voltage.

B. We know that the compensator and autotransformer supply a very controlled magnitude of power to ht ex-ray tube's high voltage transformer circuit.

1. Of course although the power is supplied at an exact magnitude this magnitude is variable - exactly.
   - We select a particular voltage and precisely obtain that voltage from the autotransformer.

C. Remember that an autotransformer has only one coil and operates on the principle of self-induction:

Consider the following example:

Notice how the secondary connections are physically made at different sections of the autotransformer coil.

These connections each correspond to a specific number of windings. Based on information about the number of windings we can increase or decrease the voltage. The magnitude of the voltage can be determined from:

Say that 220 volts are supplied by the AC-line (V_p = 220V). If the primary connections enclose 600 windings, what is the voltage experienced on the secondary side of the transformer under the following conditions.:

Secondary Side Connections:	# secondary windings:	Vs
60 to 2	600	220V(600/600) =220V
6 to 4	300	220V(300/600) =110V
6 to 1	700	220V(700/600) =257V

D. Some older systems use *effectively* two transformers instead of just one in order to supply high voltage to the x-ray tube.

1. In these situations the operator is confronted by a Major HV control and a minor HV control.

a. The minor control would control the output of the autotransformer typically within a range of 100 to 400V.

- This relatively low voltage becomes the input to the high voltage transformer which in turn supplies that high voltage required for the x-ray tube. "The kVp".

b. Notice how the term *effectively* was used above.

- It is reasonable to use the autotransformer to step up the "minor kVp" and then feed the output connection back into the autotransformer again using different secondary connections to further step up the potential (kVp).

- Very typically, however, a separate high voltage transformer is used instead of depending on the autotransformer for everything.

2. The kVp meter usually provides information about the potential that can be supplied by the arrangement of connections and transformers employed.

a. The potential exists without supplying x-rays.

- sometimes because of this, the kVp meter is referred to as a pre-reading voltmeter

<u>How about the filament circuit?</u>

A. The filament current is directly proportional to the x-ray tube intensity (i.e. the number of photons produced).

B. The more current surging through the filament - the hotter it becomes and the more thermionic emission occurs.

C. The more thermionic emission - the more electrons that are "released: in the x-ray tube that can experience the high voltage potential applied between the cathode filament and the target anode. (The kVp voltage).

D. The more electrons that are accelerated between the cathode and anode the more x-rays.

E. The higher the voltage across the filament and anode, the higher is the x-ray energy experienced.

F. Filament current is controlled through the filament circuit.

G. Voltage to power the filament circuit arises from the autotransformer.

1. The first step in the filament circuit is to reduce the voltage.

    a. This is achieved through precision resistors arranged in a series circuit.

        - this is the component adjusted when one adjusts the mA selector.

2. This potential is fed to the filament transformer.

    a. This is a step down transformer with the goal of obtaining a specific <u>current</u>.

        - this of course is the current supplied to the filament.

Notice how the voltage selected by using one of the several precision resistors determines the current output of the filament transformer.

3. Remember: $I_s/I_p = V_p/V_s$ and

$$V_p/V_s = N_p/N_s = I_s/I_p$$

example: Given a fixed turns ratio Ns:Np of 1:2 in the filament transformer, if 100 V is supplied to the primary side of the filament transformer, what will the secondary side experience:

$$V_s/V_p=N_s/N_p \qquad V_s=100V\,(1/2) = 50V$$

How about the current (The real important issue)?

Simply - $I_s = I_p(100V/50V)$.

4. The current may be measured with a milliamp meter (ammeter) in

the circuit or a mAs meter (milliamp-second meter).

a. Note how the base units of the amp are coulombs/second therefore:

(coulombs/second)(seconds) = coulombs or another words the total charge.

The key issue for a good radiograph is the number of photons reaching the image receptor.

A. The number of photons reaching the image receptor is related to:

1. The penetrability of "emergent" photons.

a. What is the effect of low energy on penetrability?

2. The filament current on the x-ray tube.

3. The time the tube is energized and allowed to produce x-rays.

B. Exposure time is therefore very important:

1. If a certain procedure requires 125 kVp and 75 mAs and you use a 100 mA selection, how much time must the exposure take?

75mAs/100mA = 0.75 seconds.

C. The timer circuit mechanically controls the high voltage across the x-ray tube.

D. There are five different types of timers used on x-ray systems:

1. Mechanical timers:

   a. A mechanical clock

   - often these lack accuracies

   - there considered to be good only for exposure times greater than 250mS in duration.

2. Synchronous timers:

   a. These are based on line frequency (usually 60hz in the United States or 50 hz in Europe).

   - the minimum exposure time form one of these units is 1/60 of a second or 17 mSeconds.

   - these are not useful for serial exposures because rest time is either slow or manual.

3. Electronic timers:

   a. These are the most complicated and most frequently used in newer equipment.

   b. These are based upon the time to charge a resistor-capacitor circuit or (RC circuit).

   - the resistor in these circuits is a variable resistor which provides for changing the time.

4. mAs timers:

   a. These measure the product of the (mA) current and the time:

[current in mA (i.e. coulomb/second)][time (seconds)] = coulombs

b. These are located on the secondary side of the filament transformer.

c. These provide the highest possible tube current in the shortest possible time.

5. Automatic exposure control:

a. The "phototimer" is not adjusted by the operator, instead the exposure time terminates when a specific measure of image quality is obtained.

- the measure of image quality may be the "optical density " indication of an image receptor. If this is the case the device depends on a photomultiplier sensing the "brightness" of a fluorescent screen. The brightness or intensity of the screen correlates to the incident radiation energy delivered.

- An alternate is to use an ionization chamber radiation detector to measure the total exposure (charge per unit mass) produced by radiation with the detector.

<u>High Voltage to the X-ray tube:</u>

A. Don't be confused, but often for convenience the high voltage transformer, the filament transformer, and the rectification circuit are placed in the same housing. All of these components are placed in transformer oil.

B. The high voltage transformer with a typical turns ratio of 500:1 to 1000:1 steps up the voltage -delivered very exactly at a specific value from the line compensator and autotransformer to the potential needed/desired at the x-ray tube, the "kVp".

1. This potential determines the energy imparted to electrons accelerated between the filament and the cathode - and hence it determines the energy of the x-ray photons produced.

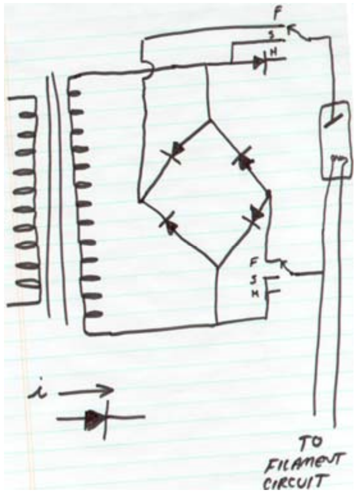
C. Since transformers only operate on AC current, the wave form on both the primary and secondary side is sinusoidal.

1. Both the primary and secondary side of the high voltage transformer have the same wave form, with the same timing.
   a. The waveform differs only in amplitude from one side of the transformer to the other.

D. Transformers only operate on AC current. Ideally, however, we would like to operate the tube in such a way that a continuous output of radiation is experienced.

1. This ideal can be achieved if we use an electronic process called rectification.

2. Rectification is the process of converting alternating current to direct current.
   a. This is accomplished using either a set of vacuum tube



b. rectifiers or semi-conductor diodes arranged in a specific
c. sequence.

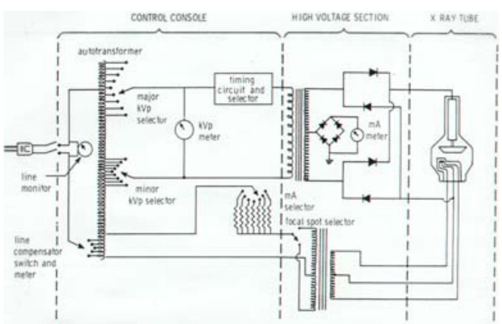


Fig. 7-31. Simplified electric circuit diagram for x-ray machine, showing three main sections: control console, high-voltage section, and x-ray tube.

Consider the following drawing:

Considering the business end of rectification:

Make your own notes here:

Consider the typical sign wave. Only half of the power produced is useable. Any oscillation in the negative direction is not of benefit, and in fact could be a detriment to the x-ray tube.

When we deal with relatively low potentials, the x-ray tube itself provides adequate rectification - referred to as self-rectification. An example of this kind of machine could be a dental x-ray system. Let's look at the diagram.

How could we get rid of the negative portion of the oscillation? The answer is half-wave rectification. How does this work. Let's look at the diagram given above:

How could we make this a much more efficient system and use all the power? We could continuously switch the direction in which power is supplied to the tube. By doing this we would have a more constant supply of power to the tube - this is referred to as full-wave rectification.

How would three phase power handle this system of rectification?

High speed frequency circuits:

Voltage Ripple: This is the variation in peak voltage wave form.

Power rating:

Power kW = mA*kVp/1000 (Three phase)

Power kW = (0.7)mA*kVp/1000 (single phase)

Capacitors in series and parallel circuits.

A capacitor is device that has the ability to store a charge or by so doing one may say that it stores a voltage potential.

At one time capacitors were referred to as condensers, a name still used in automobile mechanic's jargon.

It the most basic form a capacitor is simply two plates of a conductor material orientated in a parallel fashion and separated by an insulator.

Capacitors have a few unique properties or rules of operation.

> 1) If a capacitor is in a series circuit arrangement it only allows current to flow when it is being charged. Once it is charged current will no longer flow through the circuit.

As DC voltage is applied to a capacitor, electrons move from the negative terminal of the voltage source and pile up on one plate of the capacitor. The plate becomes negatively charged as the electrons accumulate. The accumulating negative charge repels electrons away from the other plate, the parallel plate, causing it to become positively charged to the absence of electrons. The difference in charge between the two plates provides a voltage potential between the two parallel plates. Once the voltage potential between the two plates is equal to the applied voltage of the circuit the capacitor is fully charged. Charging occurs of a period of time.

> A. Capacitor charging happens rapidly so for practical purposes a capacitor in a DC circuit
> will, except for an initial instant when charging, cause a series circuit to appear as an open circuit.
>
> > - When the DC current is stopped, current again will briefly flow as the capacitor discharges.
> > - Advantage can be taken of this time requirement for charging and discharging a capacitor. If a change in the applied voltage across a capacitor occurs so rapidly as to not allow sufficient time for the

capacitor to charge or discharge the result will be a constant or steady DC voltage. The capacitor may be thought of as dampening the oscillation in the changing system to produce a steady voltage potential in the system.

B. A capacitor in an AC circuit, since it is continuously charging and discharging, will allow current to flow almost all the time as it never is allowed a "stagnate" instant but rather is continuously charging and discharging as the current and polarity oscillate.

2) If a capacitor is fully charged, it will display a potential equal to the potential applied across the circuit.

The quantity of charge stored by a capacitor is referred to as its capacitance. The magnitude of capacitance expected is a function of:

1. The area of the plates - a larger plate area can hold more electrons resulting in a larger magnitude of capacitance.
    - To provide a larger area in a small component the plates are kept separated by an equal distance and electrically insulated from one another and then rolled into a small concentric cylinder.
2. The distance between the plates - this determines how easily electrons moving onto one plate can repel the electrons from the other plate.
3. The type of insulator or dielectric material between the plates.
    - The better the dielectric or insulating material placed between the plates the closer the plates can be spaced together without leaking the charge collected between the plates.

    - Dielectric material actually serve to enhance the repulsion effect of electrons. The electrons in a dielectric are repulsed to form non-concentric or polarized orbits which have a more pronounced repulsion effect on the secondary plate of the capacitor and thus improve or enhance the charge difference between the plates.

        + The increase in the repelling effect increases the value of the capacitor by a factor called the dielectric constant.

Example material	Dielectric constant
Mica	5
Barium-strontium titanate	7,500

The unit to quantify the physical quantity capacitance is the farad, named for the English Scientist Michael Faraday (1791-1867).

A farad (F) is a very large, almost awkwardly large unit, and thus most commonly fractions of a farad our described using the common prefixes such as micro, nano, or pico farads.

A rule of thumb is that a capacitor with an area of 24 in^2 has a capacitance of about 0.25 μF. If this is extended linearly (which is not entirely appropriate but useful for developing perspective) then it would require a plate area of about 6.7×10^5 ft^2 to produce a capacitance of 1 Farad. This is equivalent to the area of about 15 football fields.

Capacitors in Series and Parallel Circuits:

Capacitors when involved in a parallel circuit display additive capacitance. Specifically:

$$C_T = C_1 + C_2 + C_3 + C_4 + \ldots + C_i$$

This concept may be easy to envision if one were to consider the following diagram showing two capacitors in parallel:

From one perspective the area represent by the top plate of C_1 in the figure can be thought of being added to the area represented by the top plate of C_2. Since a strongly determining factor with respect to the magnitude of capacitance displayed by a capacitor is the plate area, adding plate area all other things being equal simply adds capacitance.

Example C-1:

If C1 above has a capacitance of 6μF and C_2 has a capacitance of 4 μF, What is the total capacitance of the system? Ans: 10μF.

Capacitors in series demonstrate much different behavior than capacitors in parallel.
If two capacitors are connected in series their combined capacitance will be less than that of the smaller capacitor. To determine the total capacitance of capacitors arranged in series within a circuit, the capacitance of each capacitor is combined as follows:

$$1/C_T = 1/C_1 + 1/C_2 + 1/C_3 + \ldots + 1/C_i$$

If you recollect how resistors in parallel are treated to find the total resistance of a circuit, you can probably easily see the mathematical similarity in this system for adding the capacitance of series capacitors.
Again, this behavior may be easy to envision by considering the following drawing:

In this drawing the bottom plate of C_1 and the top plate of C_2 as marked with the letter A, are non-essential. Their contribution could be ignored with respect to the area they provide for capacitance in this system, if they were hypothetically removed the behavior of the system would not be effected.
Example C-2: If C_1 = 10 μF and C_2 = 7μF with both capacitors being arranged in series as demonstrated above, what is the total capacitance of the system?

$$1/C_T = 1/\ 10\ \mu F + 1/\ 7\ \mu F = 0.2428\ \mu F^{-1}$$

$$C_T = 4.11\ \mu F$$

<u>Capacitors Combinations in series and parallel circuits:</u>
When dealing with capacitors in series and parallel circuit combinations one applies the rules of capacitor addition in much the same way the resistor circuits were handled.

Consider the following example:

Clearly, C_1 and C_2 are in series with one another. The branch of the circuit containing C_1 and C2 is in parallel with C_3.

Lets for the moment call C_{comb}, the combined capacitance of C_1 and C_2 and the magnitude of this combined capacitance is:

$1/C_{comb} = 1/\ C_1 + 1/\ C_2 = 1/\ 15\ \mu F + 1/\ 8\mu F = 0.1917\ \mu F^{-1}$
and hence $C_{comb} = 5.22\ \mu F$

Combining C_3 with C_{comb} i.e $C_3 + C_{comb} = 12\mu F + 5.22\mu F = 17.22\mu F = C_T$

The charge stored by a capacitor:

The charge stored by a capacitor is a function of its maximum capacitance and the voltage applied across the capacitor:

$Q = CE$

Where:

Q = the charge on the capacitor in units of coulombs
C = the capacitance in units of farads
E is the voltage potential applied across the capacitor.

Example: A 200-V potential is applied across a 750-µF capacitor and the capacitor is allowed to become fully charged. What is the magnitude of charge that this capacitor can discharge?

$Q = CE = (750 \times 10^{-6} F)(200V) = 0.15$ Coulombs

Incidentally, if the charge per electron is 1.6×10^{-19} coulombs, this represents an excess of:

0.15 coulombs / (1.6×10^{-19} coulombs/electron) = 9.375×10^{17} electrons.

When multiple capacitors are used together in a circuit the magnitude of charge they may store, or discharge after being charged, is determined by the type of circuit, series or parallel, and the way they relate to one another in that circuit.

The charge that may be stored on capacitors in series is determined by the combined capacitance in the system.

Consider the two capacitors in series that were described in example C-2 above that provided a total capacitance (C_T) of 4.11 µF.

Example C-2 (repeated)

This total capacitance limits the total charge of the capacitive system. If the battery depicted in example C-2 were limited to 30 V then because of the limited system capacitance the charge stored, or discharged, by this system could only be:

$$Q= CE = (4.11x10^{-6}F)(30V) =1.233x10^{-4} \text{ coulombs.}$$

Importantly this implies that in a series circuit the charge stored on each capacitor is equal, this value of charge is limited to the total capacitance of the system.

When dealing with capacitors involved with parallel circuits the charge on each capacitor in parallel is dictated by the size of each capacitor and the quantity of current experienced within each branch of the circuit.
The current associated with each branch acts to charge the capacitors in that branch.
Unlike the case of capacitors in a series circuit where one can expect a constant charge, or constant number of electrons on each capacitor, in the case of capacitors in a parallel circuit one may expect that different capacitors in different branches may store, or discharge, different quantities of charge.

Consider the parallel capacitors studied in example C-1.
Recollect that C_1 had a capacitance of 6µF and C_2 had a capacitance of 4 µF, and the total capacitance of the system was10µF.

If we assign a batter with a potential of 200 volts to this system we can know that the current moving through each branch will be different.

The only time the current would be identical in each branch is if the capacitance in each branch were equal.

The charge in the first branch containing C_1 is determined as follows:

$$Q_1 = (200V)(6x10^{-6}F) = 1.2x10^{-3} \text{ coulombs.}$$

The charge on the second branch containing C2 is determined as follows:

$$Q_2 = (200V)(4x10^{-6}F) = 8.0x10^{-4} \text{ coulombs.}$$

The total charge of this may be found in a couple of ways:

$$Q_T = Q_1 + Q_2 = 1.2x10^{-3} \text{ coulombs} + 8.0x10^{-4} \text{ coulombs.} = 2.0x10^{-3} \text{ coulombs}$$

Or alternately:

$Q_T = C_TE = (10x10^{-6}F)(200V) = 2.0x10^{-3}$ coulombs

When we combine capacitors in series and parallel combination circuits we employ the same principles determine the charge on the system.
Again consider the parallel/series circuit described in example C-3:

If the potential of the battery in this example was 200 volts then the charge on C_1 and C_2 is determined considering their combined capacitance in this series portion of the circuit. This was determined above to be 5.22 μF. The charge of this branch would be:

$$(200 V)(5.22x10^{-6}F) = 1.044x10^{-3} \text{ coulombs.}$$

Note: This is the capacitance and charge experienced on each of these two capacitors.

The charge on the branch containing capacitor C3 would be determined as:

$$(200 V)(12x10^{-6}F) = 2.44x10^{-3} \text{ coulombs.}$$

The total charge on this system $Q_T = 1.044x10^{-3}$ coulombs + $2.44x10^{-3}$ coulombs.

Notice how the charge on both branches is different.

The time requirements associated with capacitor charging and discharging.

If a DC voltage were applied to capacitor it would charge almost instantly. However, if a resistor were added in series with the capacitor, the charging of the capacitor is slowed. The amount of time required to charge the capacitor in series with a resistor depends on the magnitude of both the resistor and the capacitor.

The product of the resistance and capacitance is referred to as the RC time constant.

As an example: if a 150 kΩ resistor were in series with a 0.1 μF they together would produce:

$$(150\text{x}10^{-3}\Omega)(0.1\text{x}10^{-6}\text{F}) = 1.5\text{x}10^{-8}\text{s}$$

So $1.5\text{x}10^{-8}$s is the value of one RC time constant in this circumstance.

Charging time is an exponential process. Consider the following table:

Number of time constants	Percentage of full charge expected
1	63%
2	86%
3	95%
4	98%
5	100% (essentially)

Capacitor discharging is also an exponential process. Consider the following table:

Number of time constants	Percentage of full discharge expected
1	37%
2	14%
3	5%
4	2%
5	0% (essentially)

Typically, as demonstrated in the tables provided above, after about five time constants a series RC circuit can be expected to be fully charged or discharged.

The exact current, voltage across the resistor, or voltage drop across the resistor can be determined at any time during charging or discharging if one knows the value of the RC time constant, the value of the resistor, and the capacitance of the system. A summary of expressions to estimate these values in either charging or discharging modes is provided below:

	Charging	Discharging
Capacitor	$E_T(1 - \exp^{(-T/\tau)})$	$E_T(\exp^{(-T/\tau)})$
Resistor voltage	$E_T(\exp^{(-T/\tau)})$	$E_T(\exp^{(-T/\tau)})$
Circuit current during the charging or discharging period	$E_T/R(\exp^{(-T/\tau)})$	$E_T/R(\exp^{(-T/\tau)})$

When AC voltage is applied to capacitors, the every varying polarity causes a much different expectation of response than when DC voltage is applied.

When DC voltage is applied, the capacitor rapidly becomes charged.

When fully charged, current through the circuit ceases.

During the charging period, current continues to flow through the circuit.

As the capacitor approaches being fully charged, the magnitude of current flowing through the circuit rapidly decreases.

When AC current is applied to a capacitor at a frequency that changes faster than the capacitor can charge or discharge several things can be observed:

1. The current moving through the system never ceases.
2. As the voltage rises the capacitor charges.
3. As the voltage decreases the capacitor discharges.

These tend to move in the opposite direction to and oppose current flow. The opposition to current flow is of course resistance.
The opposition to current flow offered by a capacitor is called Capacitive Reactance represented by the variable Xc.
Note, the larger a capacitor, the longer it takes to charge or discharge and the lower the opposition to current flow.
The higher the AC frequency, the lower the opposition.
Hence Capacitive Reactance is a function of the size of the capacitor and the frequence of the AC voltage;

$$Xc = 1/(2\pi fC)$$

Xc = capacitive reactance - expressed in ohms
f = frequency of AC voltage in hertz (s^{-1})
C = capacitance expressed in farads

Examples:

Resistor-Capacitor circuits in AC applications
Consider a typical AC circuit.

First current flows in one direction followed by a switched polarity and current flow in the opposite direction.

As the current flows the capacitor begins to charge, but current flow direction changes to rapidly for the capacitor to fully charge.

Since voltage rise on the capacitor takes time, the charge accumulating on the capacitor lags behind the current in the circuit.

To quantify this observation one must be able to characterize aspects of a sign wave. Consider the following figure which explains the angular relationship of an oscillating wave:

If considering an AC Resistor Capacitor circuit, we expect the following:

The current and voltage oscillation in the resistor of the RC combination is expected to be in phase with that applied current.

Because of the delay in capacitor charging, the current in the capacitor will lag the current applied to the circuit.

- It can be said that the current in the capacitor will lag behind that in the circuit by 90 degrees, i.e. 1/4 a full wave length.

This implies that the capacitor voltage is also 90 degrees out of phase.
The total voltage experienced by the RC combination because of the lag in the capacitor will lag that applied to the circuit.

It is expected that the total voltage in the RC circuit will lag that applied to the system by about 45 degrees.

The following figure from Basic Electricity for Electronics (Blitzer..John Wiley & Sons NY1974 ISBN 0-471-08160-4 page 532) depicts this set of phase relationship.

The 90-degree difference between the resistor voltage and the capacitor voltage is not entirely obvious.

As an alternate these can be described using either a vector or otherwise phasor approach.

Remember that a vector has both magnitude and direction.

A vector can be used to represent a sine-wave varying voltage, or current when there is a known frequency.

When voltage or current in such a circumstance is analyzed using the vector approach, the vector is thought of as rotating counterclockwise and changing magnitude in a way consistent with the oscillation of the system.

A rotating vector is called a phasor.

The frequency of the oscillation corresponds to the rotational speed of the vector around a circle like the hands of a clock - except counterclockwise.

A vector, or phasor, rotating at 60 hz is moving at 60 rotations/second.

The length of this vector represents the magnitude of current or voltage.

In this situation, for instance the voltage on a resistor and a capacitor of an RC circuit, one can sum those by the rules of vector addition to determine the total voltage of the combined components.
Consider the following example:

Since the capacitor voltage and the resistor voltage are 90 degrees out of phase with one another they may be added as if two legs of a right triangle to determine the magnitude of the resultant vector.

If the potential on the capacitor (Ec) is 100 volts and that expected at the resistor (Er) is 100 volts than the total system potential (Et) is:

$$Et = [(100v)^2 + (100v^2)]^{1/2} = 141\text{ v}$$

How would you find the magnitude of the capacitor potential (Ec) given that across the resistor (Er) and the total on the system (Et)

The angle θ between Et and the current I is called the phase angle...as we shall see this too is an important aspect of understanding the characteristics of an AC circuit.
First lets focus on characteristics of the resistor.

A resistor always resists the flow of electrical current.
The total opposition to current flow offered by the resistor in an RC circuit with an applied AC current and voltage is called the impedance as is typically designated by the variable Z.

Impedance in an RC circuit is the Phasor sum of the resistance and capacitive reactance (Xc).

One again it may be observed that the resistance offered by the resistor and the capacitive reactance (Xc) are 90 degrees out of phase, hence they too can be added to one another as if two legs of a right triangle to determine the magnitude of the resultant vector.
The observation of the phase relationship between the resistance (R) and the capacitive reactance (Xc) may be more apparent if ohms law is remembered:

$$Er = (I)(R)$$
$$Ec = (I)(Xc)$$

Since Er and Ec are 90 degrees out of phase then R and Xc must be 90 degrees out of phase.

Imagine that the RC circuit described in the last example had 50 mA of current. If the resistor has a value of 2 kΩ and the capacitive reactance was 2 kΩ what is the system impedance?

$$Z = [(2000)^2 + (2000)^2] = 2.82\ k\Omega$$

Remember that Et was 141 volts. It can also be seen that:

$$Z = Et/I \qquad = 141\ V/50x10\text{-}3A = 2{,}820\ \Omega = 2.82\ k\Omega$$

Consider the following example:

Say we had two RC circuits in series with one another in a circuit with a 100 Hz frequency and a 15-volt AC power supply:

If the first resistor had a resistance of 70 Ω and the first capacitor had a capacitance of 5 μF while the second resistor had a resistance of 80 Ω and the second capacitor had a value of 20 μF, what is the total capacitive reactance and total impedance of this system?

To find the capacitive reactance one must first find the capacitance:

$$1/Ct = 1/5\ \mu F + 1/20\ \mu F = 0.25\ \mu F^{-1}$$

$$\text{So } Ct = 4\ \mu F$$

and therefore the total reactive capacitance is:

$$Xct = 1/(2\pi fCt) = 1/[2\pi(100\ Hz)(4x10^{-6}\ F)] = 398\ \Omega$$

The total resistance (Rt) in this system is 70 Ω + 80 Ω = 150 Ω

The total impedance (Zt) is hence:

$$Zt = [(Rt)^2 + (Xct)^2]^{1/2} = [(150)^2 + (398)^2]^{1/2} = 425\ \Omega$$

The current in this system is determined as I = Et/Zt

$$I = 15\ v/\ 425\ \Omega = 35.3\ mA$$

The voltage drop across the first resistor is:

$$E_{R1} = I\ R_1 = (35x10^{-3}A)(70\ \Omega) = 2.47\ \text{volts}$$

The voltage drop across the second resistor is:

$$E_{R2} = I\ R_2 = (35x10^{-3}A)(80\ \Omega) = 2.82\ \text{volts}$$

The voltage drop across the first capacitor is:

$$E_{XC1} = I\ Xc_1 = (35x10^{-3}A)(318\ \Omega) = 11.2\ \text{volts}$$

The voltage drop across the Second Capacitor is:

$$E_{XC2} = I\ Xc_2 = (35x10^{-3}A)(79.6\ \Omega) = 2.81\ \text{volts}$$

Notice that the 318 Ω arises from:

$$1/(2\pi fC_1) = 1/(2\pi(100\ Hz)(5x10^{-6}\ F)) = 318\ \Omega$$

and that the 79.6 Ω arises from:

$$1/(2\pi fC_2) = 1/(2\pi(100\ Hz)(20x10^{-6}\ F)) = 79.6\ \Omega$$

Also notice that the simple sum of the voltage drop across each component is greater than 15 volts

(i.e. 2.47 v + 2.82 v + 11.2 v + 2.81 v = 19.3 v)

This is because these voltages are not experienced simultaneously, rather the capacitance voltage lags behind the voltage drops across the resistors by 90 degrees.

To obtain the sum of the resistor potentials and the sum of the capacitive potentials are both determined (additively) and these two are treated like any other phasor with two components 90 degrees out of phase:

$$Et = [(2.47\ v + 2.82\ v)^2 + (11.2\ v + 2.81\ v)^2]^{1/2} = 15\ v$$

Power in Resistor-Capacitor Circuits

A pure capacitor, assuming no increase in temperature during operation, would consume no power.

During charging a capacitor stores power but this is “re-injected” into the circuit when the capacitor discharges.

Therefore, when considering power dissipation in an RC circuit, one considers only the resistor. Remember when we were discussing power dissipation in a resistive circuit it was shown that power (P) is equal to:

$$P = (\text{Current})(\text{Voltage})\ .$$

But this expression essentially: $P_T = (I_T)(E_T)$ <u>is not actually correct if a reactance exists</u> within the system:

If one employs this expression in a circuit that displays both reactance and resistance one calculates something called the **apparent power ($P_{apparent}$).**

$$\mathbf{P_{apparent}} = (I_T)(E_T)$$

Because no power is lost in the capacitor, to calculate the **true power P_{true}** in an RC circuit, (with an applied AC voltage) one must calculate power based only upon the current and resistance values (e.g.):

$$\mathbf{P_{true}} = I^2R = E_RI = E_R^2/R$$

Notice on how only terms involved with resistance are employed in these expressions.

Obviously true power will always be less than apparent power.
The ratio of true power to apparent power is called the power factor.

$$\text{Power factor} = \mathbf{P_{true} / P_{apparent}}$$

The power factor is always less than one except in a purely resistive circuit where the ratio of true to apparent power is unity. (Note this makes for a good test question).

In typical systems one may be quoted the power factor, and then considering the circuit may be able to ascertain the apparent power.

By multiplying the power factor and the apparent power one obtains the true power.

If one uses a watt-meter to determine the power consumption of an RC circuit one will be directly measuring true power.
Capacitors and resistors in parallel and considering phase relationships:
If a Capacitor and resistor were place in parallel branches of an alternating-current parallel-circuit, there are a number of observations that could be anticipated:

1) The applied voltage across the capacitor and the resistor is common to both of the components.

2) Current through the resistor is always in phase with the voltage across the resistor.

3) The capacitor voltage is lagging the capacitor current by 90 degrees. (This is always the anticipated situation).

4) Because of this situation where capacitive current is 90 degrees out of phase with resistive current, the total capacitive current is found by adding the two components with one another as if two legs of a right triangle to determine the magnitude of the resultant vector.
5) The phase angle θ in this circuit is the angle between the total circuit current I_T and the total potential E_T. Here E_T lags I_T by the phase angle θ.

Impedance in the parallel RC circuit under AC conditions:

Clearly The resistor and capacitor are in parallel in this circumstance.

The total impedance (opposition) to current flow in this situation is given as:

$$Z_T = (R)(X_C)/[(R^2 + X_c^2)^{½}]$$

just remember Z_T = (product)/(sum)

Consider an example with a resistor that has a resistance of 30 Ω and a capacitor that has a capacitive reactance of 40 Ω in parallel to one another with a 12 V AC power source as shown below:

The total Impedance Z_T is :

$$Z_T = (30\ \Omega)(40\ \Omega)/\{[(30\ \Omega)^2 + (40\ \Omega)^2]^{1/2}\} = 24\ \Omega$$

The current in each branch of this circuit is determined using Ohm's law:

so: E_T/R = 12 v/ 30 Ω = 0.4 A
and E_T/X_C = 12 v/ 40 Ω = 0.3 A

As stated previously, the capacitor and resistor currents are 90 degrees out of face, hence consistent with previous operations, the total current I_T is given as:

$$I_T = [(I_R)^2 + (I_{XC})^2]^{1/2} = [(0.4)^2 + (0.3)^2]^{1/2} = 0.5\ A$$

If I_T and E_T are known the total impedance Z_T can be determined using ohm's law:

$$Z_T = E_T/I_T = 12\ v / 0.5\ A = 24\ \Omega$$

Example:

A 2,500 Ω resistor is in parallel with a capacitor having a capacitive reactance of 3,000 Ω and a 75 v AC potential is applied to this system
Find the total impedance of this system, the current through each branch, and the total current.

Example: Multiple RC branches in an AC circuit.

Electrical Shock/Electrical Safety Hazards

ELECTRICAL CURRENT KILLS!

A) Electricity is ubiquitous in our world. The potential hazard associated with electrical current is therefore also ubiquitous.

1. Perhaps as many as 1,000 Americans a year are accidentally electrocuted.

2. Additionally, electrical shock may be considered an auxiliary hazard to many other health hazards.

B) The occurrence of a deleterious physiological effect from electricity, "a shock" requires that the body becomes part of an electric circuit. Current therefore flow through tissue causing damage.

1. Current must enter at one point and leave the body at some other point.

2. The path taken by the current as it travels through the body in part determines the outcome of this event.

3. The magnitude of current experienced by the tissues within the shocked body depends on three things:

a. The applied voltage

b. The impedance of the body

c. The nature of contact interfaces along the path of current flow.

Consider a shock scenario:

source → skin → arm → torso → leg → skin → ground

The skin if wet offers a resistance of about 2000 Ω
if dry its resistance may be from 100,000 Ω to 2,000,000 Ω

the arm may offer 200 Ω of resistance, the torso 100 Ω, the leg an additional 200 Ω.

From a very simple approach we know that E = IR. If the source were 1000 V what current would be flowing through this circuit under wet and dry skin conditions?

wet: 1000 V = (4,500 Ω)(I) ∴ I = 0.22 amps
dry: 1000 V = (200500 Ω)(I) ∴ I = 5 mA
to dry: 1000 V = (4000500 Ω)(I) ∴ I = 0.25 mA

Incidentally, we know that power is given by the expression
$P = I^2R$

Hence the power deposition in a wet person would be something like:
Total
(0.22 amps)2(4,500 Ω) = 218 watts
skin
(0.22 amps)2(4,000 Ω) = 194 watts – A skin burn may be apparent.
arm
(0.22 amps)2(200 Ω) = 9.7 watts
torso
(0.22 amps)2(100 Ω) = 4.8 watts
leg
(0.22 amps)2(200 Ω) = 9.7 watts

What would happen if the individual were wet, but the voltage was only 120 volts?

120 V = (4,500 Ω)(I) therefore, I = 0.027 amps = 27 mA

Total power:
P = I2 R (0.027)2(4,500 Ω) = 3.28 watts

Skin

$$P = I2R = (0.027)2(4000\ \Omega) = 2.92 \text{ watts}$$

Torso

$$P = I2R = (0.027)2(100\ \Omega) = 0.07 \text{ watts}$$

In this situation, a person may die due to the current through the torso (as we shall see shortly) but their probably will be no evidence of tissue burns.

4. There are three general effects experienced by tissues which are subjected to current flow:

    a. Electrical stimulation of excitable tissues (nerve and muscle)

    b. Resistive heating of tissue

    c. electrochemical burns (when direct current is used)

5. The physiological effects experienced by shocked humans depends on the magnitude of current flow.

    a. The minimum perceptible current is referred to as the Threshold of Perception.

    b. Although there is considerable variability among people, the threshold of perception is usually observed between about 0.5 mA and 5 mA for 60 hz exposures.

        i. For men, the mean value for the threshold of perception is 1.1 mA.
        ii. For women, the mean value for the threshold of perception is 0.7 mA.
        iv. At this point the local current density is just large enough to excite nerve endings in the skin.
        v. The subject may feel a tingling sensation.

c. For direct current exposures the threshold of perception varies from about 2 mA to 10 mA.

        i. A slight warming of the skin is perceived.

Note: The physiological effects given above and below are based on experiments with an average 70 kg man and for 60-hz current applied for 1 to 3 s to moistened hands grasping a No. 8 copper wire. Minimal rather than average values are often most important for safety considerations.

d. The next highest level of effect from exposure to electrical current is referred to as the Let-Go-Current.

i. The Let-Go-Current is defined as the maximum current that an individual can experience and yet maintain the ability to voluntarily withdrawal.

ii. As the magnitude of current is increased above the threshold of perception nerves and muscles become more and more vigorously stimulated.

- Such stimulation may cause involuntary muscle contractions or reflex reactions to occur.

  * This action is known to cause many secondary injuries, particularly related to falls.

- Eventually as the magnitude of current increases the "shocked individual" will experience pain and fatigue.

- As the magnitude of current increases a point is reached at which an individual can no longer voluntarily withdraw; the let-go-current level has been obtained.

- The minimum let-go-current at 60 hz in men has been found to be 9.5 mA (at the 50 percentile).
- The minimum let-go-current at 60 hz in women has been found to be 6 mA (at the 50 percentile).

- The minimum let-go-current occurs for commercial power-line frequencies of 50 to 60 hz.

- for frequencies below 10 hz, let-go-currents rise. This is probably because the muscles can partially relax during part of each cycle.

- for frequencies above several hundred hz the let-go-currents also rise. This could be associated with strength-duration tradeoffs and the refractoriness of excitable tissue.

- Let-Go-Current responses appear to follow Gaussian Distributions. There is a large standard deviation associated with this end-point.

- For men the mean let-go-current for 60 hz frequencies is around 16 mA.

- For women the mean let-go-current for 60 hz frequencies is around 10.5 mA.

e. Currents above the Let-Go-Current are known to cause pain and fatigue particularly if long exposures are experienced.
f. As the level of current is increased well beyond the let-go-current, involuntary contraction of respiratory muscles may occur.

i. These contractions may be severe enough to cause asphyxiation if the current is not interrupted.

ii. Respiratory arrest has been observed at 18 mA to 22 mA of current.

g. Hence, currents above the let-go-current may cause respiratory paralysis, pain and fatigue.

h. If the heart is subjected to electrical current an individual may face several different dangers all of which may be fatal.

i. If the magnitude of current is sufficient to excite part of the heart muscle, then the normal propagation of electrical activity in the heart muscle is disturbed.

* The desynchronization of the ventricles of the heart ceases the heart's efficient pumping action and death will occur within minutes.

* The desynchronization of the cardiac muscle tissue is referred to as fibrillation.

* Once started fibrillation will not stop unless the muscle cells are simultaneously depolarized and then allowed to rest in which case they will spontaneously resume their normal rhythm.

  - This depolarization might be achieved using a defibrillator which provides a brief high-current pulse to the heart muscle.

  - The threshold for ventricular fibrillation for an averaged sized man varies from 75 mA to 400 mA.

  - Fibrillating-current threshold for animals increase sharply for shocks that last less than about 1s.

  - The point of the heart cycle at which the shock occurs also effects the likelihood of fibrillation.

    A shock occurring during the 100 milliseconds that corresponds to the repolarization of the ventricles catches the heart in its most vulnerable position.

The heart is less susceptible to shock during other portions of the heart cycle.

- There is some evidence to indicate that the fibrillation threshold increases with body weight.

i. When greater currents from 1 Amp to 6 Amps are experienced by heart muscle, the entire heart muscle contracts.

* This may be referred to as sustained myocardial contraction.

* The heart stops beating while such high currents are applied.

* When the current stops normal heart rhythm resumes.

* No irreversible damage to the heart is known to result from such currents.

j. For currents greater than 10 amps several items may be expected:

* Because skin resistance is high, resistive heating is expected to cause entry burns.

* Excessive currents may cause muscular contraction with such force that muscle attachments may be pulled away from bones.

* The brain and other nervous tissues are expected to lose all functional excitability when high currents are passed through them.

k. Very high voltages (greater than 240 V) may be capable of puncturing the skin.

6. An important aspect which must be considered when discussing the potential

deleterious effects associated with electrical shock are the points of entry and exit.

a. As shown previously, when current is applied externally to the body only a small fraction of the total current flows through the heart.

b. The magnitude of current needed to fibrillate the heart is far greater when the current is applied on the surface of the body than it would be if the current were applied directly to the heart.

i. If current is applied outside the body this is referred to as a macroshock.

ii. If current is applied directly inside the body, this is referred to as microshock.

- microshock scenarios are of particular concern in hospitals were electrical leads may penetrate the high resistivity skin barrier.

- There is some evidence to show that an intra-cardiac catheter "accidentally" delivering a current of as little as 80 to 600 μA can cause fibrillation. Hence, patients that have direct electrical connections to their heart are called electrically susceptible patients.

c. The macroshock entry and exit points should be considered when evaluating shock hazards or shock damage.

i. If two points are both on the same extremity, the risk of fibrillation is small, even for high currents.

ii. If the two contacts are such that a current pathway through the heart exists, then the risk for fibrillation rapidly increases.