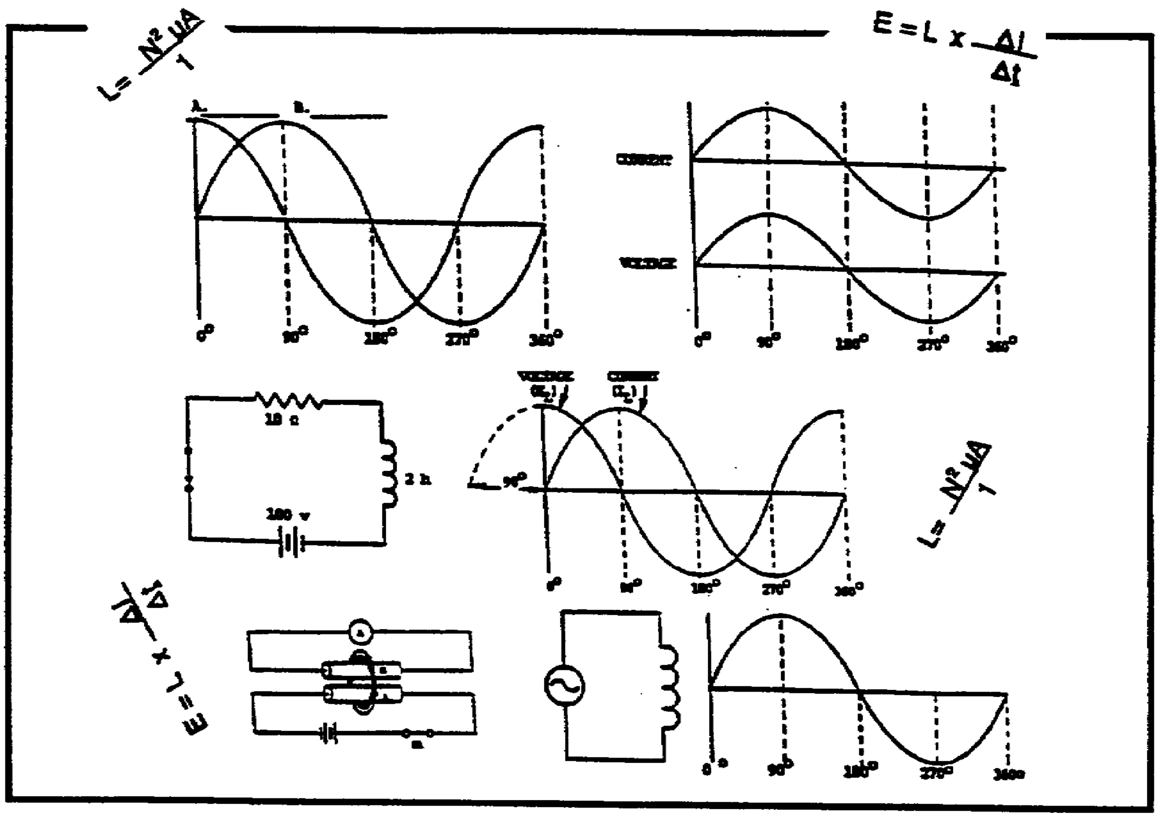
SUBCOURSE
IT0353

EDITION
A

US ARMY INTELLIGENCE CENTER

INDUCTANCE



THE ARMY INSTITUTE FOR PROFESSIONAL DEVELOPMENT

ARMY CORRESPONDENCE COURSE PROGRAM

AIPD

READINESS/ PROFESSIONALISM THRU GROWTH

Subcourse Number IT0353

EDITION A

US ARMY INTELLIGENCE CENTER
FORT HUACHUCA, AZ 85613-6000

4 Credit Hours

Edition Date: October 1997

SUBCOURSE OVERVIEW

This subcourse is designed to teach basic theory of inductance, the relationship between current in a conductor and its associated magnetic field, Lenz's Law, and mutual inductance.

This subcourse replaces SA0747.

There are no prerequisites for this subcourse.

TERMINAL LEARNING OBJECTIVE:

ACTION: You will select statements which describe or answer questions concerning inductance, the relationship existing between current in a conductor and the surrounding magnetic field, Lenz's law, mutual inductance, and factors affecting inductance. Additionally you will solve for the time-constant of simple RL circuits.

CONDITION: You will have this subcourse booklet for self-paced study. All information required is contained herein.

STANDARD: To demonstrate competency of this task, you must achieve a minimum score of 70% on the subcourse examination.

TABLE OF CONTENTS

LESSON 1

INDUCTANCE

OVERVIEW

LESSON DESCRIPTION: This lesson defines inductance; expresses the relationship between a changing current in a conductor and the magnetic field surrounding the conductor; defines Len's Law; describes inductors; introduces symbols related to inductance; describes mutual inductance; introduces mathematical equations to calculate unknowns; and presents problems for the student to solve.

TERMINAL LEARNING OBJECTIVE:

ACTION: You will select statements which describe or answer questions concerning inductance, the relationship existing between current in a conductor and the surrounding magnetic field, Len's law, mutual inductance, and factors affecting inductance. Additionally you will solve for the time-constant of simple RL circuits.

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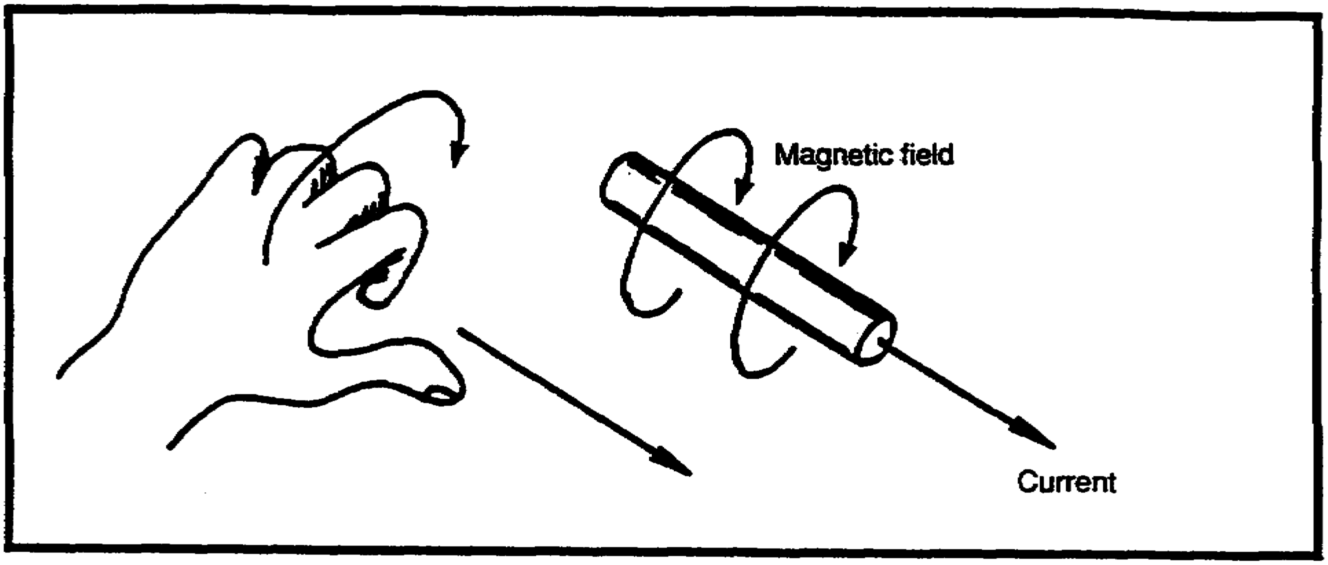
1. Inertia is the property of an object to oppose any change in the direction of its motion. Because of inertia, a body at rest tends to remain at rest; a body in motion tends to remain in motion. Electrical circuits have a property which is very similar to inertia. If current in a circuit changes, a force in that circuit opposes the change. This opposition of a change in current is called **INDUCTANCE**.

2. In 1819, Hans Christian Oersted, a Danish physicist, discovered that a magnetic field surrounds any conductor that is carrying current. The strength of this magnetic field depends on the amount of current flowing in the conductor. The direction of the magnetic field depends on the direction of the current flow within the conductor. The left hand rule for conductors, illustrated below, is used to determine the direction of the magnetic field.

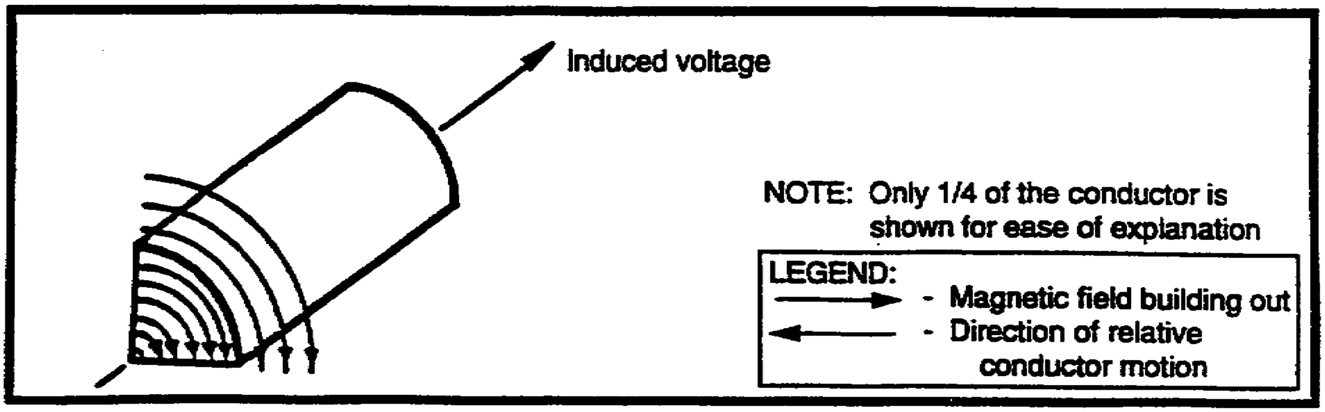


When the current is increased, the magnetic lines of force expand; when the current is decreased, the lines of force tend to collapse. The expansion or collapse of the magnetic field (the magnetic field in motion) causes a voltage to be induced in the conductor. This voltage is called self-induced emf. The three requirements for producing an electromagnetic force (EM) by electromagnetic induction are:

(1) a conductor,
(2) a magnetic field,
(3) and a relative motion between the two

The drawing on the next page illustrates how self-induced emf is created in a conductor. Note that the magnetic field originates in the center of the conductor; hence, the field cuts the conductor, which causes the same effect as relative motion between the field and the conductor.

2. (CONTINUED)



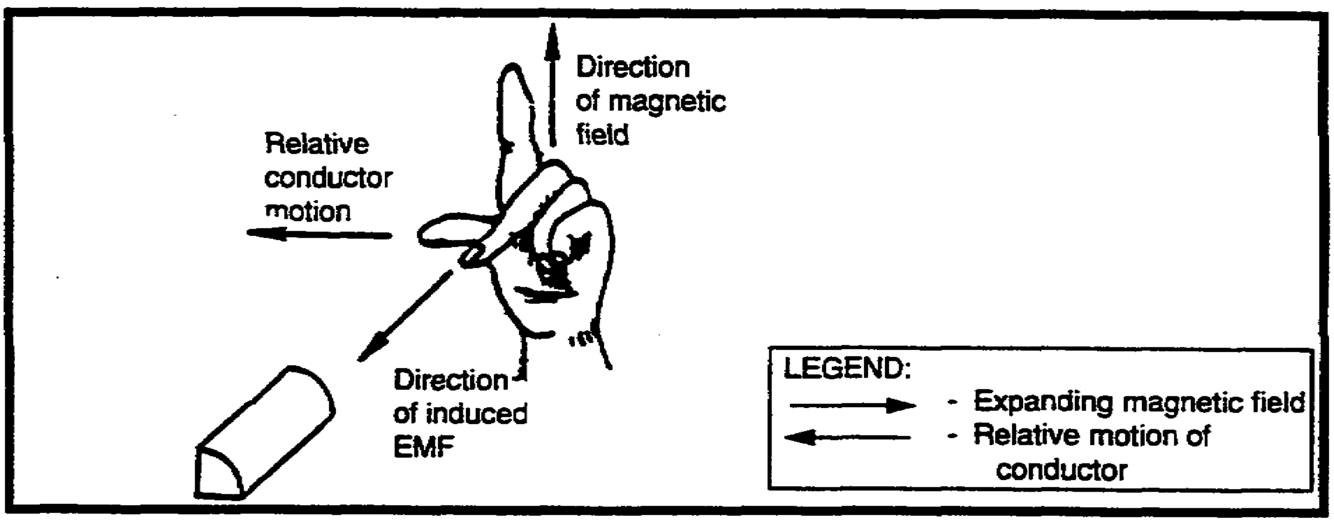
Q. The three requirements for producing an emf by electromagnetic induction are:

(1) a ____ ,

(2) a ____ ,

(3) and ______________________________________ .

3. The left hand rule for generators is used to determine the direction of self-inducted emf in a conductor. In applying this rule, the thumb of the left hand points in the direction of relative motion of the conductor in the magnetic field . (In this case, the field is moving, which causes the same effect as the conductor moving in the opposite direction.) The index finger points in the direction of the magnetic field. The middle finger, extended as shown, will indicate the direction of induce voltage.



Q. a. When the current in a conductor increases, does the magnetic field surrounding the conductor expand or collapse?

Q. b. When the current in a conductor decreases, does the magnetic field surrounding the conductor expand or collapse?

SOLUTIONS.

2. (1) Conductor (2) magnetic field; (3) relative motion between the two
3. a. expands; b. collapses

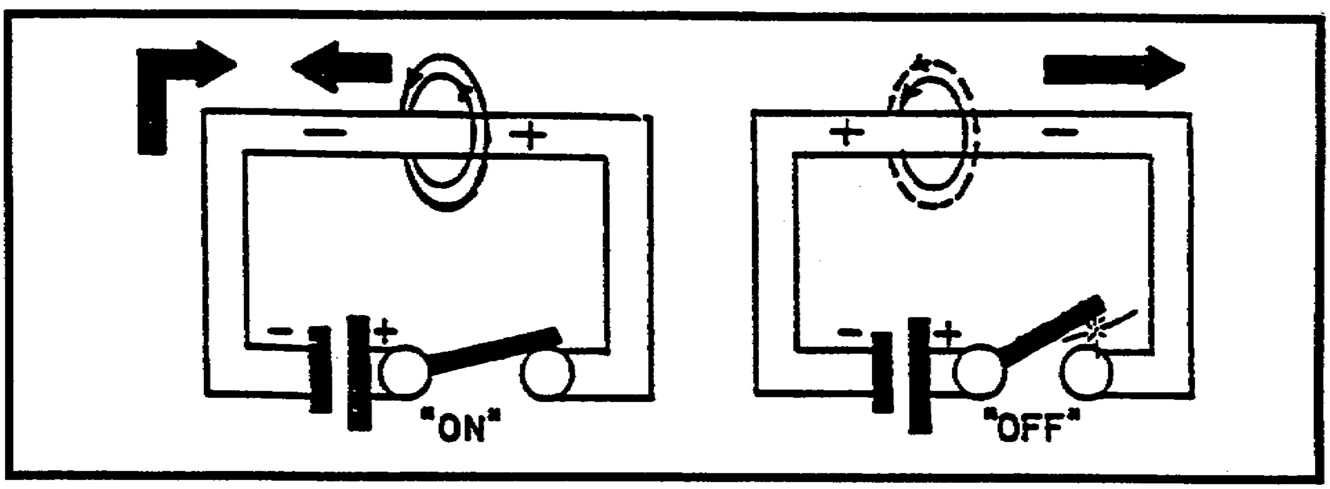
4. Inductance is the property of an electrical circuit that

a. opposes a change in voltage.
b. opposes a change in current.
c. opposes current flow.

5. In 1834, H.F.E. Lenz, a German physicist, formulated a law which is still the basis for explanation of the property of inductance. Lenz's law states:

The inducted emf in any circuit is always in a direction to oppose the effect that produced it.

The voltage induced in a circuit by a changing current is called counter emf. When circuit current increases, the expanding magnetic field induces an emf (counter emf) that opposes the applied voltage and the increase in current. When circuit current decreases, the collapsing magnetic field induces a voltage of opposite polarity which tends to maintain current flow in the same direction and to oppose a decrease in current. The drawings below show the effect of counter emf in a d-c circuit. When the circuit is turned "on," the counter emf opposes the increased in current. When the circuit is turned "off", the counter emf tries to maintain the same direction of current flow. A spark is produced as the switch is opened.

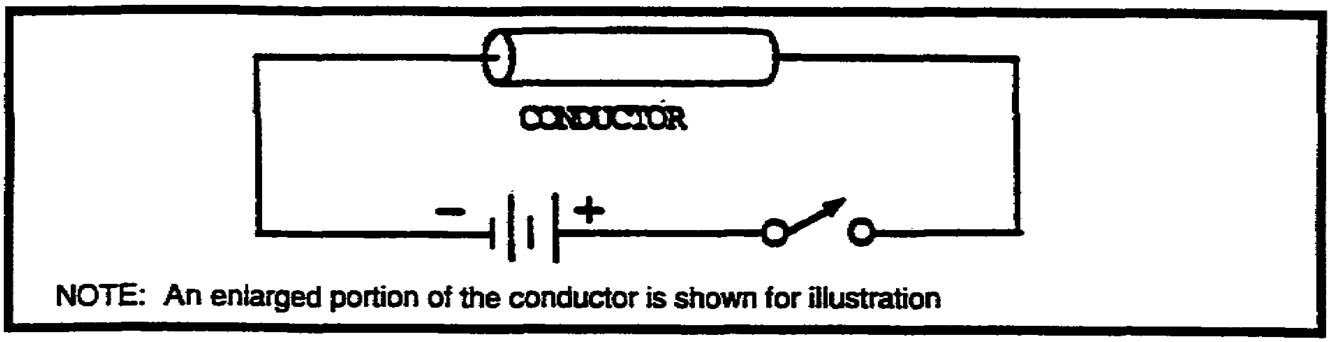


Lenz's law states that the induced emf in any circuit is always in a direction to ____________________ (aid/oppose) the effect that produced ft.

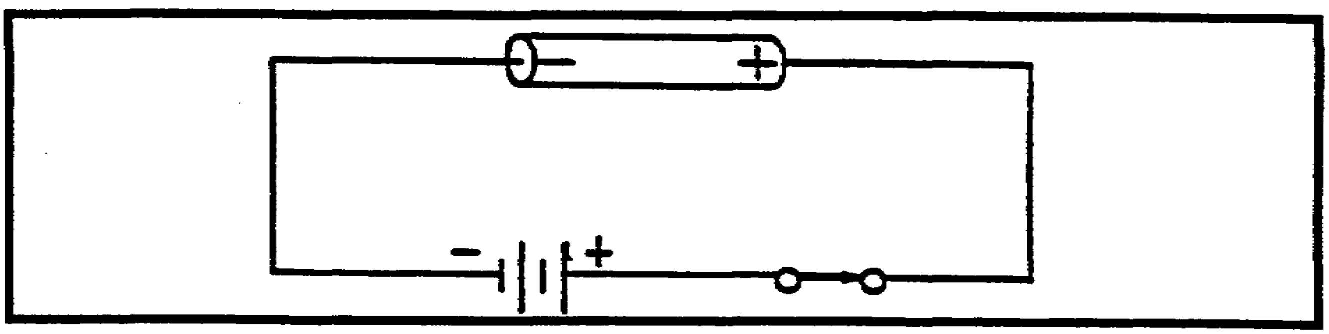
6. What will the magnetic field surrounding a conductor do if the current in a conductor increases?

   a. collapse.
   b. expand.
   c. disappear.
   d. remain unchanged.

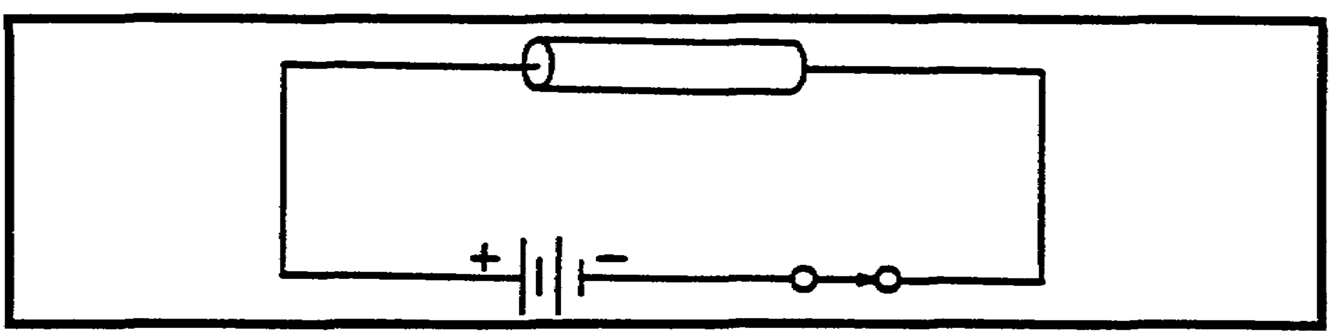
7. The drawing below illustrates the effect of counter emf. When the switch is open, no current will flow.

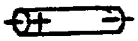


Current does not build up immediately when the switch is closed, because the counter emf <u>opposes</u> the applied voltage. The polarity of the counter emf at the instant that the switch is closed is shown on the enlarged potion of the conductor below.



On the conductor shown below, label the polarity of the counter emf at the instant the switch is closed.

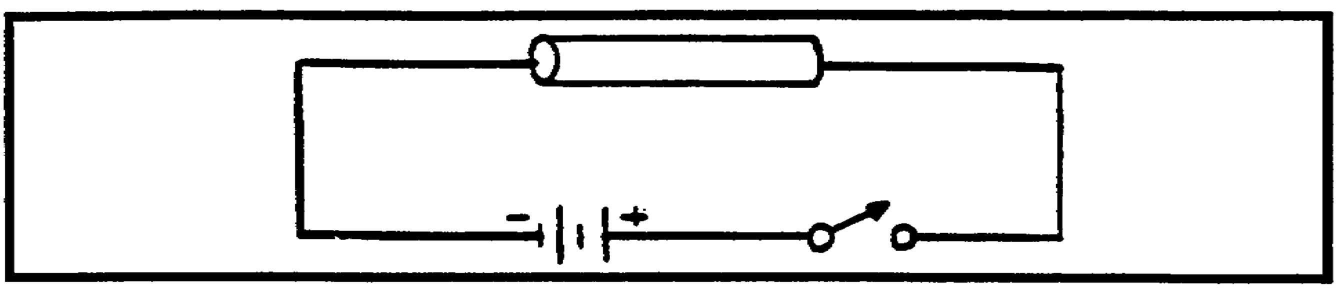


SOLUTIONS.
4. b.
5. oppose
6. b.
7. 

8. Lenz's law states that the induced emf in any circuit is always in a direction to _______________ the effect that produced it.
(aid/oppose)

9. Select the definition of inductance.
a. Inductance is the property of an electrical circuit that opposes a change in voltage.
b. Inductance is the property of an object to oppose any change in its state of motion.
c. Inductance is the property of an electrical circuit that opposes a change in current.
d. Inductance is the property of an electrical circuit that opposes current flow.

10.



What is the polarity of the induced counter emf in the conductor shown above at the instant the switch is closed; a or b.

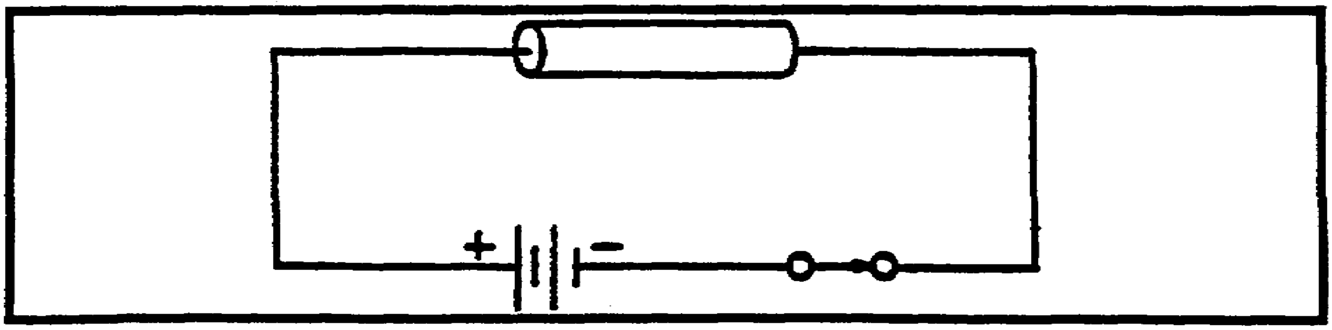
a.

b.

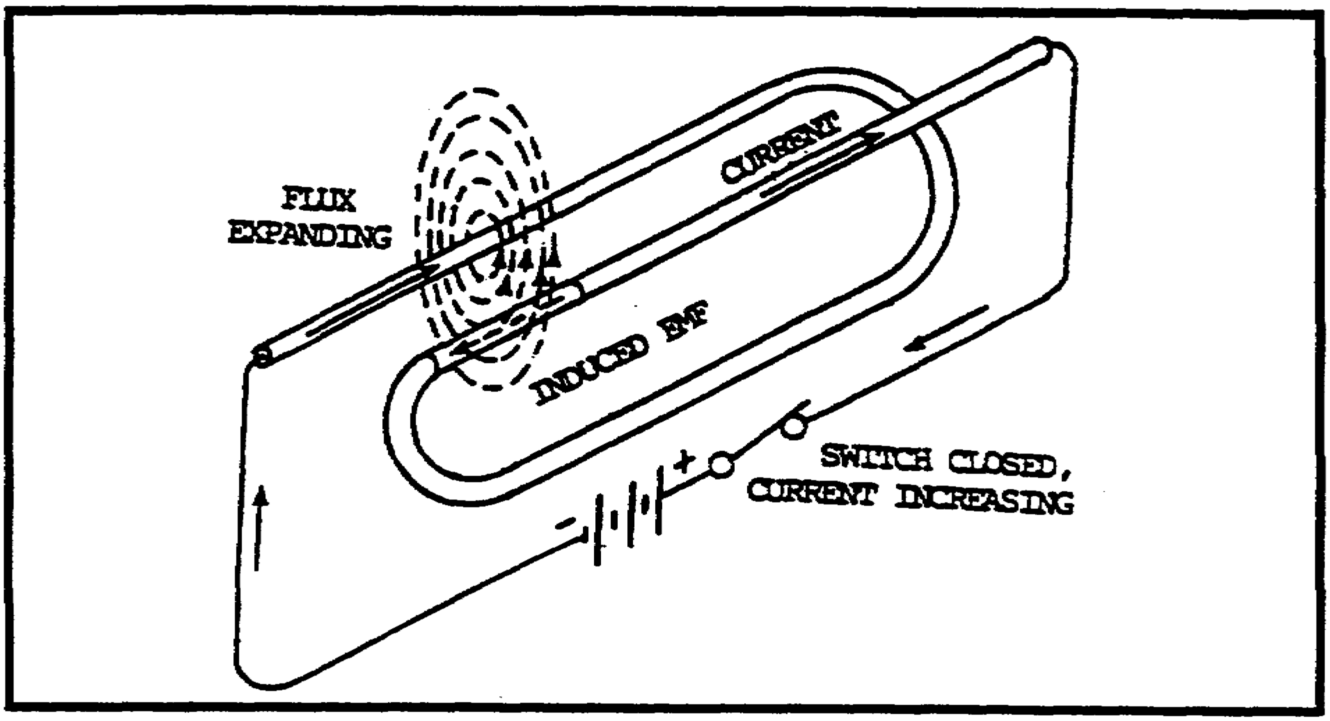
11. State the relationship between a changing current in a conductor and the magnetic field surrounding the conductor.

12. State Lenz's law.

13. Label the figure below with the polarity of the induced counter emf in the conductor at the instant the switch is closed.



14. When a conductor is formed into a coil, a changing magnetic field around one turn of the coil cuts across adjacent turns, thereby inducing a counter emf in the adjacent turns that, in turn, increases the total counter emf of the conductor. This action is illustrated below.



Because of this "linkage" between the turns, a coil of wire has more inductance than a straight piece of wire. The symbol for inductance is "L" (for linkage). When a coil of wire is wound so it has a specific amount of inductance, it is called an INDUCTOR. Sometimes an inductor is called a choke or a coil.

Q. What is the symbol for inductance?

Q. What is a coil of wire with a specific amount of inductance called?

SOLUTIONS.
8. oppose
9. c
10. a
11. When the current increases, the magnetic field expands; and when the current decreases, the magnetic field collapses.
12. The induced voltage emf in any circuit is always in a direction to oppose the effect that produced it.
13. 

14. a. L b. inductor

15. The unit of measurement of inductance is the HENRY, and its associated symbol is an "h." An inductor has an inductance of 1 henry if 1 volt is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. This relationship may be stated mathematically as:

$$E = L \times \frac{\Delta I}{\Delta t}$$

where E = the induced emf in volts
L = the inductance in henrys
I = the change in current in amperes
and t = the change in time in seconds

NOTE: The symbol Δ (Delta) means "a change in..." Remember, it is the change in current, not the current itself, that is opposed by the inductor

The henry is a large unit of inductance. The more common units employed with inductors are millihenry (mh) and the microhenry (µh).

Q. What is the unit of measurement of inductance and its associated symbol?

16. The inductance of a coil depends on four factors:
(1) the number of turns of wire in the coil (N),
(2) the cross-sectional area of the coil (A),
(3) the length of the coil (1), and
(4) the permeability of the coils core (µ).
The formula expressing is relationship is:

$$L = \frac{N^2 \mu A}{1}$$

16. Continued.

If the number of turns increases, the inductance will increase. If the cross-sectional area increases, the inductance will increase. If the core material is changed, the inductance will change directly in proportion to the permeability of the core material. The permeability of the core is a measure of the cores ability to conduct magnetic lines of flux, as compared with that of air. If these three factors remain constant and the length of the coil changes, the inductance will vary inversely; that is, the length increases, the inductance decreases.

The inductance of a coil is determined by four factors:
(1) the number of turns of wire in the coil (N),
(2) the cross-sectional area of the coil (A),
(3) the length of the coil (1), and
(4) ________________________________ ?

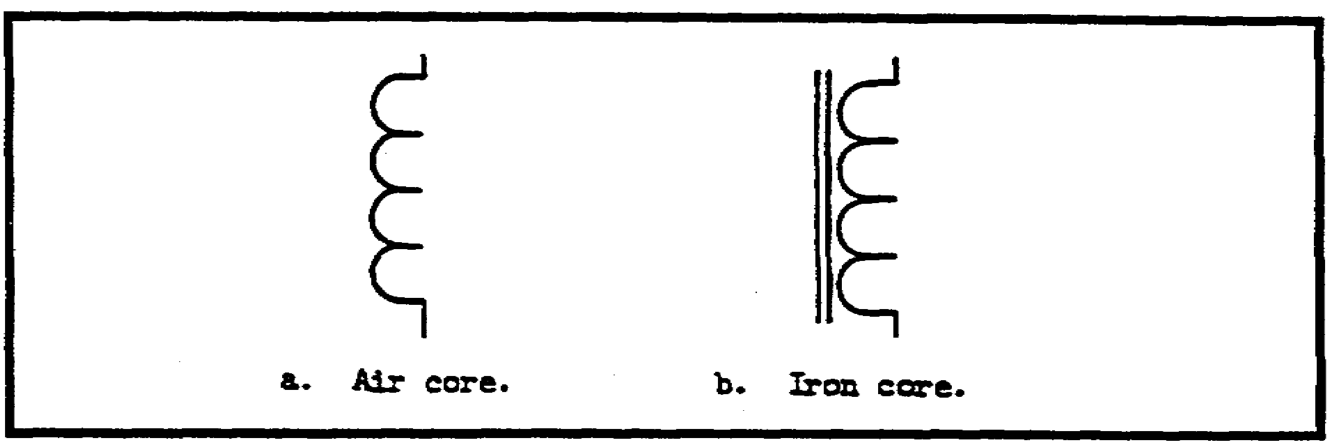
17. Select the definition of an inductor.
a. It is a coil with an undetermined amount of inductance.
b. It is a coil with an undetermined amount of resistance.
c. It is a coil with a specific amount of resistance.
d. It is a coil with a specific amount of inductance.

18. What is the symbol for inductance?

19. The formula for the inductance of a coil is

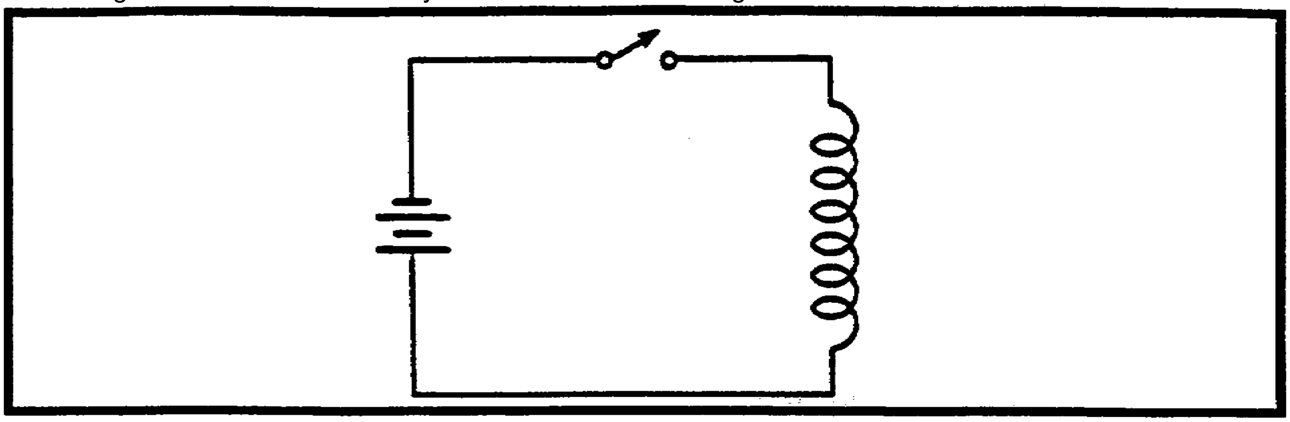
$$L = \frac{N^2 \mu A}{1}$$

Permeability (μ) of the core plays an important role in the construction of an inductor. Iron is commonly used as a core material for inductors, because iron has a much higher permeability than air. The symbols for air-core and iron-core inductors are shown below. Which of the coils has the highest value of inductance, assuming that the only difference is the type of core material used?

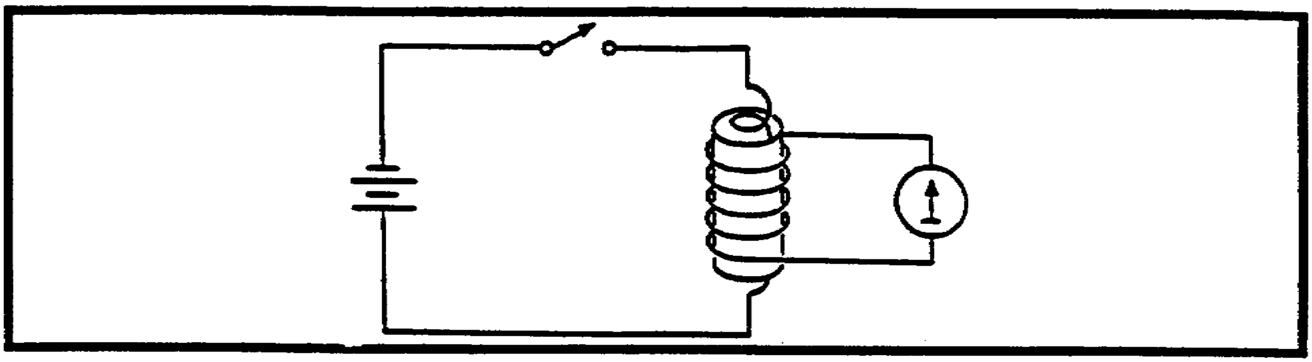


SOLUTIONS.
15. henry; h
16 . the permeability of the core
17. d.
18. L
19. b.

20. The figure below shows a battery connected to a coil through a switch.

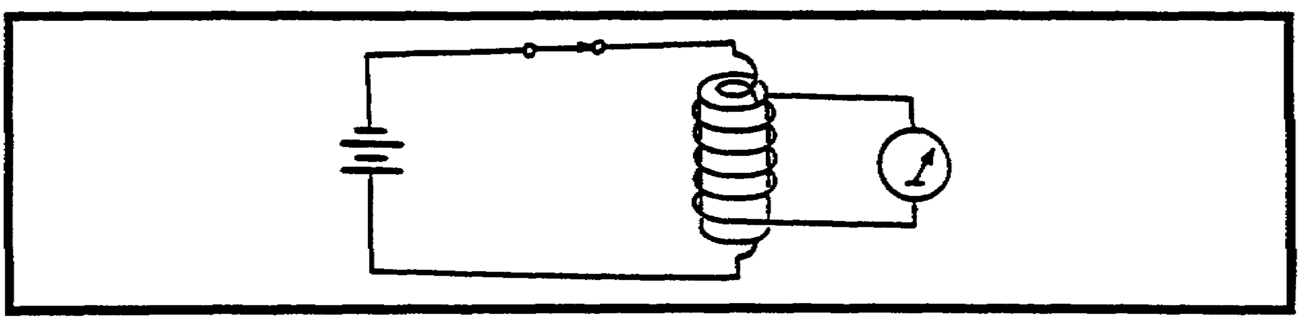


In the following figure, the coil is inserted into a second coil whose terminals are connected to a meter.



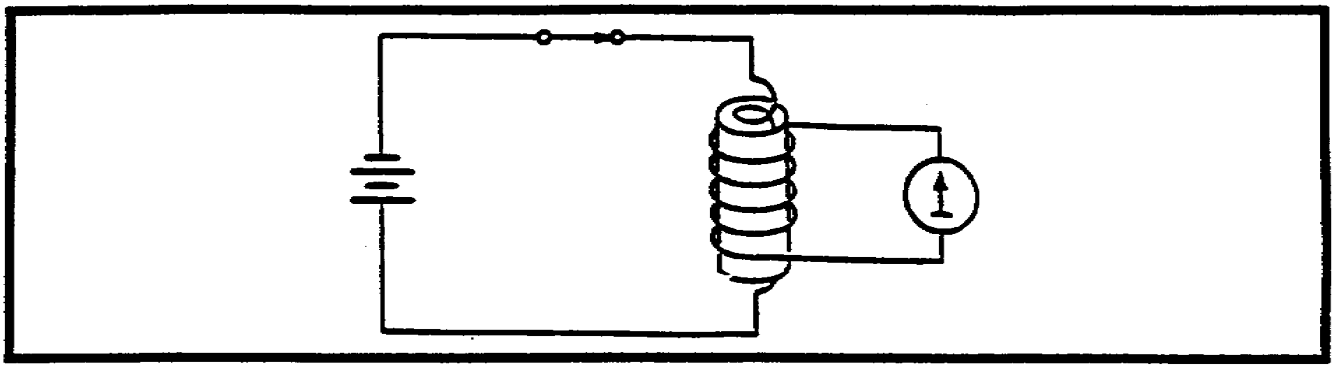
The coil connected to the current source (battery) is called the PRIMARY; the coil connected to the load (meter) is called the SECONDARY.

When the switch is closed, the magnetic field building out from the primary will cut the windings of the secondary, which induces an emf in the secondary. Note the meter direction.

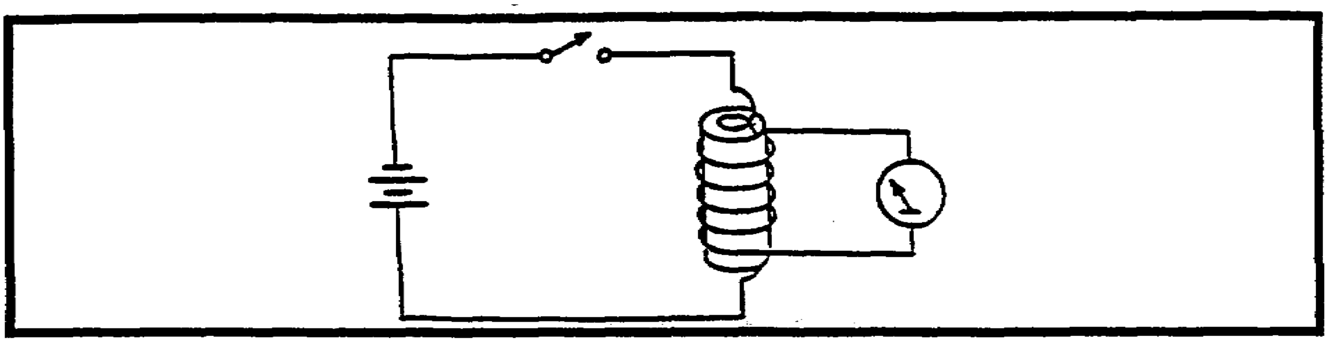


20. Continued.

When the magnetic field is at its full strength (no longer expanding), there is no relative motion and no induced emf, as shown on the meter in the figure below.



When the switch is opened, the magnetic field collapses, which induces an emf of the opposite polarity in the secondary.



An emf is induced across the secondary whenever the magnetic field linking the secondary is increased or decreased. Two circuits arranged so that a change in magnitude of current in one causes an emf to be induced in the other show the effects of **MUTUAL INDUCTANCE**.

Q. How is energy transferred from a primary coil to a secondary coil?

21. The symbol for mutual inductance is M or Lm. The unit of measurement of mutual inductance is the henry, the same unit of measurement used for inductance. The mutual inductance of two circuits is 1 henry when 1 volt of emf is induced in the secondary as the current in the primary is changing at the rate of 1 ampere per second. The formula expressing this is:

$$M = \frac{-E_s}{\Delta I_p/\Delta t}$$

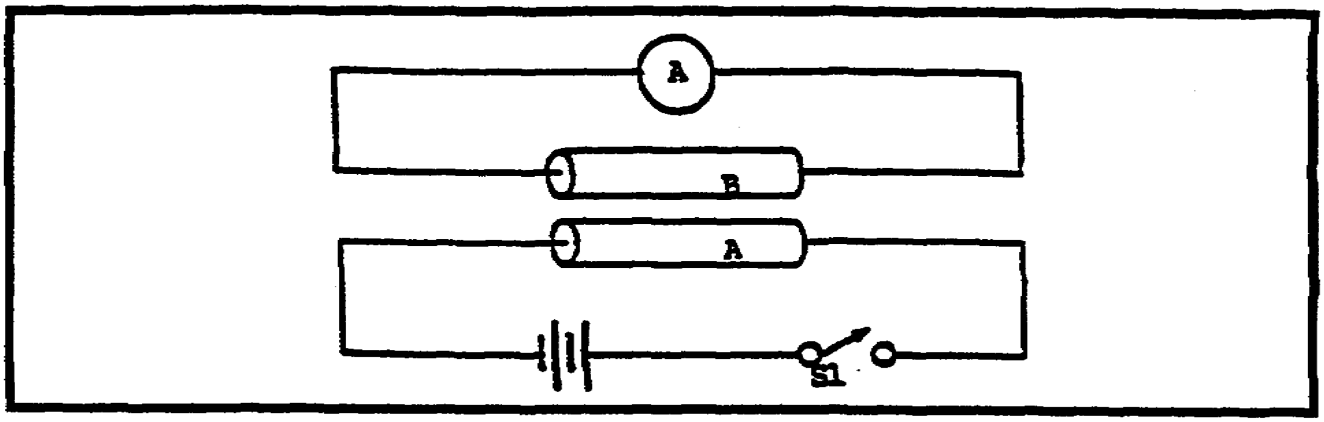
where M is the mutual inductance of the two circuits in henrys,
Es is the emf induced in the secondary, and
ΔIp/Δt is the rate of change of current in the primary in amperes per second.

Q. What do the symbols (M) and (Lm) represent?

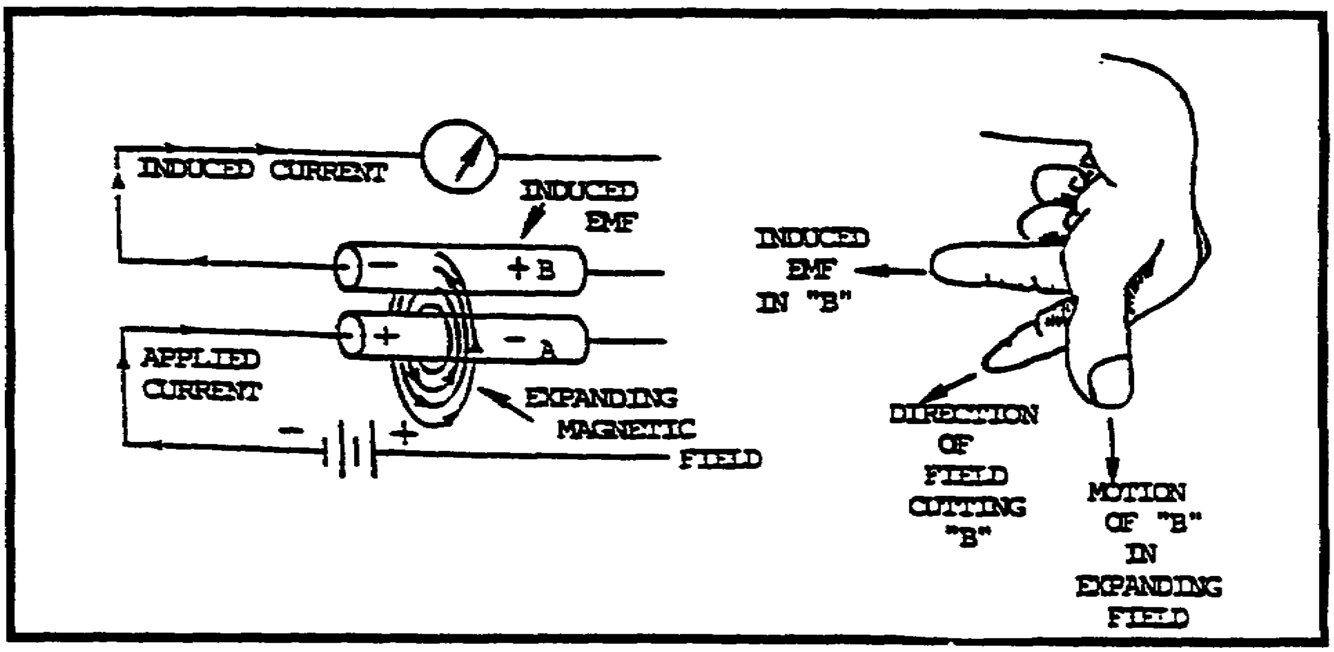
SOLUTIONS.
20. mutual inductance
21. mutual inductance

22. Q. What property is displayed when two circuits are arranged so a changing current in one causes an emf in the other circuit.

23. Shown below are two conductors, A and B. Conductor A is connected to a battery through a switch (S1). Conductor B is near conductor A, but is not connected to any voltage source. A meter is installed in series with conductor B and indicates any current flow in conductor B.



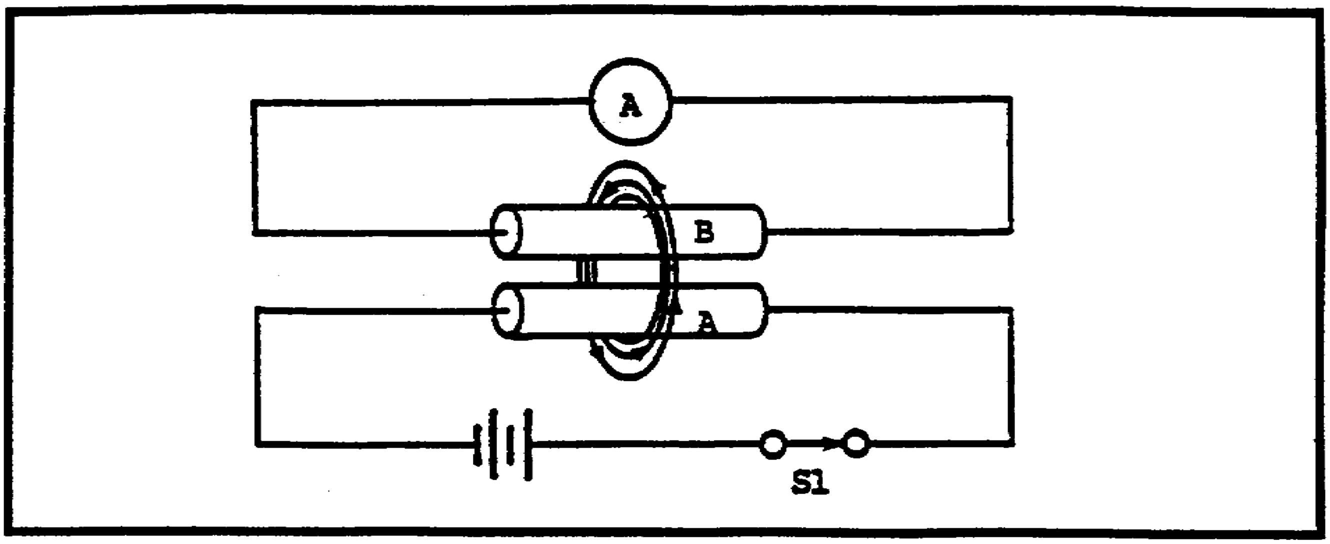
When the switch is closed, current builds up in conductor A. Lines of magnetic flux expand around conductor A and conductor b, as shown in the following drawing. A voltage is induced in wire B. The direction of the induced voltage in conductor B is determined by the left hand rule for generators. The current in conductor B is <u>opposite</u> in direction to the current in conductor A <u>at the point of induction</u>.



On the parallel conductors shown below,

a. Using a plus and minus sign, label the polarity of the induced voltage in conductor B when the switch is closed.

b. Using an arrow, indicate the direction of current flow through the meter when the switch is closed.



24. Which two symbols indicate mutual inductance.

a. M
b. L
c. h
d. Lm

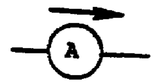
25. So far, the effect of mutual inductance has been discussed only as it apples to d-c circuits. This effect occurs only when the circuit is turned on or off, because that is the only time the magnetic field is changing. However, mutual inductance has a much greater and more useful effect in an a-c circuit, because the current in an a-c circuit is constantly changing. By placing a coil of wire near another and by applying an a-c voltage to the first coil, an a-c voltage is induced into the second coil. This device is known as a TRANSFORMER. Coils are used in transformers because a stronger magnetic field is produced by a coil than by a straight piece of wire. Transformers are used to transfer a-c electrical energy from one circuit to another by mutual inductance.

SOLUTIONS:

22. mutual inductance

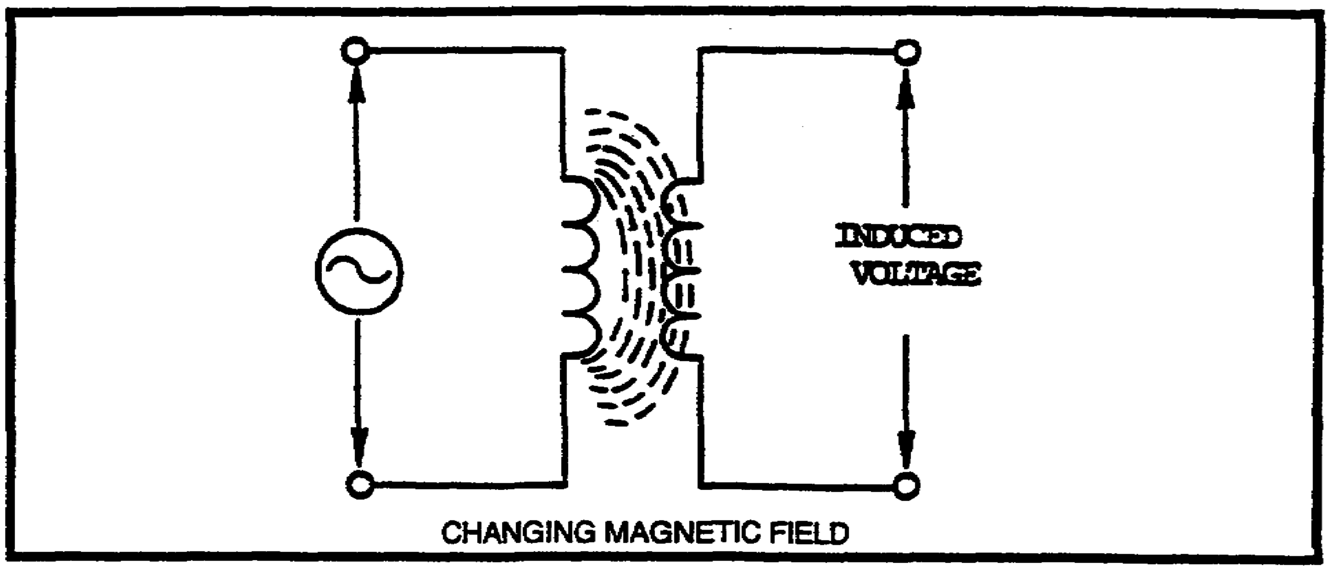
23. a.

b.



24. a & d.

25. CONTINUED.



In order to have mutual inductance, there must be a changing magnetic field. An a-c voltage produces a constantly changing magnetic field.

Q. Under what conditions can a d-c voltage produce a changing magnetic field?

26. Transformers are coils that transfer a-c energy from one winding to the other winding by mutual inductance. The mutual inductance between two coils is determined by two factors:

(1) The inductance of the coils in henrys, and

(2) The coefficient of coupling between the two coils.

26. (CONTINUED)

The larger the inductance of the coils in henrys, the greater the mutual inductance between the two. The coefficient of coupling is the percentage of magnetic lines of force originating in one coil that cut the other coil. Three factors determine the coefficient of coupling:

(1) Angular displacement between the two coils,

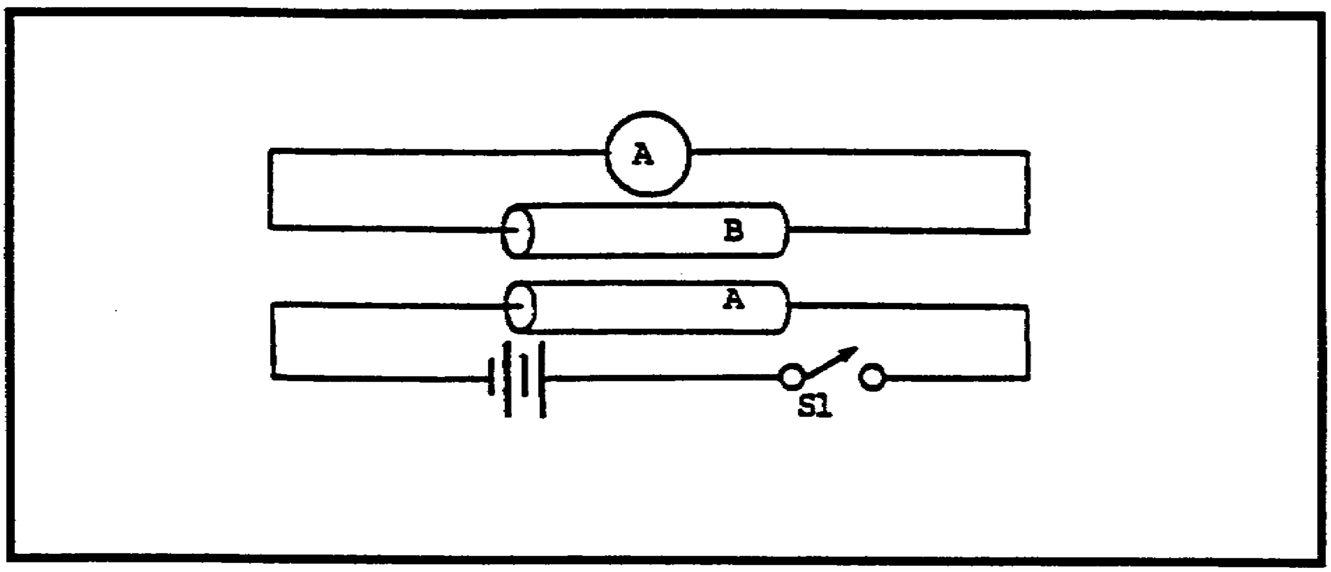
(2) permeability of the core material in each coil, and

(3) the distance between the two coils.

If the coefficient of coupling between two coils is 0.5 or 50 percent, only half of the lines of force produced by the first coil cut the second coil.

Q. What are the two factors that determine mutual inductance between two coils?

27. Using a plus and minus sign, label the polarity of the induced voltage in conductor B the instant the switch is closed; and draw an arrow indicating the direction of current flow through the meter.

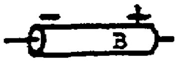


SOLUTIONS.

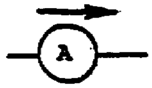
25. At the instant the circuit is energized or de-energized.

26. (1) inductance (2) coefficient

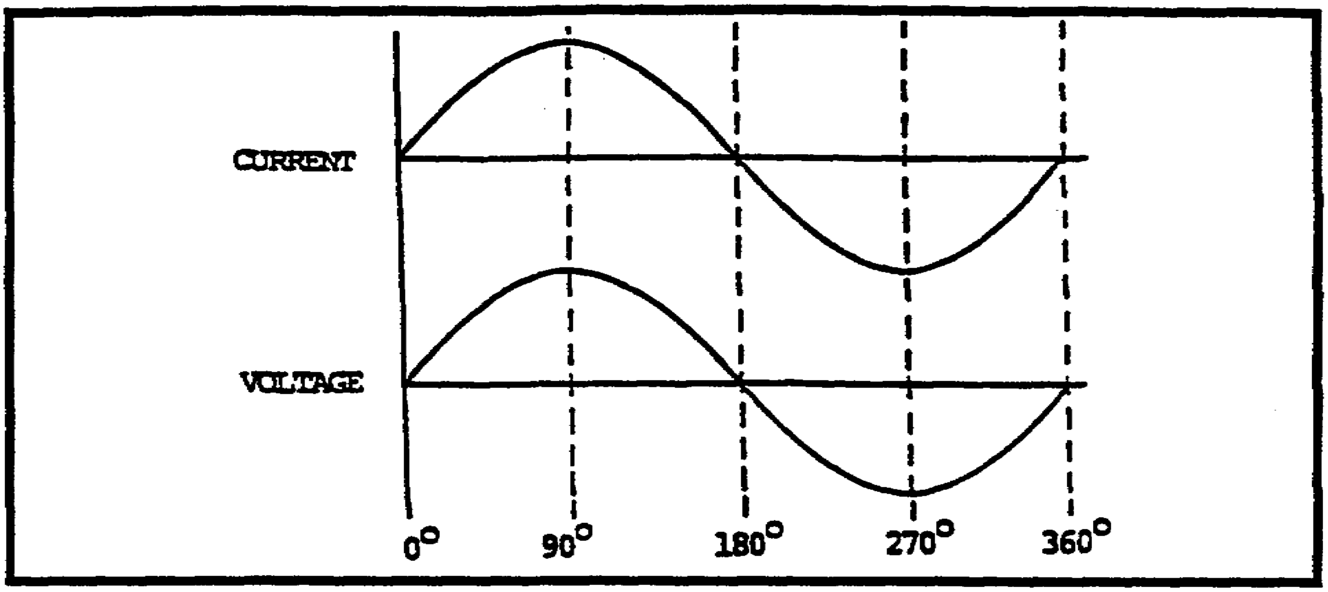
27. a.



b.



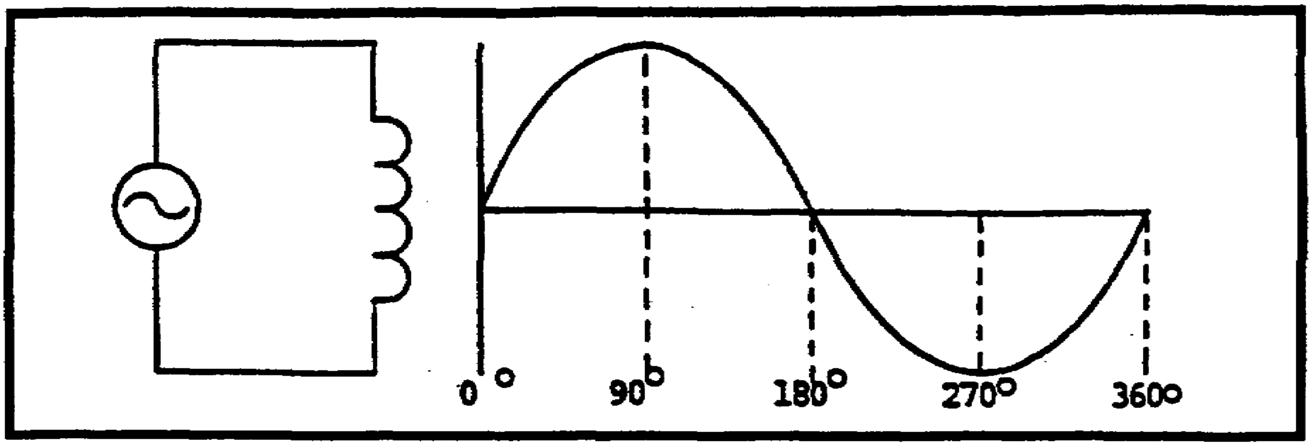
28. A generator produces an a-c voltage that varies at a sine-wave rate. One revolution of the generator rotor produces one sine wave (cycle) of voltage. When two or more sine waves are compared, to observe if they occur at the same time, their phase relationships are being compared. Shown below is a comparison of the a-c voltage sine wave and the a-c current sine wave in a purely resistive circuit. (A circuit with only resistors.)



The two sine waves are in phase, because their maximum and minimum points occur at the same time. When the sine waves are in phase, any change (increase or decrease) in voltage causes a corresponding change in current.

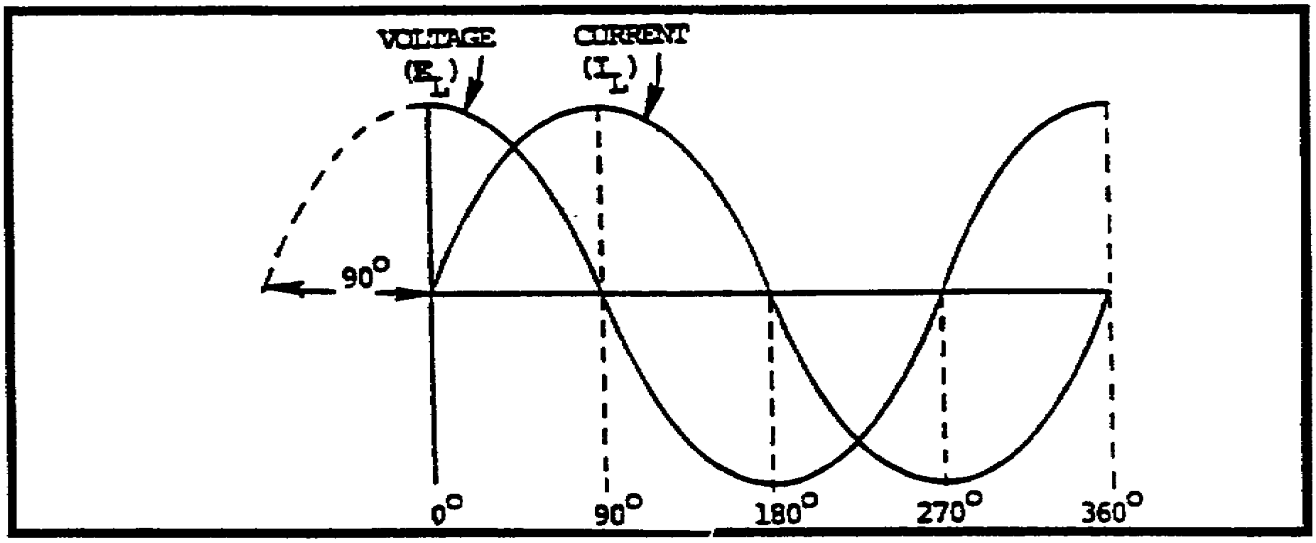
28. (CONTINUED)

In an a-c circuit which has an inductor instead of a resistor, there will be a phase difference between voltage and current. Shown below is a generator connected to an inductor. The sine wave represents the current flowing through the inductor.



On any sine wave, the greatest rate of change of current occurs at 0° and 180°. (Note: 360° is the same as 0°.) Since the most opposition to a-c current occurs as the current is changing at its greatest rate, the greatest amount of opposition occurs at 0° and 180°.

An opposition to a changing current in an inductor is in the form of an induced voltage; therefore, the maximum induced voltage in an inductor occurs as the current is changing at its greatest rate, the greatest amount of opposition occurs at 0° and 180°. The drawing below illustrates the relationship between the inductor voltage and the inductor current.



From the comparison above, it can be seen that the voltage leads the current by 90° in an inductor. (Another way to say this would be that the voltage is at its maximum value at 90° before the current at its maximum value.)

Q. In an inductor, the voltage ________________ the current by 90°.
(leads/lags)

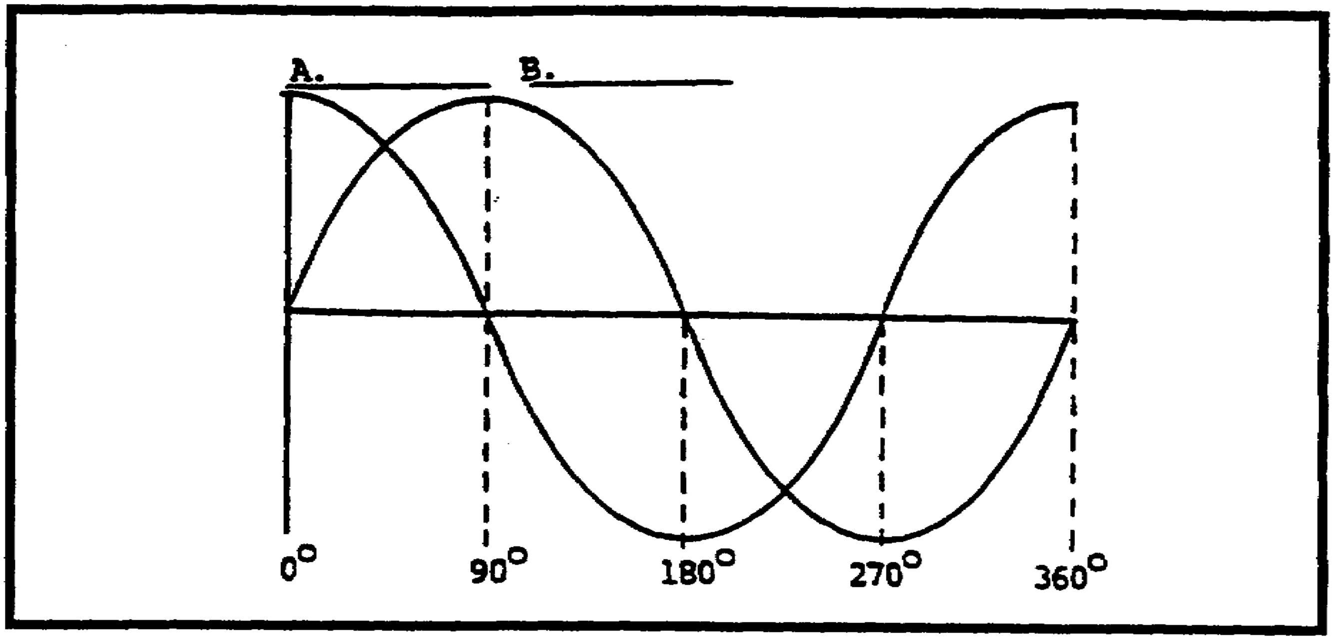
28. (CONTINUED)

The name E L I is a "crutch" for remembering the phase relationship between voltage and current in an inductor of and inductive circuit.

E L I

Voltage Leads Current
(L = INDUCTANCE)

The curves below represent the relationship between current and voltage in a purely inductive circuit. Label the circuit current waveform and the inductor voltage waveform.



29. Q. Which statement correctly identifies a purely inductive circuit?
   a. The voltage leads the current by 90°.
   b. The current leads the voltage by 90°.
   c. The voltage lags the current by 180°.
   d. The voltage leads the current by 180°.

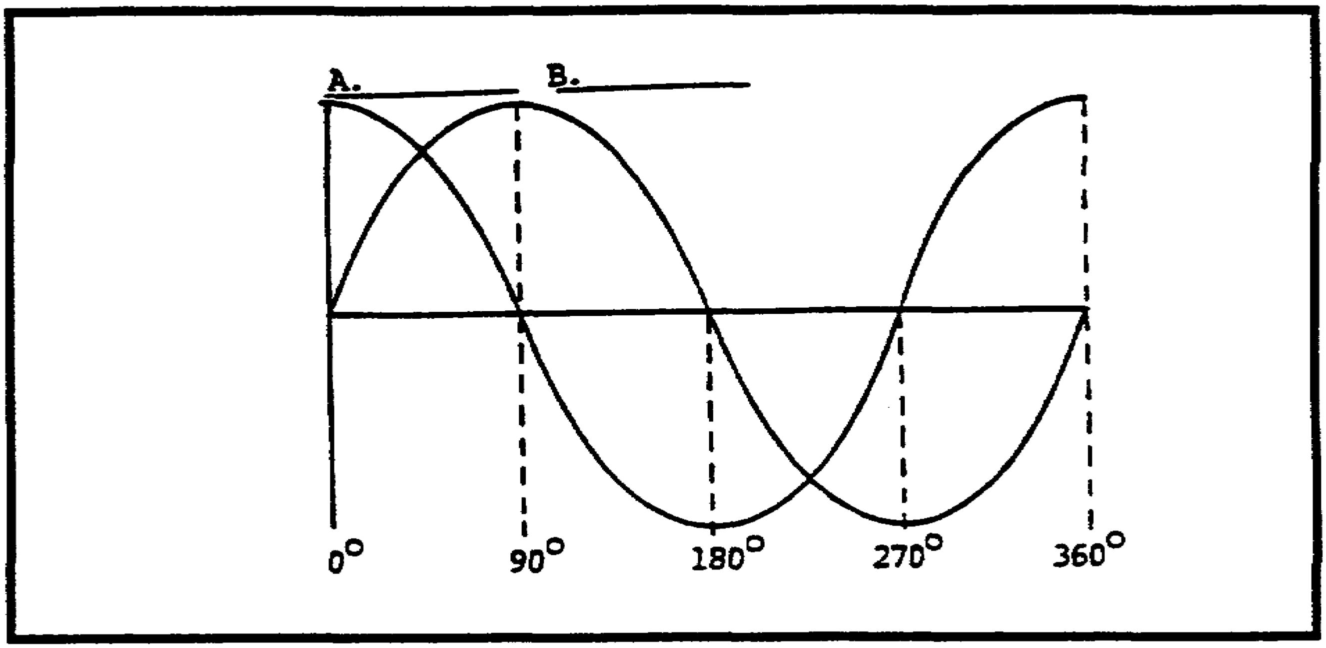
30. Because of the property of inductance to oppose a change in current, a certain amount of time is required for current change. The time it takes the current in a circuit containing only resistance, inductance, and a d-c voltage source to change 63.2 percent of its value, is known as the L/R TIME CONSTANT. The time constant is determined by the ratio of circuit inductance to circuit resistance. The mathematical equation is:

$$TC = \frac{L}{R}$$

where TC = time constant in seconds
L = circuit inductance in henrys
R = circuit resistance in ohms

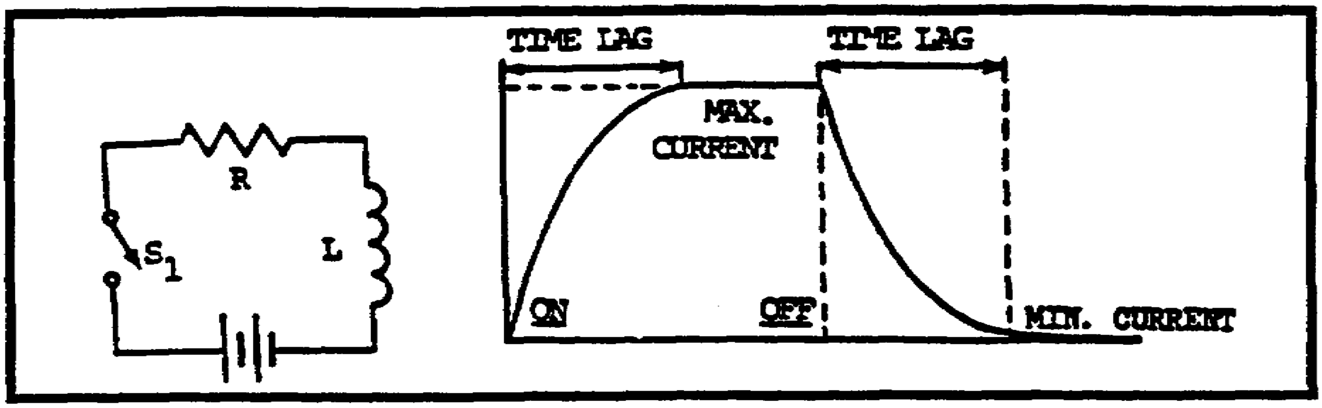
Calculate the L/R time constant of a circuit with 2h of inductance and 10 Ω of resistance.

31. On the inductive waveforms shown below, label the current and voltage waveform.



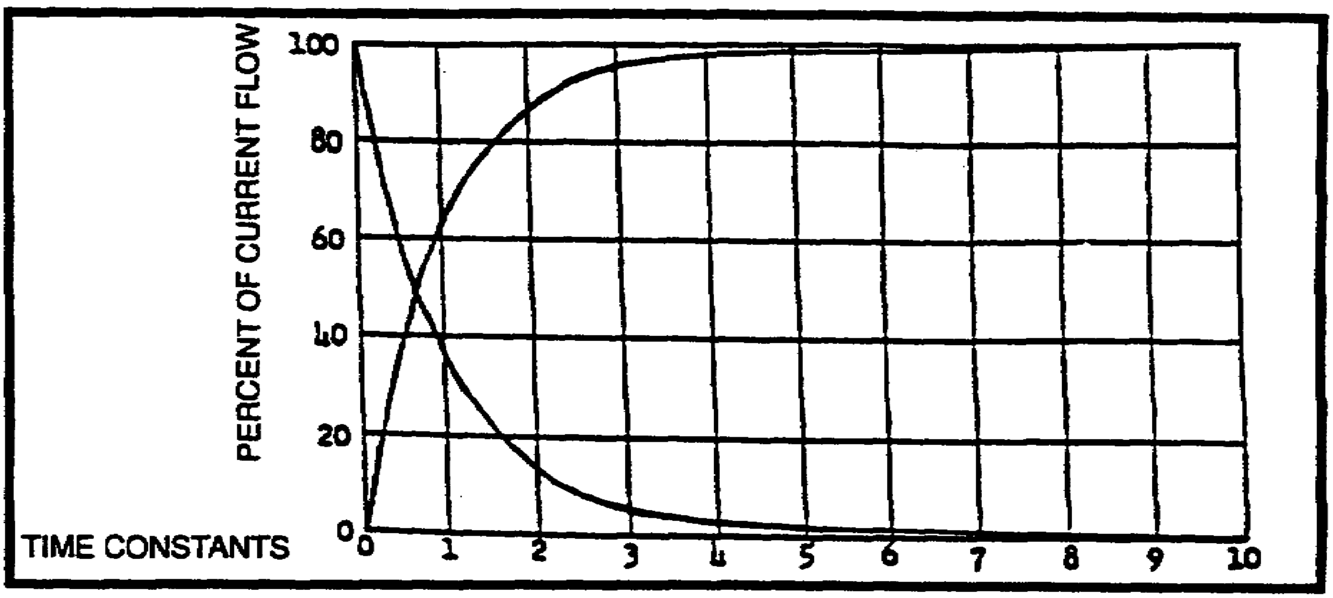
SOLUTIONS.
28. leads; A. Voltage B. Current
29. a
30. 0.2 seconds
31. A. Voltage B. Current

32. The L/R time constant is very important in radar and television circuits. To better understand L/R time constants, observe the d-c circuit below which contains a battery, a switch, an inductor, and a resistor.



When S1 is closed, current does not immediately flow, because of the counter emf produced by the coil as the magnetic field expands about it. Instead, current "builds-up" at a specific rate, depending on the value of resistance and inductance. The current reaches its maximum value only when the magnetic field about the inductor has become stationary. The current “build-up” is at an exponential rate, which is not linear. When the current is turned off, the magnetic field collapses around the wire and tries to keep current flowing after the switch is opened. Current decreases to zero at an exponential rate.

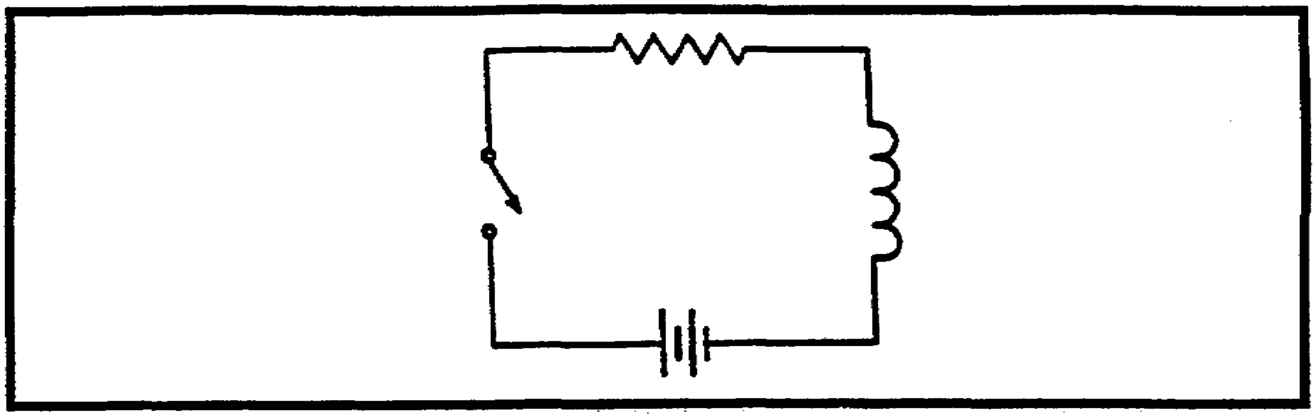
The exponential rate is plotted as a curve on the following chart, which is known as a Universal Time Constant Chart.



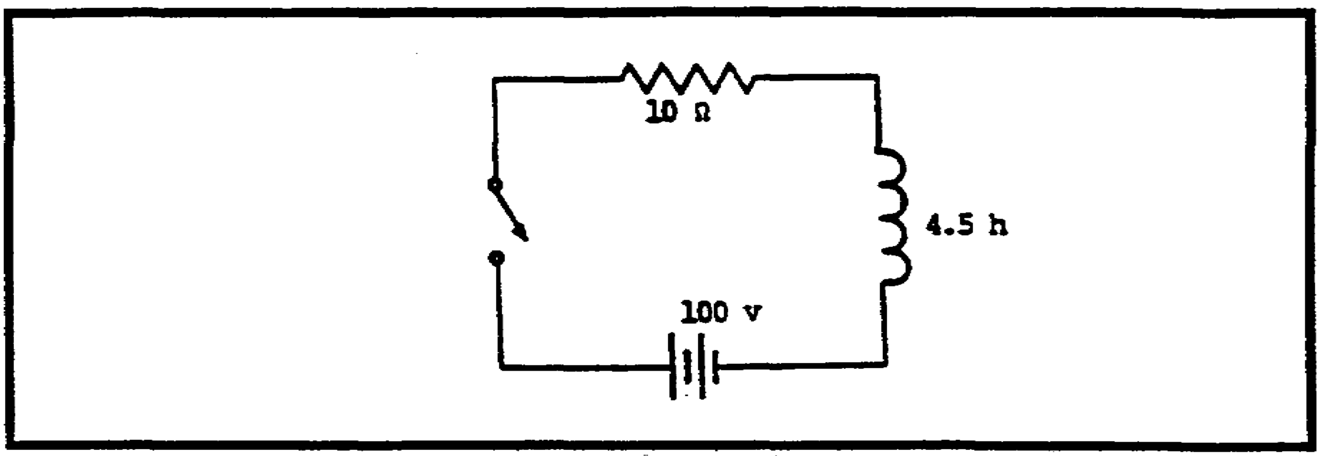
32. (CONTINUED)

It can be observed from the chart that one time constant is the length of time required for current to build to 63.2 percent of its maximum value, or from its maximum value to zero.

Q. How many time constants will be required for the current in the figure below to reach its maximum value after the switch is closed?



33. What is the L/R time constant of the circuit shown below?

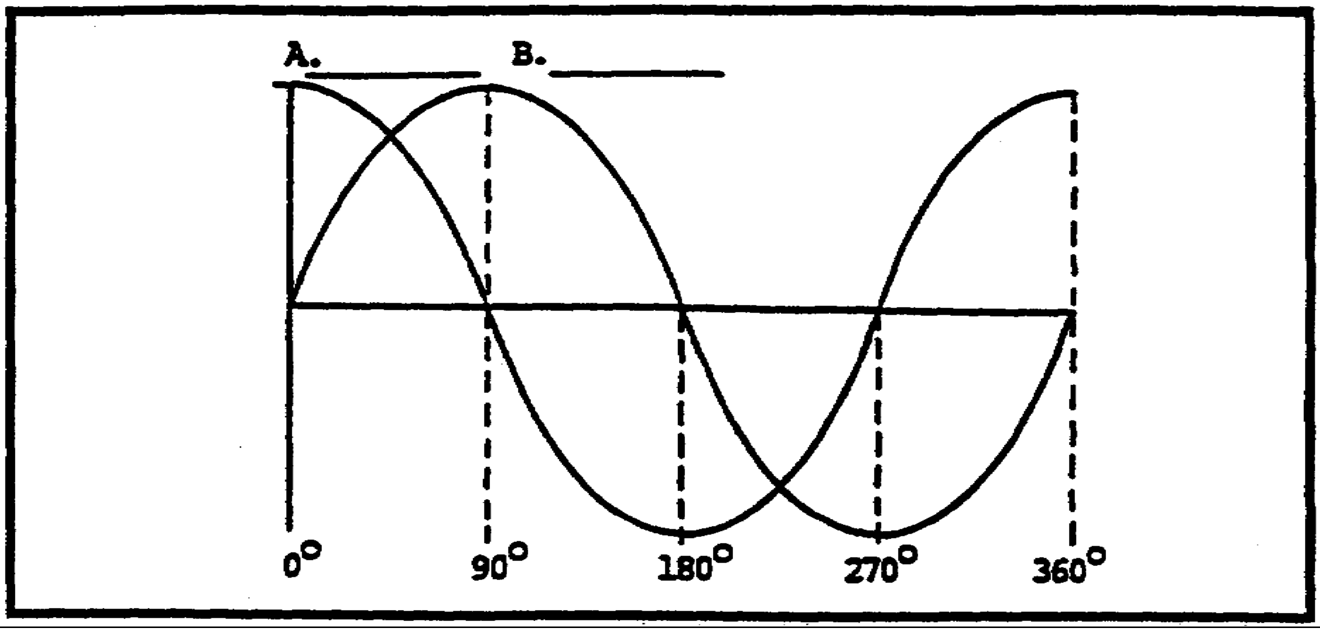


34. State the relationship between the voltage and the current in a purely inductive circuit.

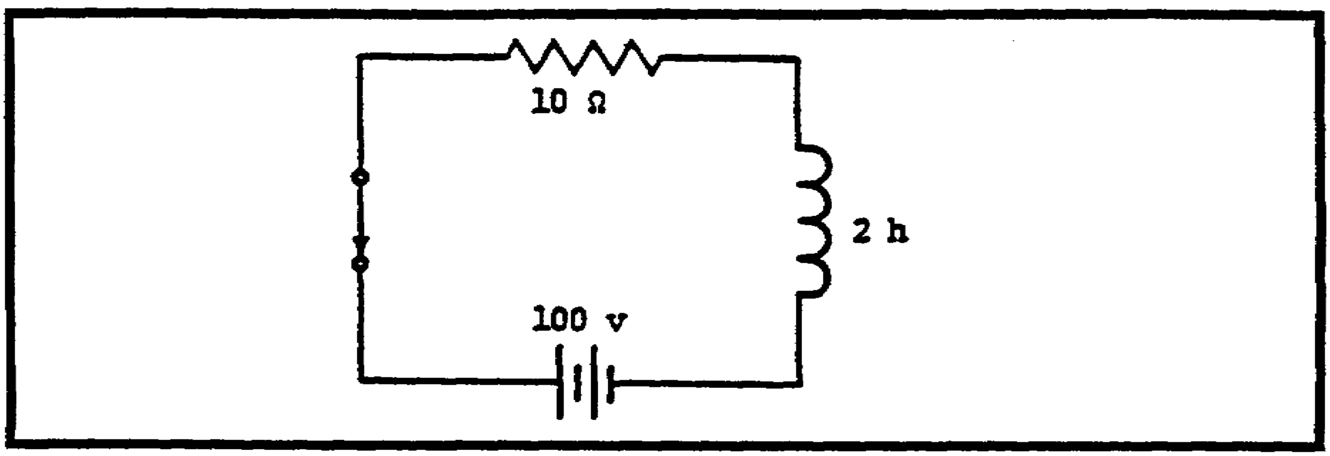
35. Q. How many time constants are required for maximum current to flow in an L/R circuit after it's energized?

SOLUTIONS
32. Ten
33. 0.45 seconds.
34. The voltage leads the current by 90°.
35. Ten

36. Label the current and voltage waveform on the drawing shown below.



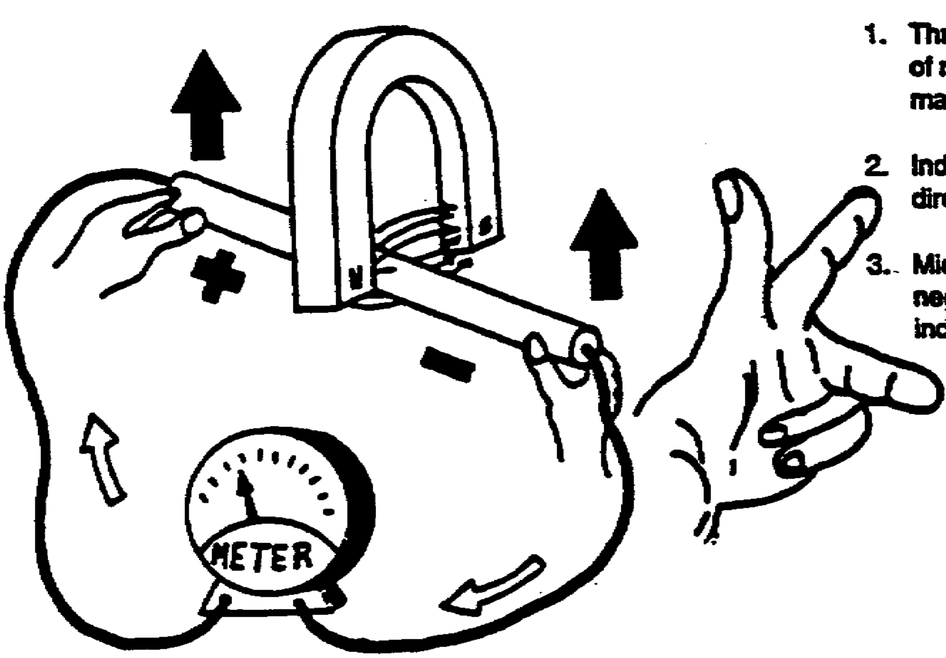
37. What is the L/R time constant of the circuit shown below?



38. How many time constants are required for maximum current flow in a circuit after it has been energized?

39. In 1831, Michael Faraday, an English physicist, showed that when a conductor was passed through a magnetic field, an emf (voltage) was induced in that conductor, which caused current to flow through the conductor.

A drawing depicting Faraday's experiment is shown below.



NOTE: The left-hand rule for generators can be used to determine the polarity of the induced emf.

1. Thumb points in the direction of motion of conductor in the magnetic field.
2. Index finger points in direction of the magnetic field.
3. Middle finger the points to the negative (-) polarity of the induced emf.

SOLUTIONS

36. A. Voltage B. Current
37. 0.2 seconds
38. Ten