Fundamentals of Core Memories

MI-1100

FIELD ENGINEERING DEPARTMENT
Univac Division
SPERRY RAND CORPORATION

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PREFACE

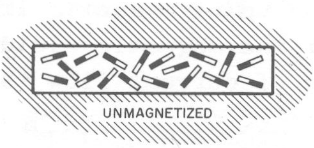
This handbook was prepared by Training and Publications personnel of the Field Engineering Department Training Center (Ilion/Utica) to familiarize the student with the basic theory of magnetic cores and their application to magnetic core memories. It is hoped that this book will provide the student with a background which will aid him when he starts formal classroom training.

Fundamentals of Core Memories was written by Robert E. Hanson, illustrated by Eugene A. Yelle, and edited by Alan B. Gilmore. Manuscript typing was done by Mary Sterling.

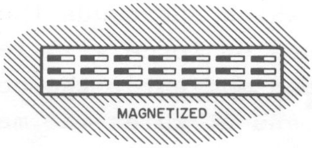
MAGNETIC CORE MEMORIES

Magnetic core memories are widely used in computers because they are compact, reliable and consume very little power. Furthermore, their access time (the time it takes to extract information from the memory) is usually in microseconds. Since the magnetic core is nothing more than a small magnet, a brief review of magnetism will be given.

One theory of magnetism states that in magnetic materials, there are groups of atoms which have their magnetic fields more or less permanently lined up. These groups of atoms are called domains and may be represented by a number of small magnetic particles within the material itself.



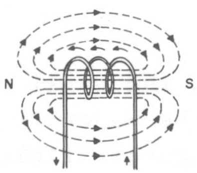
When the material is magnetized, the small magnetic particles are aligned so the majority are aiding one another, causing a magnetic field to be built up through and around the material.

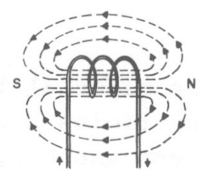


When the material has been magnetized completely, it is saturated and an increase of applied magnetizing force does not result in an increase of magnetism.

After the magnetizing force has been removed, many substances will retain most of their magnetism; these substances are known as permanent magnets. Some substances will become magnetized easily but will lose most of their magnetism after the magnetizing force has been removed. These substances are known as temporary magnets.

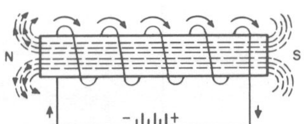
One method of magnetizing a material is by the use of a coil of wire which can pass current in either direction. If current is passed through a coil of wire, a magnetic field will be developed around and through the coil of wire. This magnetic field is made up of magnetic lines of force. The direction of the magnetic field will depend on the direction of current flow through the wire.





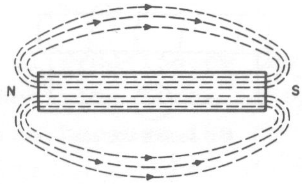
As long as current is allowed to flow through the wire, the magnetic lines of force will travel through the air which surrounds the coil of wire. The magnetic lines of force will leave the coil of wire at one end and enter the coil at the other end. The end at which the magnetic lines of force leave the coil is called the North Pole of the magnet and the end at which the magnetic lines of force enter the coil is called the South Pole of the magnet. Therefore, while the current is flowing through the coil, the area around the coil is acting as a magnet. But, since air is a poor magnetic substance, the magnetism will be lost as soon as current stops flowing in the coil of wire.

However, if a good magnetic substance (one which magnetizes easily and retains most of its magnetism after the magnetizing force has been taken away) is placed inside the coil of wire and current is passed through the wire, the magnetic field set up by the coil will magnetize the material. This is accomplished by the magnetic field passing through the material and aligning all of the magnetic particles in a certain direction. The direction, of course, will be determined by the direction of the magnetic field that is applied.



BATTERY

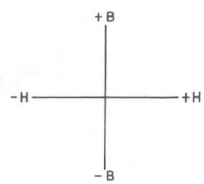
If, after the material becomes magnetized, the magnetizing force is taken away, the material will retain most of its magnetism.



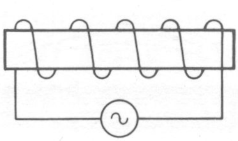
RESIDUAL MAGNETISM

The magnetic lines of force (magnetism) within or surrounding a magnetic material are commonly called magnetic flux, and the density of these lines of force, in a good magnetic substance, will vary in proportion to the magnetizing force up to the point of saturation.

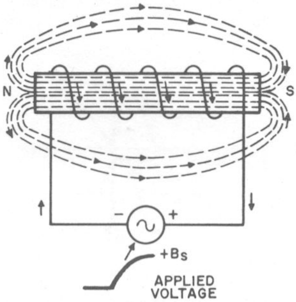
A good method of representing the way flux density (B) in a magnetic material varies with the magnetizing force (H) is through the use of curves, where flux density (magnetism) is plotted as a function of the magnetizing force (current). In the curves, the flux density (quantity B) is measured in gausses, one gauss being equal to one magnetic line of force per square centimeter or 6.45 lines per square inch and the magnetizing force (quantity H) is measured in oersteds, one oersted being equal to 0.4π ampere turns per centimeter or 2.015 ampere turns per inch.

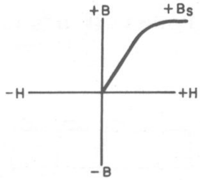


If an A-C source is applied to a coil wound around a magnetic material,

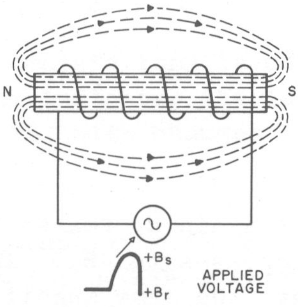


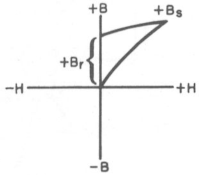
the material is first magnetized to positive flux saturation, designated $+B_s$, when the current flows in one direction.



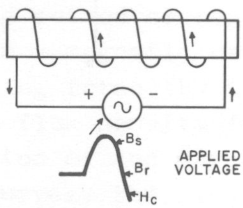


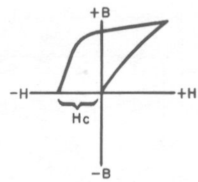
When the current decreases to zero, the magnetizing force (H) decreases to zero also, but the flux density or measure of magnetization is only partially reduced. This remaining flux which is present when the magnetizing force is zero, is called residual magnetism and is designated as B_r.



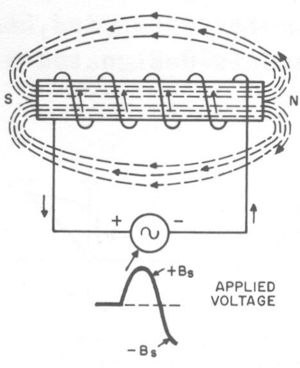


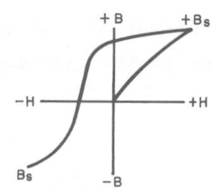
During the next alternation of the applied source, the magnetizing force is applied in the opposite direction because the current flow is reversed. A point is reached at which the flux density is reduced to zero. The amount of magnetizing force of opposite polarity which must be applied to decrease the flux density to zero is called the coercive force and is designated as H_c.



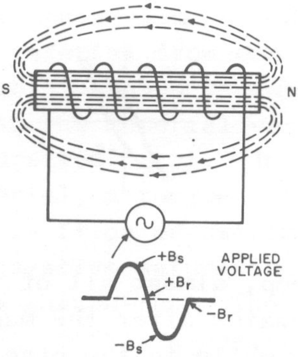


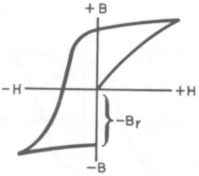
As the magnetizing force is increased further, the magnetic flux density increases to a negative flux saturation, designated as $-B_s$.



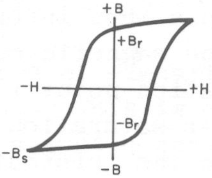


As the magnetizing current again decreases to zero, the flux density decreases to $-B_r$. The quantities $+B_r$ and $-B_r$ have the same magnitude but opposite magnetic characteristics.



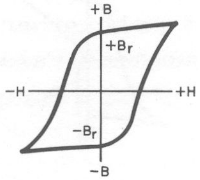


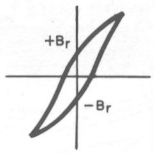
During the next alternation the material is again driven to $+B_S$, and on all subsequent cycles the material will go through this loop.



The complete loop is called a hysteresis loop and it indicates the lag in changes of flux density (B) with changes in the magnetizing force (H).

If a comparison is made between the hysteresis loops for a GOOD magnetic substance (one which retains most of its magnetism) and a magnetic substance which loses most of its magnetism, after the magnetizing force has been removed, it will be evident that the hysteresis loop for the good magnetic substance is much squarer than the other.



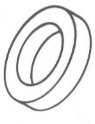


Notice that in the square loop, almost all of the magnetic flux (magnetism) remains after the magnetizing current is removed, while in the other loop almost all of the magnetic flux is lost after the magnetizing current is removed.

The material used for magnetic cores must be a good magnetic substance with a high residual characteristic because when information is stored in magnetic cores the magnetic material will be driven to one saturation point for a bit condition and to the other saturation point for a no-bit condition. Once the information is stored in the cores, only the residual properties of the material can retain this bit or no-bit indication.

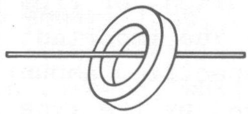
In comparing the two loops, notice that the square loop requires a greater amount of current to merely overcome the remanent magnetism and bring the material to a neutral condition and that any additional current produces flux in the opposite direction until the material again reaches its saturated condition. Notice also that the change from positive to negative saturation is very sharp. As the magnetizing current is applied, it will have very little effect on the remanent flux until the current reaches the knee of the curve. Thus, this value of current is needed to switch the material from one polarity to the other. A slight increase in current beyond this value will bring the material very rapidly to the opposite saturation point. In switching a core or magnetic material, a toggle action takes place, which simply flips or switches the material from positive to negative saturation, or from negative to positive saturation. The important thing to understand is that a specified amount of magnetizing current (determined by the type of core used) is required to switch the material and anything less than this value could not overcome the remanent magnetism and the material would simply stay magnetized in its original polarity (either positive or negative saturation).

Now consider a piece of magnetic material in the shape of a doughnut. This is commonly referred to as a toroid or magnetic core.

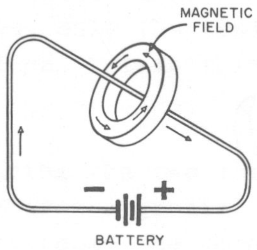


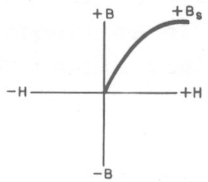
The magnetic cores used in core memories are made of a highly retentive ferrite material. This means that once the material has been magnetized in one direction or the other, it will retain most of the magnetism.

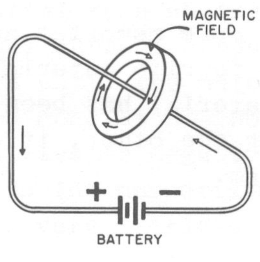
The method of magnetizing the magnetic core is very similar to the common method of surrounding a magnetic material with a coil of wire and passing current through the wire. However, instead of surrounding the magnetic material with a coil of wire, the wire is surrounded by the doughnut shaped core.

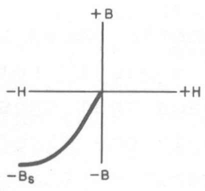


If a current is passed through the wire, lines of magnetic force will extend outward from the wire. These lines of force will produce a magnetic field in the core material. This magnetic field will tend to set up a magnetic field in the material itself. The direction of the magnetic field will depend upon the direction of current flow through the wire.



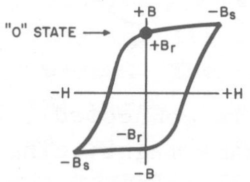


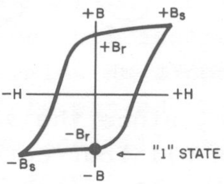




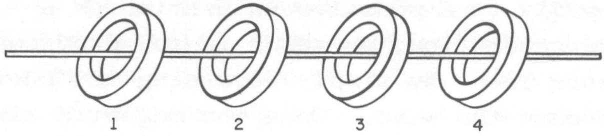
The magnetic field in the core can be switched very rapidly to a positive saturation or a negative saturation, as shown in the previous hysteresis loop, by simply reversing the current flow through the wire. Once the magnetic field is set up in the core, the current can be removed from the wire and the core will remain in an almost saturated condition.

As shown earlier, magnetic cores can be driven to either of two stable conditions of magnetic saturation. One condition exists when the magnetic field is clockwise within the core and the other when the field is counterclockwise. Therefore, by using one state as a "0" and the other state as a "1", the core can be used to store information in the form of a "1" or "0". In this text the $-B_r$ saturation point will indicate a stored "1" and the $+B_r$ saturation point will indicate a stored "0". Thus by simply passing current through a wire to drive the core to a positive saturation or a negative saturation, information can be written and stored in a magnetic core.

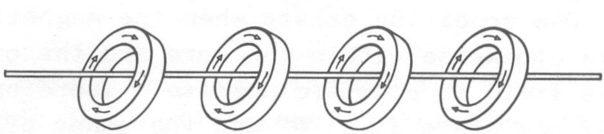




Now that you have seen how a magnetic core can be switched from one state to the other to store information, assume there are four cores in which to store information.

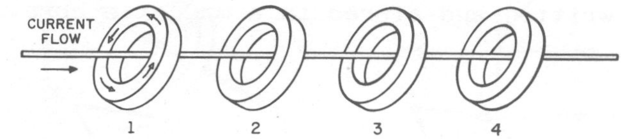


With a single wire being used to store information in the cores, all of the cores will receive the same information. To understand this, assume all of the cores are storing a "1" indication.

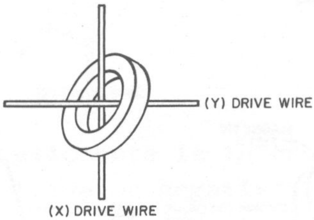


ALL CORES ARE STORING A "1" INDICATION

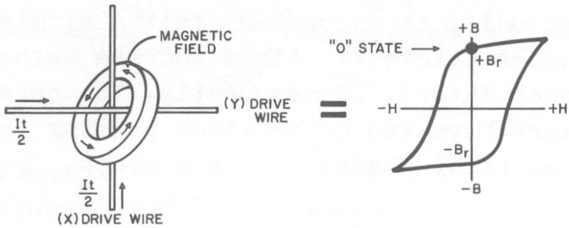
If a "O" indication is to be stored in core #1, current is passed through the wire in a direction which will switch the magnetic field in core #1 to the opposite direction.

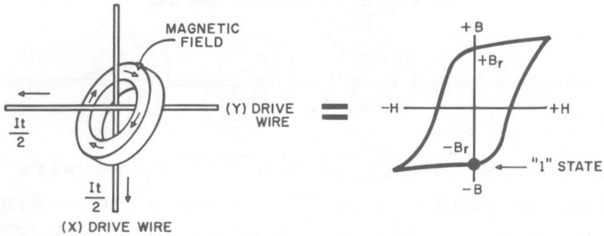


However, since the same wire is connected through all four cores, the same magnetizing current will switch all four cores at the same time thereby changing the information stored in cores 2, 3 and 4 to the "O" state also. This means that although one wire can switch a core from positive to negative saturation, or vice versa, it cannot permit the cores to be separately controlled. Since there must be some method of addressing or selecting each individual core in the memory unit, it is obvious that a single drive wire is not sufficient. (This address method will be explained later). Consequently, the cores used in computers have two drive wires passing through the core at right angles to one another.



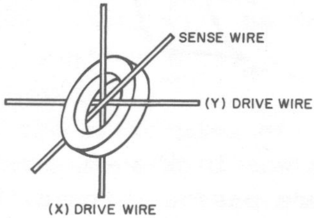
One drive line is called the "Y" drive wire and the other is called the "X" drive wire. Since two drive wires are used, the total current needed to magnetize a core (I_t) must be divided equally between the X drive wire and the Y drive wire. The core is magnetized to a "1" or "O" condition by the coincident current method. With this method, one half of the magnetizing current ($\frac{I_t}{2}$) is applied to the X wire and the other half of the magnetizing current ($\frac{I_t}{2}$) is applied to the Y wire. This results in I_t at the intersection of the two wires. The magnetic fields developed around the wires, when current is passed through the wires, will aid one another and will supply the necessary magnetizing force to magnetize the core in a positive or negative direction.





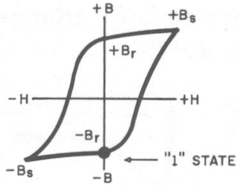
An important point to note is that current must be present in the X and Y wires in order to switch the cores. For example, if current is passed through only the Y drive wire and not the X drive wire, only one half of the magnetizing current is present and the core will remain magnetized in its original direction. Thus, in actual core memories, information ("1" or "0") can only be written into the cores by passing current through the X and Y drive wires in the proper direction.

Once information is written into a magnetic core, there is no outward indication of what is stored ("0" or "1"). Therefore, in order to use the stored information there must be a method of reading this information out of the cores. This is called sensing the cores. Reading out of, or sensing the cores, can be accomplished by threading a third wire, called the sense wire, through the core which will detect any change in magnetic flux within the core.



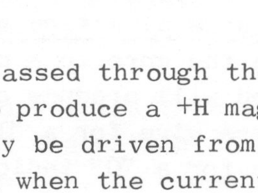
Whenever the magnetic core is in one saturated state, either positive or negative, and drive currents are applied in a direction which will saturate or switch the core to the opposite direction, a considerable change in magnetic flux occurs. As this large flux change occurs, the changing magnetic lines of force will cut across the sense wire and induce a small voltage into the sense wire. This voltage is then amplified and is used as the output signal from the core. As can be seen, the output signal could be a "1" or "0" depending on the direction of current flow in the drive wires and whether the core was near a negative saturation point ($-B_r$) or a positive saturation point ($+B_r$). When the core is sensed, the currents which are passed through the drive wires will always be in the same direction and will always attempt to switch the core to a positive saturation. This method will produce a large output signal on the sense wire for a "1" indication and a very small output for a "0" indication.

To further illustrate this, reconsider the hysteresis loop.



Assume the core was in the $-B_r$ state ("1" state) and currents were passed through the drive wires in a direction to produce a +H magnetizing force. This will drive the core to a positive saturation which switches the core. When the core switches, the large flux change will induce a signal into the sense wire which will be amplified as a "1" output.

A different effect is produced when a core is sensed that is originally in the $+B_r$ state ("O" state).



If currents are passed through the drive wires in a direction to produce a +H magnetizing force, the core will only be driven from the $+B_r$ state to the $+B_s$ state and when the currents drop back to zero in the drive wires, the core will settle back to the $+B_r$ point. It should be noted that when the currents were applied to the drive wires and the core was driven to the saturation point, the core was actually being saturated in the same direction that it was originally magnetized. Thus, small flux and voltage changes are developed and a small voltage is developed on the sense wire. This will be detected as a "0" output.

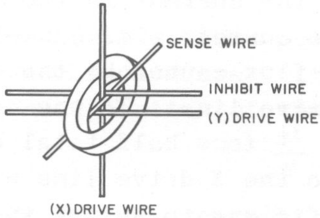
Keeping in mind the principles of sensing a core, notice that a core which originally stored a "1" was switched to the "0" state when it was sensed or read and the core that was originally storing a "0" was not switched when it was sensed. This indicates that the original information stored in the core is lost upon sensing if it contained a "1". But if it contained a "0", the core was not affected, and after sensing, the core still contained the original information. From this, it can be seen that a method is necessary to return the original information back to the cores after a sense operation has taken place.

Before explaining how this is done, it is necessary to explain the overall operation of reading and writing into a core memory. First, there are two basic cycles of operation that take place. One is a read/restore cycle in which information is read out of the cores and is automatically returned or written back into the same cores from which it was read. The other cycle is a clear/write cycle in which new information is to be written into the cores. At the beginning of the write cycle the cores which are to be written into are all cleared to "0"'s and then, during the actual write operation, the new information is placed in the cores.

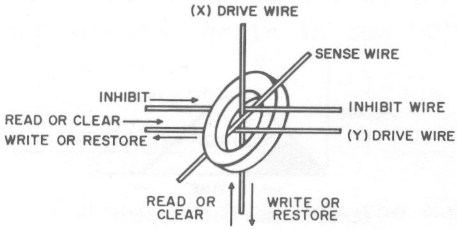
CLEAR/WRITE CYCLE

The clear portion of the clear/write cycle begins by clearing to "O" all cores into which information will be written. This is achieved by applying currents to the X and Y drive wires in a direction to switch the selected cores so that at the end of the read out, all of the selected cores will be in a "O" state. Although information being read out of the selected cores will be present on the sense wires, it is not used. During the clear portion of a clear/write cycle, the new information to be written into the specified cores, is temporarily stored in flip-flop circuits. Immediately following the clear operation, the currents in the X and Y drive wires are applied in a direction which will switch all of the selected cores to "1"'s. Wherever a "1" is present in the new information to be written, only those cores which are to receive "1"'s will be switched from the "O" state to the "1" state. Therefore, the cores that are to remain in the "O" state must be inhibited so they cannot be switched to the "1" state.

To do this, another wire (the fourth and last) is threaded through the magnetic core. This wire is called the inhibit wire and it is placed directly in parallel with the Y drive wire or the X drive wire depending upon the computer being used. (In this book, it is assumed to be parallel with the Y drive wire).



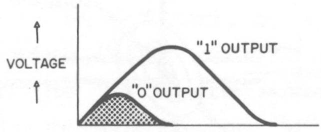
The purpose of the inhibit wire is to prevent a "1" from being written into the core where a "0" is to be stored. Remember that a core is magnetized to a "0" condition when it is sensed, since $\frac{I_t}{2}$ (one half the total drive current) is applied to the X and Y drive wires in a direction which drives the core to a positive saturation. Now to write a "1" into the core, $\frac{I_t}{2}$ is applied to the X and Y drive wires in the opposite direction and the core is driven to a negative saturation.



To restore a "0" into a core, the currents applied to the X and Y drive wires must not be allowed to switch the core to a negative saturation. This is accomplished by passing a current ($\frac{I_t}{2}$) through the inhibit wire. This current must be equal in magnitude but opposite in direction to the current in the Y drive line. The inhibit wire current will cancel the effect of the magnetic flux caused by the current through the Y drive line. To the core, this acts as if only $\frac{I_t}{2}$ (one half total current) is being applied to the X drive line and of course, this is not sufficient to switch the core.

READ/RESTORE CYCLE

During a Read/Restore Cycle, the current applied to the X and Y drive wires is always in a direction which will switch the cores to the "O" state. If a core was originally in the "1" state, a large flux occurs inducing a large voltage on the sense wire. If a core was originally in the "O" state a small flux change occurs and a small voltage is induced on the sense wire.



SENSE WINDING OUTPUT CURVES

The information read from the cores to the sense wires is temporarily stored in flip-flop circuits. This is done for two reasons; (1) the information can be taken from the flip-flops and used in the computer as needed; (2) while the information is temporarily stored, it is used to indicate what must be restored to the cores from which the information was taken.

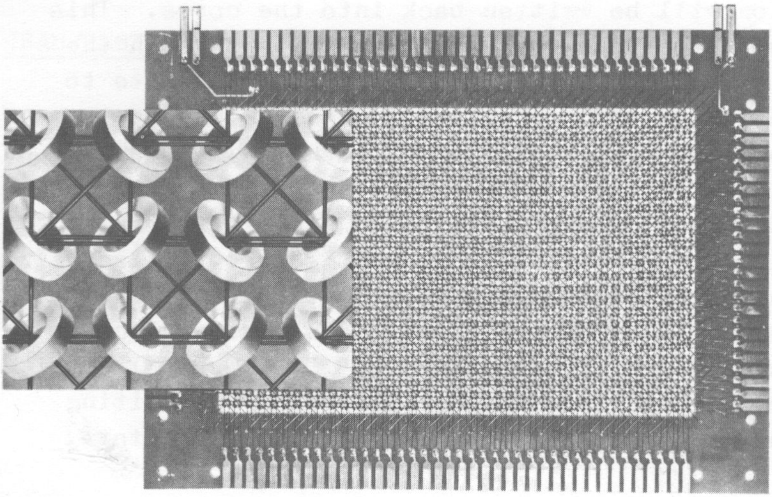
It is important to note at this point, that all cores that were sensed are left in the "O" state after the read portion of the Read/ Restore cycle.

Immediately after the read operation, a restore operation will take place in which the information will be written back into the cores. This is accomplished by passing current through the X and Y drive wires in a direction opposite to that of a read operation. Since in a read operation the direction of current would switch all cores to the "O" state, the current for the restore operation will be in a direction which will switch the cores to a "1" state. All of the cores that were sensed in the read operation may not have contained a "1", so only the cores that originally contained a "1" will be allowed to switch. This is accomplished by inhibiting the cores that are to remain in the "O" state.

MAGNETIC CORE MATRICES

In addition to understanding how the magnetic core works and how information can be written into or read out of cores, it is also necessary to understand the arrangement of the cores in a memory unit and how the different cores can be selected.

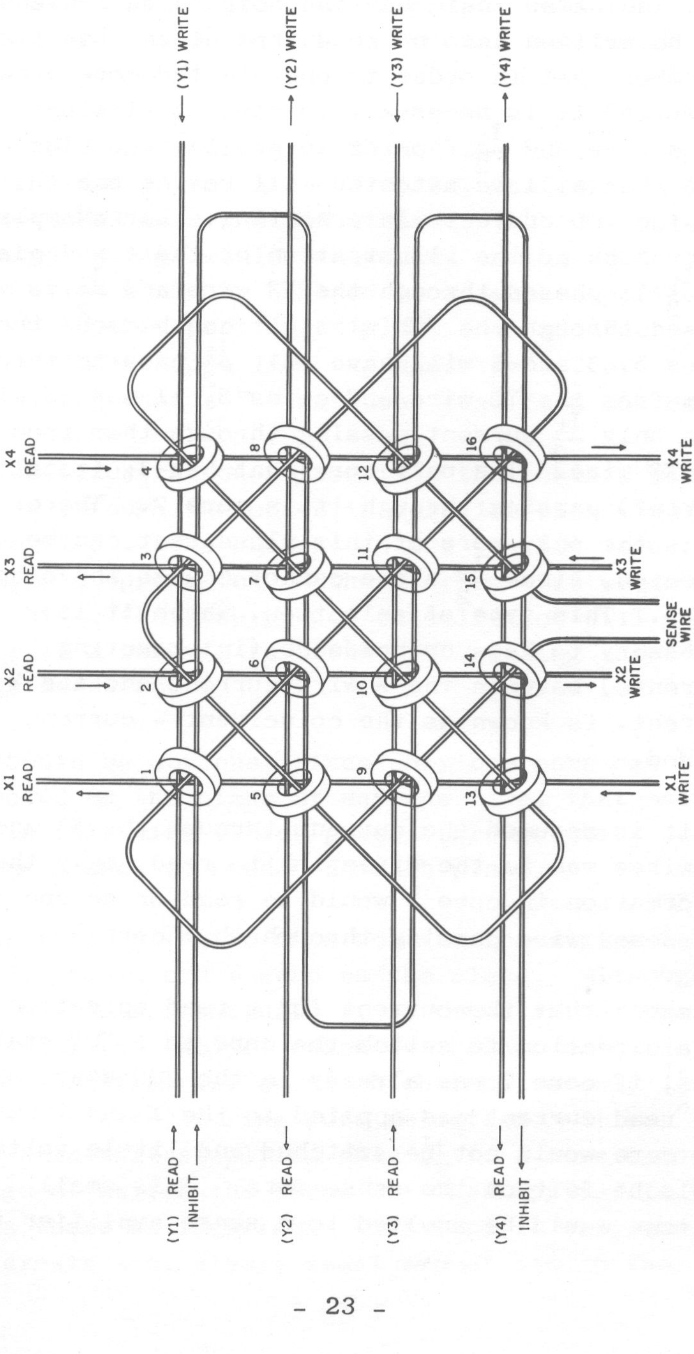
The small magnetic cores are arranged into a matrix on a board, commonly called a memory plane or digit plane, with four wires passing through each core on the plane. The number of cores on a plane will vary from one computer to another since the number of cores used determines the number of words that can be stored. In some computers, memory planes consist of a great many cores on one plane as shown on the following illustration.



MAGNETIC CORE MEMORY

For simplicity, the plane used for explanation here will contain only 16 cores (4 x 4).

Notice on the following illustration of the 16 core (4 x 4) memory plane that each X wire and each Y wire passes through four cores on the plane, while the sense wire and the inhibit wire pass through every core on the plane.


X1 READ
X2 READ
X3 READ
X4 READ
(Y1) WRITE
(Y2) WRITE
(Y3) WRITE
(Y4) WRITE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
X1 WRITE
X2 WRITE
X3 WRITE
X4 WRITE
SENSE WIRE
(Y1) READ
INHIBIT
(Y2) READ
(Y3) READ
(Y4) READ
INHIBIT

This indicates that only one core on each plane can be written into or read from at any one time. Remember that in order to operate the core (read or write) it is necessary to have $\frac{I_t}{2}$ flowing in the X wire and $\frac{I_t}{2}$ flowing in the Y wire. The only core that will be affected will be the one that has the two currents intersecting. For example, refer back to the illustration of the 4 x 4 plane. If $\frac{I_t}{2}$ is passed through the X3 wire and $\frac{I_t}{2}$ is passed through the Y2 wire, it can be seen that cores 5, 6 and 8 will have only $\frac{I_t}{2}$ passing through them from the Y2 wire and cores 3, 11 and 15 will have only $\frac{I_t}{2}$ current passing through them from the X3 wire. The only core that has I_t (total current) passing through it is core 7. Therefore it is the only core of this plane that can be selected, since $\frac{I_t}{2}$ alone cannot change the other cores. This type of selection, where it is necessary to have coincidence (intersecting currents) between the X wire current and the Y wire current, is known as the coincident - current method.

If it is assumed the current through the X3 and Y2 wires was in the direction to read, only the information in core 7 would be read or sensed on the sense wire passing through that core.

Remember that the current for a read operation is in a direction to switch the core to a "0" state. Thus, if core 7 was already in the "0" state and the read current was applied to the X and Y wires, the core would not be switched and little voltage would be felt on the sense wire. This small voltage would be applied to a sense amplifier for that particular plane and no output would be developed indicating that a "0" had been read from the core.

If core 7 was storing a "1" and the read current was applied to the X and Y wires, the core would be switched from the "1" state to the "0" state. A large voltage would be induced on the sense wire which would be applied to a sense amplifier common to this particular plane and an output would be developed from the sense amplifier indicating that a "1" had been read from the core.

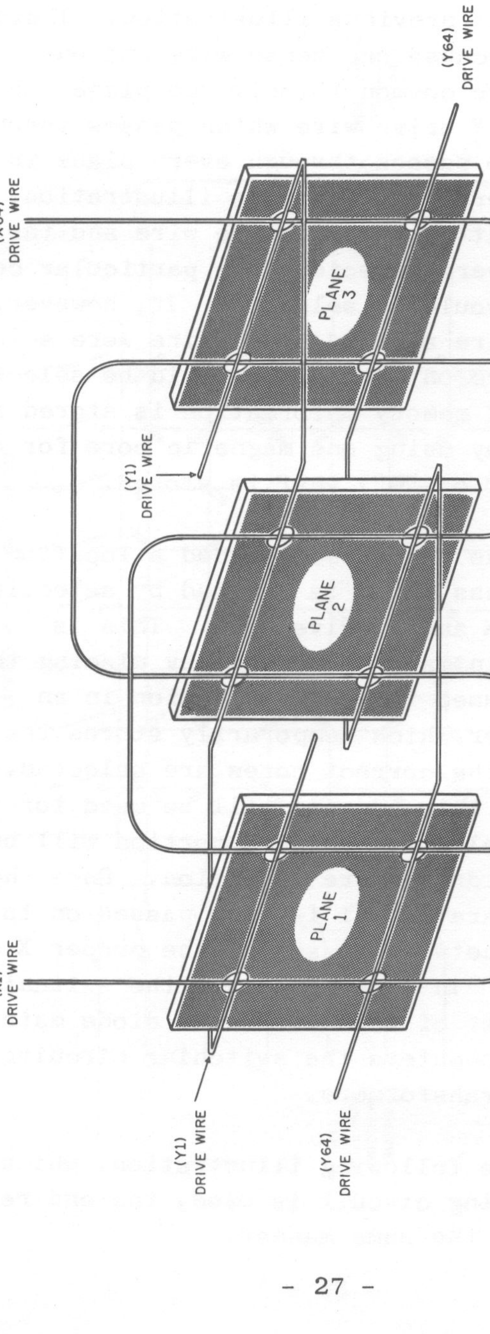
In the illustration notice that the inhibit wire passes through the cores in parallel with the Y drive wires. The current in the inhibit wire is always in opposition to the Y drive wire write current so that the proper cancellation will take place if a core is to store a "0" during the write sequence.

It should be obvious, since only one core can be selected on the plane at any one time, that only one inhibit wire (which passes through every core on the plane) is needed on each plane.

It is interesting to note how the sense wire is wound through every core on the plane. Although this may appear unusual, it is wound in this manner to cancel the "noise" which is induced onto the sense wire from the cores which receive only $\frac{It}{2}$ (half currents) during core selection. It has been said that supplying only $\frac{It}{2}$ to a core cannot change or switch the core, but when applied to the cores these half currents will tend to vary the hysteresis loop a very small amount around the residual point (B_r) of the curve. These small magnetic changes in the core do not switch or change the state of the core, but they will induce a very small voltage on the sense wire, which is called "noise". This means, for example, that if a 64 x 64 plane is being used, 63 cores along the X wire and 63 cores along the Y wire are receiving half currents. If many of these cores happened to be in a particular state, the small voltages induced onto the sense wire would be additive and in some cases become quite large (near the amplitude caused by a "1" output). To provide a compensating effect, the sense wire is wound through the cores in a manner which will cancel these small, additive noise voltages.

A single memory plane or digit plane would be practically useless as a memory unit since only one core could be selected at one time for a read or write operation. Thus, in a core memory unit many planes are stacked together. The number of planes used will vary from one type of computer to another according to the number of computer words to be stored and the computer word length.

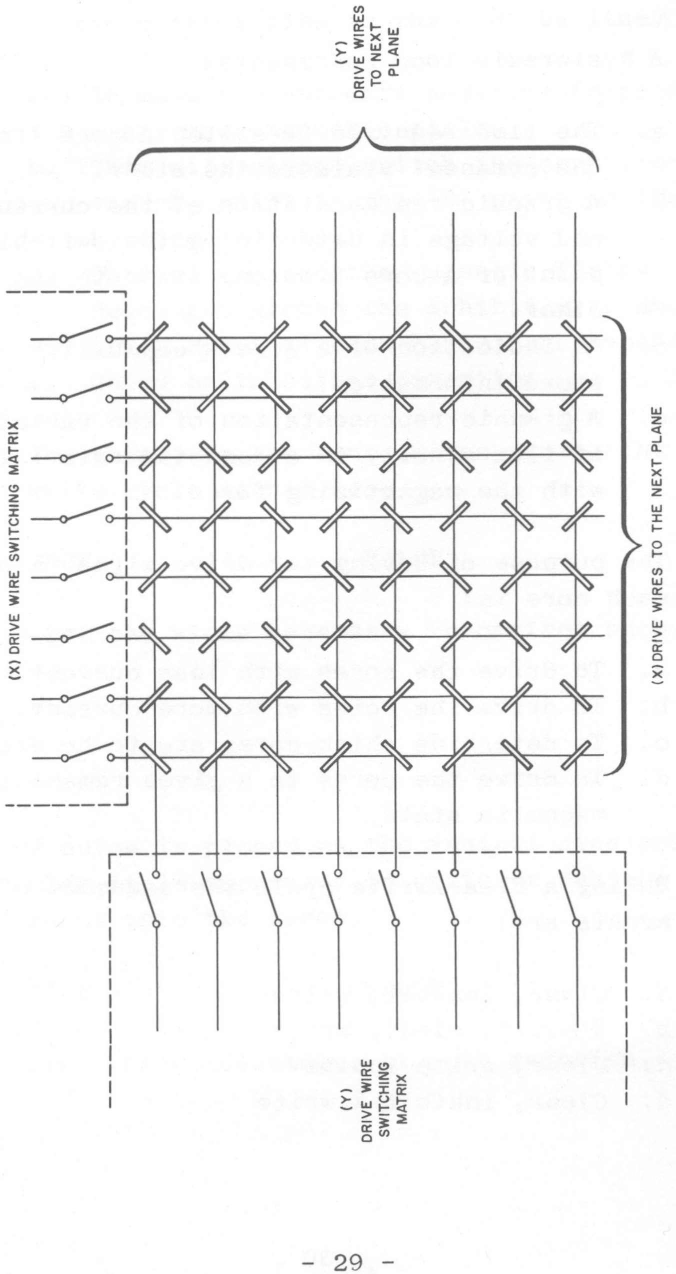
The following illustration shows how core planes are stacked together as well as the method of wiring the X and Y drive lines from one plane to the next.


PLANE 1
PLANE 2
PLANE 3
(X1) DRIVE WIRE
(Y1) DRIVE WIRE
(Y64) DRIVE WIRE
(X64) DRIVE WIRE
(X1) DRIVE WIRE
(Y1) DRIVE WIRE
(X64) DRIVE WIRE
(Y64) DRIVE WIRE

Notice the absence of sense and inhibit wires on the plane in the previous illustration. These were omitted because one sense wire and one inhibit wire are common to only one plane. However each X or Y drive wire which passes through one plane, also passes through every plane in the stack. Therefore, from the illustration, it can be seen that if the X1 drive wire and the Y1 drive wire were selected, one particular core on each plane would be selected. If, however, the X1 drive wire and Y64 drive wire were selected, a different core on each plane would be selected. In this type of memory information is stored in a parallel form by using one magnetic core for each binary bit ("1" or "0") that is stored.

Each core on the plane is assigned a location number or address which is located by selection of the proper X and Y drive wire. This is accomplished, in many computers, by placing the address to be used for core selection in an address register which temporarily stores the address until the correct cores are selected. One portion of this address will be used for the X drive wire selection and one portion will be used for the Y drive wire selection. Once the address is separated, it is then passed on to the switching network to select the proper X and Y drive wires. In some computers the switching networks consist of transistors or diode matrices and in other computers the switching circuits are comprised of transformers.

As shown in the following illustration, whichever type of switching circuit is used, the end result is achieved in the same manner.


(Y)
DRIVE WIRES
TO NEXT
PLANE
(X) DRIVE WIRE SWITCHING MATRIX
(X) DRIVE WIRES TO THE NEXT PLANE
(Y)
DRIVE WIRE
SWITCHING
MATRIX

CORE QUESTIONS

1. A hysteresis loop represents:

   a. The time required to switch a core from one remanent state to the other.
   b. A graphic representation of the current and voltage in determining the switching point of a core from one state to the other.
   c. An indication of a core's capability to store information.
   d. A graphic representation of the variation of flux density in a magnetic material with the magnetizing force.

2. The purpose of having two drive wires through each core is:

   a. To drive the cores with less current.
   b. To drive the cores with more current.
   c. To determine which cores are to be driven.
   d. To drive the cores to a given remanent magnetic state.

3. During a clear/write cycle the sequence of events are:

   a. Clear, inhibit, write
   b. Inhibit, clear, write
   c. Clear, write inhibit
   d. Clear, inhibit & write

4. Why is it necessary to have current flow in the inhibit wire in the opposite direction of the current flow in the Y drive line?

   a. To make the currents additive to produce a stronger magnetic field.
   b. This will always switch the core from the $+B_r$ point to the $-B_r$ point on the hysteresis loop.
   c. This will cause the magnetic fields developed around the inhibit wire and the Y drive wire to cancel one another.
   d. Could be in either direction.

5. The output on the sense wires during the write cycle is not used.

   TRUE FALSE

6. List the wires necessary to control each core.

7. A pulse is placed on the inhibit line only when it is necessary to write or restore zeros into the cores.

   TRUE FALSE

8. List three advantages of core memories.

9. Why does information have to be restored in a core after it has been sensed?

10. One sense wire is common to every core on one core plane.

TRUE FALSE