

13.1 Characteristics of the Memory Hierarchy

We've discussed the organization and operation of RAM, but RAM is only one level of the group of components used to store information in a computer. The hard drive, for example, stores all of the data and code for the computer in a non-volatile format, and unless a file has been opened, this information can only be found on the hard drive.

Even though the hard drive stores all of the data necessary to operate the computer, other storage methods are needed. This is for a number of reasons, most notably the hard drive is slow and running programs from it would be impossible. When the processor needs data or applications, it first loads them into main memory (RAM).

Main memory and the hard drive are two levels of the computer's *memory hierarchy*. A memory hierarchy is an organization of storage devices that takes advantage of the characteristics of different storage technologies in order to improve the overall performance of a computer system. Figure 13-1 presents the components of the standard memory hierarchy of a computer. Each of these components and their function in the hierarchy is described in this chapter.

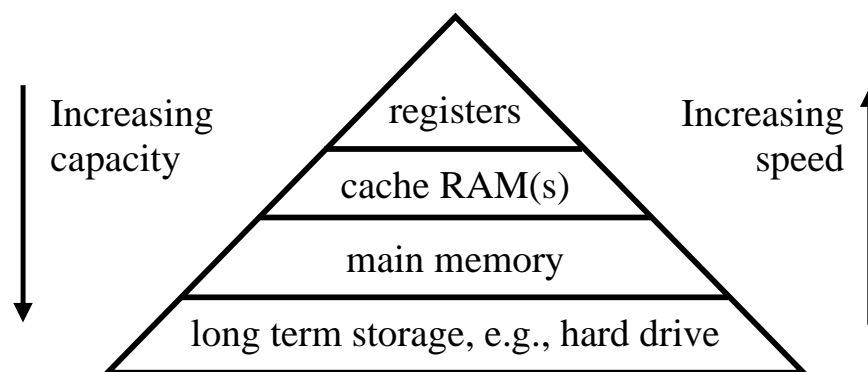


Figure 13-1 Block Diagram of a Standard Memory Hierarchy

13.2 Physical Characteristics of a Hard Drive

At the bottom of the hierarchy is long-term, high-capacity storage. This type of memory is slow which makes it a poor choice for the

memory that the processor uses for execution of programs and data access. This section covers the most common high capacity, non-volatile storage method: hard drives.

Hard drives are the most cost-effective method of storing data. In the mid-1980's, a 30 Megabyte hard drive could be purchased for around \$300 or about \$10 per MB. In 2005, retailers advertised a 120 Gigabyte Hard drive for around \$110 or about \$0.00092 per MB. In other words, the cost to store a byte of data is almost 1/11,000th cheaper today than it was two decades ago.

Hard drives store data in well-organized patterns of ones and zeros across a thin sheet of magnetic material. This magnetic material is spread either on one or both sides of a lightweight, rigid disk called a *substrate*. The substrate needs to be lightweight because it is meant to spin at very high speeds. The combination of magnetic material and substrate is called a *platter*.

The more rigid the substrate is, the better the reliability of the disk. This was especially true when the mechanisms that were used to read and write data from and to the disks were prone to scraping across the substrate's surface if the substrate was not perfectly flat. The condition where the read-write mechanism comes in contact with the disk is called a hard drive "crash" and would result in magnetic material being scraped away from the disk.

Substrates used to be made from aluminum. Unfortunately, extreme heat sometimes warped the aluminum disk. Now glass is used as a substrate. It improves on aluminum by adding:

- better surface uniformity which increases reliability;
- fewer surface defects which reduces read/write errors;
- better resistance to warping;
- better resistance to shock; and
- the ability to have the read/write mechanism ride closer to the surface allowing for better data density.

13.2.1 Hard Drive Read/Write Head

Data is recorded to the platter using a conductive coil called a head. Older drives and floppy drives use the same head for reading the data too. The head is shaped like a "C" with the gap between the ends positioned to face the magnetic material. A coil of wire is wrapped

around the portion of the head that is furthest from the magnetic material. Figure 13-2 shows the configuration of this type of head.

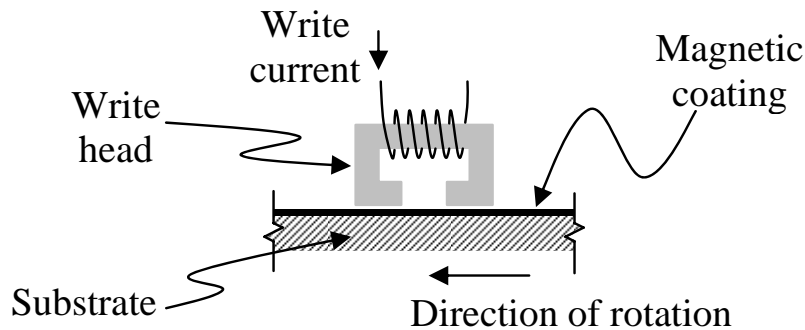


Figure 13-2 Configuration of a Hard Drive Write Head

In order to write data, an electrical current is passed through the wire creating a magnetic field within the gap of the head close to the disk. This field magnetizes the material on the platter in a specific direction. Reversing the current would polarize the magnetic material in the opposite direction. By spinning the platter under the head, patterns of magnetic polarization can be stored in circular paths on the disk. By moving the head along the radius, nested circular paths can be created. The magnetized patterns on the platter represent the data.

It is possible to use the same head to read data back from the disk. If a magnetized material *moves* past a coil of wire, it produces a small current. This is the same principle that allows the alternator in your car to produce electricity. The direction of the current generated by the disk's motion changes if the direction of the magnetization changes. In this way, the same coil that is used to write the data can be used to read it. Just like the alternator in your car though, if the disk is not spinning, no current is generated that can be used to read the data.

Newer hard drives use two heads, one for reading and one for writing. The read head works differently than the old heads in that it is made of a special material that changes its resistance depending on the magnetic field that is passing under it. These changes in resistance affect a current that the hard drive controller is passing through the read head during the read operation. In this way, the hard drive controller can detect changes in the magnetic polarization of the material directly under the read head.

There is another characteristic of the read/write head that is important to the physical operation of the hard drive. As was stated

earlier, the size of area of substrate that can be polarized by the head is equal to the gap in the write head. In order to polarize a smaller area thereby increasing the data density, the gap must be made smaller. To do this, the distance between the head and the platter must be reduced.

When the magnetic material is deposited on a flexible substrate such as a floppy diskette or a cassette tape, the flex in the material makes it possible for the head to come in contact with the substrate without experiencing reliability problems. This is not true for hard disks. Since the platters are rigid and because the platters spin at thousands of rotations per minute, any contact that the head makes with the platter will result in magnetic material being scraped off. In addition, the heat from the friction will eventually cause the head to fail.

These two issues indicate that the read/write head should come as close to the platters as possible without touching. Originally, this was done by making the platter as flat as possible while mounting the head to a rigid arm. The gap would hopefully stay constant. Any defects or warpage in the platter, however, would cause the head to crash onto the platter resulting in damaged data.

A third type of head, the *Winchester head* or "flying head" is designed to float on a cushion of air that keeps it a fixed distance from the spinning platter. This is done by shaping the head into an airfoil that takes advantage of the air current generated by the spinning platter. This means that the head can operate much closer to the surface of the platter and avoid crashing even if there are imperfections.

13.2.2 *Data Encoding*

It might seem natural to use the two directions of magnetic polarization to represent ones and zeros. This is not the case, however. One reason for this is that the controllers detect the *changes* in magnetic direction, not the direction of the field itself. Second, large blocks of data that are all ones or all zeros would be difficult to read because eventually the controller might lose track or synchronization of where one bit ended and the next began.

The typical method for storing data to a platter involves setting up a clock to define the bit positions, and watching how the magnetic field changes with respect to that clock. Each period of the clock defines a single bit time, e.g., if a single bit takes 10 nanoseconds to pass under the read-write head when the platter is spinning, then a clock with a period of 10 nanoseconds, i.e., a frequency of $(10 \times 10^{-9})^{-1} = 100 \text{ MHz}$ is used to tell the controller when the next bit position is coming.

Originally, a magnetic field change at the beginning and middle of a bit time represented a logic one while a magnetic field change only at the beginning represented a logic zero. This method was referred to as **Frequency Modulation (FM)**. Figure 13-3 uses an example to show the relationship between the bit-periods, the magnetic field changes, and the data stored using FM encoding.

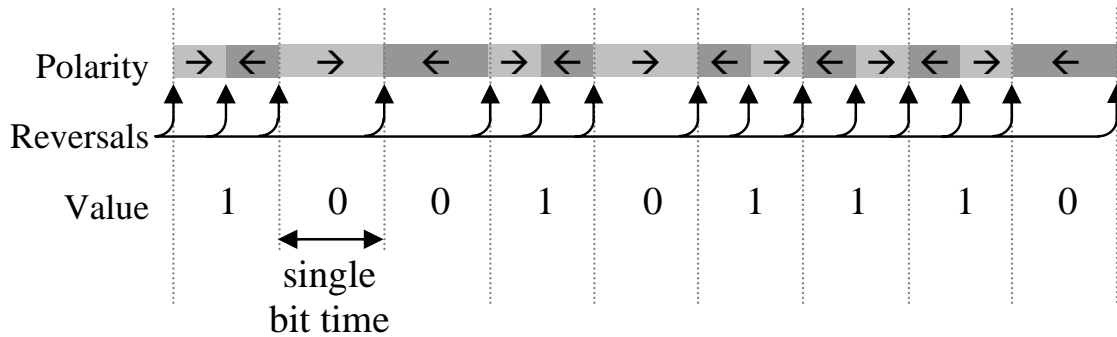


Figure 13-3 Sample FM Magnetic Encoding

To store a one using FM encoding, the polarization of the magnetic field must change twice within the space of a bit. This means that in order to store a single bit, FM encoding takes twice the width of the smallest magnetic field that can be written to the substrate. If the maximum number of polarity changes per bit could be reduced, more data could be stored to the same disk.

Modified Frequency Modulation (MFM) does this by changing the way in which the magnetic polarization represents a one or a zero. MFM defines a change in polarization in the middle of a bit time as a one and no change in the middle as a zero. If two or more zeros are placed next to each other, a change in polarization is made between each of the bit times. This is done to prevent a stream zeros from creating a long block of unidirectional polarization. Figure 13-4 uses an example to show the relationship between the bit-periods, the magnetic field changes, and the data stored using MFM encoding.

For MFM encoding, the longest period between polarity changes occurs for the bit sequence 1-0-1. In this case, the polarity changes are separated by two bit periods. The shortest period between polarity changes occurs when a one follows a one or a zero follows a zero. In these cases, the polarity changes are separated by a single bit period. This allows us to double the data density over FM encoding using the same magnetic surface and head configuration. The hard drive controller, however, must be able to handle the increased data rate.

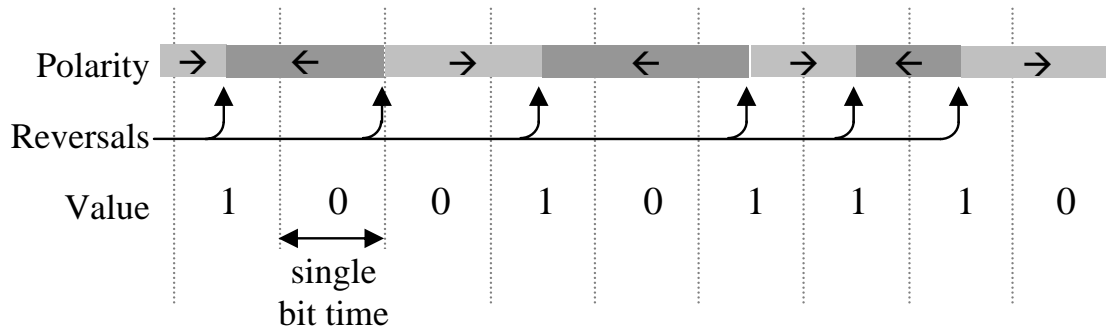


Figure 13-4 Sample MFM Magnetic Encoding

Run Length Limited (RLL) encoding uses polarity changes to define sequences of bits rather than single bits. By equating different patterns of polarity changes to different sequences of ones and zeros, the density of bits stored to a platter can be further increased. There is a science behind generating these sequences and their corresponding polarity changes. It is based on satisfying the following requirements:

- to ensure enough polarity changes to maintain bit synchronization;
- to ensure enough bit sequences are defined so that any sequence of ones and zeros can be handled; and
- to allow for the highest number of bits to be represented with the fewest number of polarity changes.

Figure 13-5 presents a sample set of RLL encoding polarity changes and the bit sequences that correspond to each of them. Any pattern of ones and zeros can be represented using this sample set of sequences.

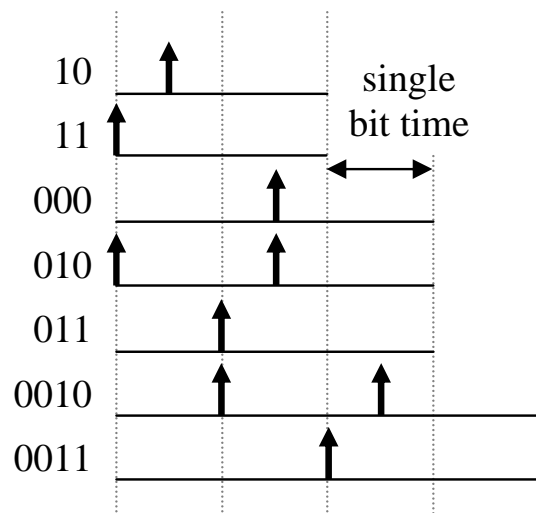


Figure 13-5 RLL Relation between Bit Patterns and Polarity Changes

Note that the shortest possible period between polarity changes is one and a half bit periods. This produces a 50% increased data density over MFM encoding. Figure 13-6 presents the sample data used in Figures 13-3 and 13-4 encoded with RLL encoding.

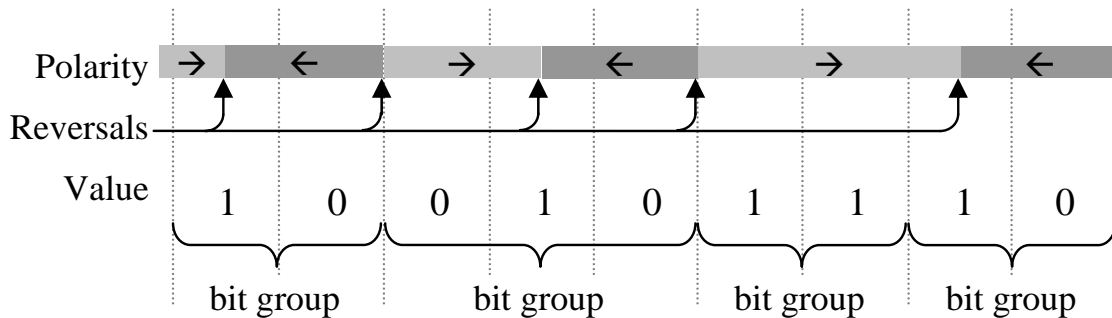


Figure 13-6 Sample RLL Magnetic Encoding

Improved encoding methods have been introduced since the development of RLL that use digital signal processing and other methods to realize better data densities. These methods include Partial Response, Maximum Likelihood (PRML) and Extended PRML (EPRML) encoding. A discussion of the details of these methods is beyond the scope of this text because it depends on a better understanding of sampling theory and electrical principles.

13.2.3 Self-Monitoring, Analysis & Reporting Technology System

A hard drive crash rarely comes without a warning. The user may be unaware of any changes in their hard drive's operation preceding a mechanical failure, but there are changes. For example, if a hard drive's platters are taking longer to get up to full speed, it may be that the bearings are going bad. A hard drive that has been experiencing higher than normal operating temperatures may also be about to fail.

Newer drives now support a feature referred to as **Self-Monitoring Analysis and Reporting Technology** (SMART). SMART enabled drives can provide an alert to the computer's BIOS warning of a parameter that is functioning outside of its normal range. This usually results in a message to the user to replace the drive before it fails.

SMART attribute values are stored in the hard drive as an integer in the range from 1 to 253. The lower the value, the worse the condition is. Depending on the parameter and the manufacturer, different failure thresholds are set for each of the parameters.

The exact parameters measured vary from drive to drive with each drive typically monitoring about twenty parameters. The following is a sample of some of the available measurements:

- **Power On Hours:** This indicates the age of the drive.
- **Spin Up Time:** A longer spin up time may indicate a problem with the assembly that spins the platters.
- **Temperature:** Higher temperatures also might indicate a problem with the assembly that spins the platters.
- **Head Flying Height:** A reduction in the flying height of a Winchester head may indicate it is about to crash into the platters.

There are still unpredictable failures such as the failure of an IC or a failure caused by a catastrophic event such as a power surge, but now the user can be forewarned of most mechanical failures.

13.3 Organization of Data on a Hard Drive

The width of a hard drive's read/write head is much smaller than that of the platter. This means that there are a number of non-overlapping positions for the read/write head along the platter's radius. By allowing the movable read/write head to be positioned at intervals along the radius of the disk, information can be recorded to any of a number of concentric circles on the magnetic material. Each one of these circles is called a *track*. A typical hard drive disk contains thousands of these tracks, each being the width of the read/write head. Figure 13-7 shows how these tracks correspond to the movement and size of the read/write head.

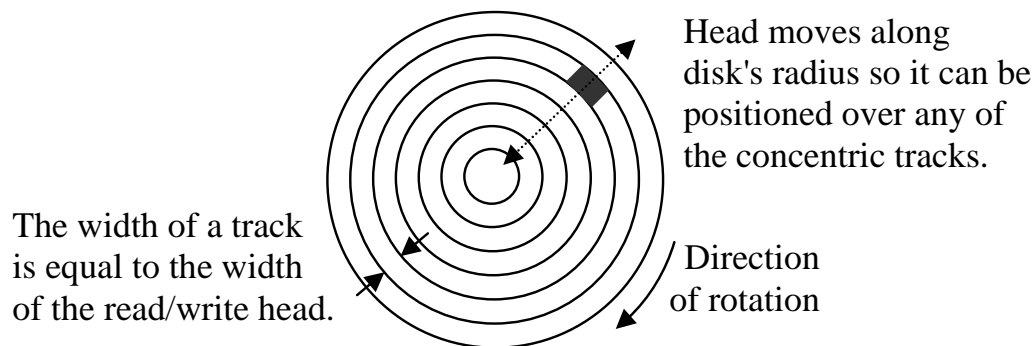


Figure 13-7 Relation between Read/Write Head and Tracks

A small gap called an *intertrack gap* is placed between the tracks to avoid interference from neighboring data. Reducing this gap allows for more data to be stored on a disk, but it also increases the risk of having data corrupted when data from an adjacent track bleeds over.

Each track is divided into sections of around 512 bytes apiece. These sections are called *sectors*. A platter may have sectors that are fixed in size for the whole platter or they may have variable amounts of data depending on their location on the platter relative to the center of rotation. There are typically hundreds of sectors per track.

In addition to the gaps left between the tracks, gaps are also left between the sectors. These gaps allow for a physical separation between the blocks of data and are typically used to help the hard drive controller when reading from or writing to the disk. These gaps are called *intersector gaps*. Figure 13-8 shows the relationship of these gaps to the tracks and sectors.

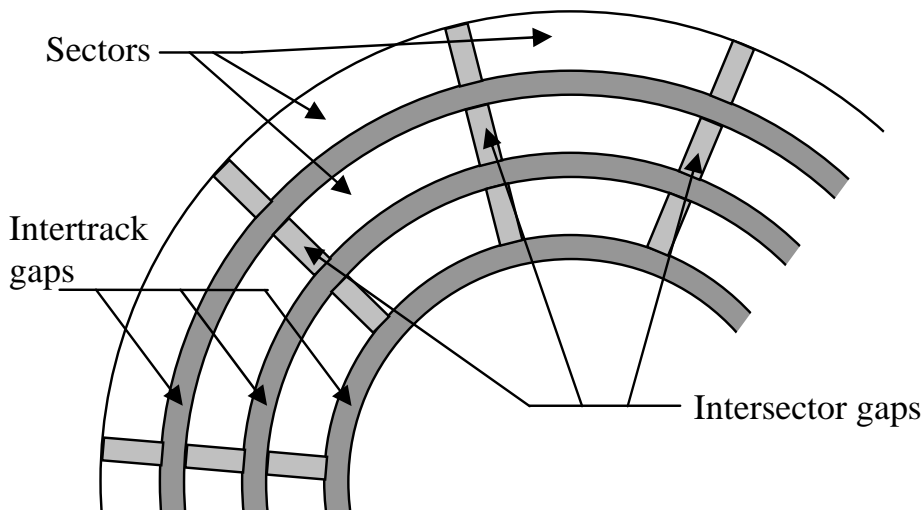


Figure 13-8 Organization of Hard Disk Platter

One way to increase the capacity of a hard drive is to increase the number of surfaces upon which the magnetic material is placed. The first way to do this is to place magnetic material on both sides of the platter. When this is done, a second read-write head must be placed on the opposite side of the platter to read the second magnetic surface. By using the same organization of sectors and tracks, this doubles the capacity of the hard drive.

A second method for increasing capacity is to mount multiple platters on a single spindle, the axis around which all of the platters rotate. Each additional magnetic surface adds to the capacity of the drive, and as with putting magnetic material on both sides of a single platter, all magnetic surfaces have the same organization of sectors and tracks, each sector lining up with the ones above it and below it. Every additional magnetic surface requires an additional read-write head.

All of the heads of a hard drive are locked together so that they are reading from the exact same location on each of their respective surfaces. Therefore, each track on each surface that is the same distance from the spindle can be treated as a unit because the hard drive controller is accessing them simultaneously. The set of all tracks, one from each surface, that are equidistant from the spindle are referred to as a *cylinder*. This virtual entity is depicted in Figure 13-9.

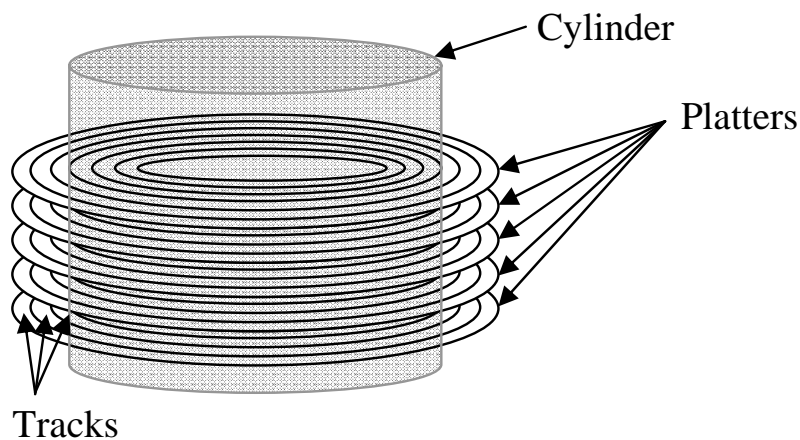
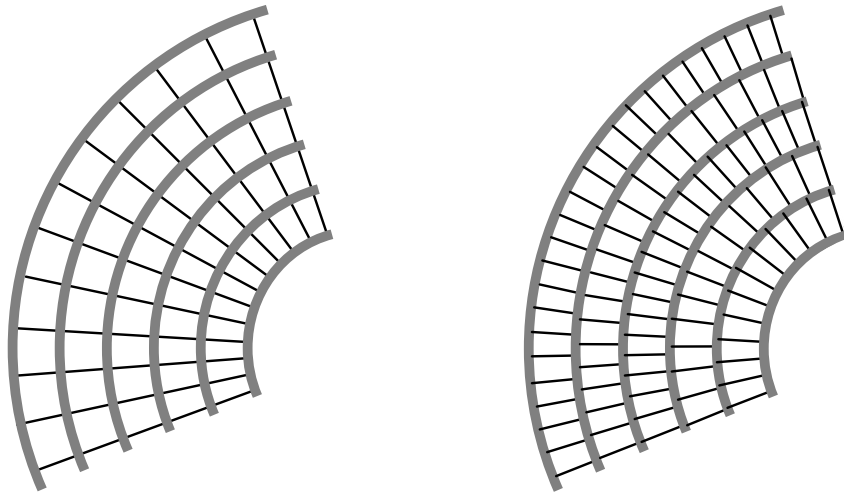


Figure 13-9 Illustration of a Hard Drive Cylinder

Using this information, we can develop a method for calculating the capacity of a hard drive. In general, the capacity of a hard drive equals the number of bytes per sector multiplied by the number of sectors per track multiplied by the number of cylinders (which is equal to the number of tracks per side of a platter) multiplied by 2 if the platters have magnetic material on both sides and finally multiplied by the number of platters.

Figure 13-8 shows a platter that has the same number of sectors per track regardless of the radius of the track. From this figure, it can be seen that the physical size of a sector becomes smaller as its distance from the spindle is reduced. Figure 13-10a shows that if the number of

bits in a sector is held fixed, then as the radius is reduced, the size of a bit is reduced.



a.) Equal number of bits per sector b.) Equal sized bits

Figure 13-10 Equal Number of Bits per Track versus Equal Sized Bits

Because the smallest allowable size for a bit is dictated by the size of the read-write head, the number of bits per sector is limited by the number of bits that can fit on the smallest track, i.e., the one closest to the spindle. Because of this limitation, the outside tracks waste space when the bits become wider than necessary.

A better use of the space on the platter can be realized by letting the width of all of the bits be defined by the width of the read-write head. This allows for more bits to be stored on the outer tracks. This tighter arrangement of bits can be seen in Figure 13-10b.

The problem with doing this is that as the read-write head moves to the outer tracks, the rate at which the bits pass under the head increases dramatically over that for the smallest track. This contrasts with the fixed number of bits per track which has the same data rate regardless of the position of the read-write head. This means that the hard drive controller for the fixed number of bits per track is far simpler than that for the fixed bit size.

Regardless of how the bits are arranged on the platters, the number of *bits per sector* remains constant for all of the tracks. For the method where increased drive capacity is realized by packing more data on the outer tracks, this means that instead of increasing the number of bits on

subsequently larger tracks, the number of bits per track stays constant until there is enough room to add another sector. This creates "zones" where groups of neighboring tracks have the same number of sectors, and therefore, the same number of bits.

The first method of data storage where the number of sectors per track is kept constant is called ***constant angular velocity***. The second method where the outer tracks have more sectors is called ***multiple zoned recording***. Figure 13-11 compares the sector arrangement of these two methods.

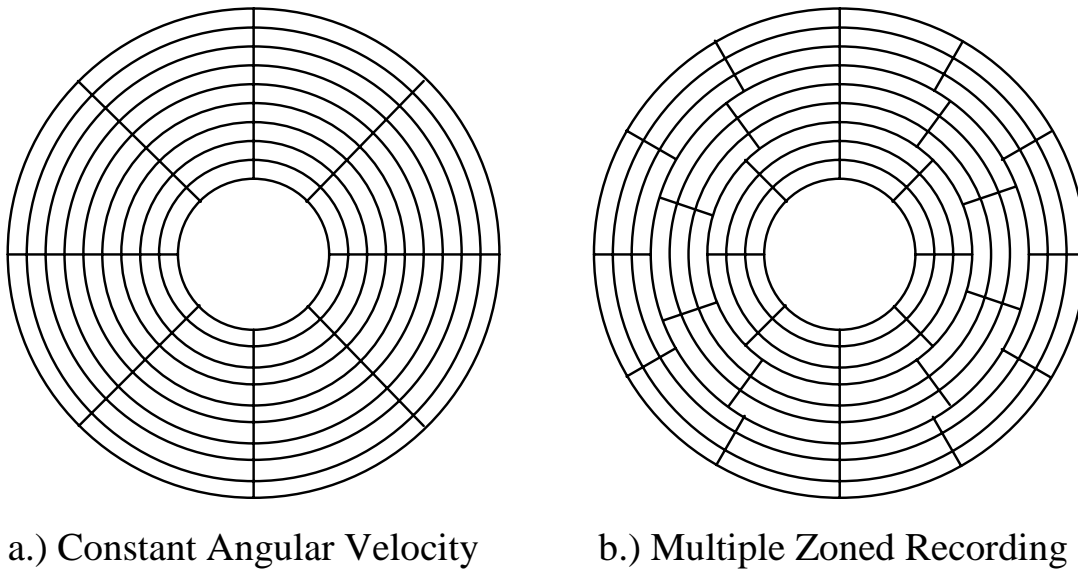


Figure 13-11 Comparison of Sector Organizations

This brings us to the next layer of data organization on a hard drive: formatting. Formatting is the process of setting or clearing bits on the platters in an effort to organize and locate the files that will be stored on the hard drive. The methods used by hard drives to organize data can also be found on other rotational storage media such as floppy disks and Zip® disks.

Every hard drive utilizes two types of formatting: low-level and O/S-level. ***Low-level formatting (LLF)*** depends on the mechanics of the hard drive and its controller. It divides the platters into usable subsections by defining the tracks and sectors. In addition to defining the divisions, it also stores digital information allowing the controller to properly access the data. This additional information includes:

- Synchronization fields that provide timing and positional information to the controller;
- ID information to allow the controller to identify which track and sector its heads are currently positioned over; and
- Error correcting codes to detect and correct errors in the data.

LLF is driven by the mechanical operation of the hard drive and is independent of the operating system that uses it. At one time, an LLF could be performed with a computer's BIOS, but because of the complexity of modern hard drives, LLF is now performed at the factory only. The closest function currently available is a utility called a *zero fill*. This function erases all data on a hard drive by filling the sectors with zeroes.

O/S-level formatting is used to create a file system so that the operating system can find and load data from the hard drive. This includes information such as the folder structure, file attributes, and on which sectors the files are stored.

There is a level of logical hard drive organization between low-level formatting and O/S level formatting called *partitioning*. Partitioning uses a table contained on the hard drive that defines individual, non-overlapping "logical drives," i.e., drives that look like separate drives themselves, but in actuality are all contained on a single set of platters.

One of the original uses of partitioning was to divide a hard drive into smaller logical units when the hard drives that manufacturers produced became too large for a BIOS or operating system to handle. For example, to install a 2 Gigabyte hard drive on a system where the BIOS was only capable of seeing 512 Megabyte drives, the hard drive has to be logically divided into at least four drives.

Another application of partitioning is if different O/S-level formatting is needed on a single hard drive. If, for example, a user wishes to load both Windows and Linux on the same hard drive, three logical drives would be needed, one with a Windows format, one with a Linux native format, and one with a Linux swap format.

At one time, performance benefits could be realized with effective partitioning, but with advances in hard drive technologies, this is no longer true.

13.4 Cache RAM

Regardless of advances in hard drive technology, it will never be practical to execute programs or access data directly from these mechanical devices. They are far too slow. Therefore, when the processor needs to access information, it is first loaded from the hard drive into main memory where the higher performance RAM allows fast access to the data and applications. When the processor is finished with the data, the information can either be discarded or used to update the hard drive.

Because of its expense, the capacity of a computer's main memory falls short of that of its hard drive. This should not matter though. Not all of the data on a hard drive needs to be accessed all of the time by the processor. Only the currently active data or applications need to be in RAM. Additional performance improvements can be realized by taking this concept to another level.

Remember from our discussion in Chapter 12 that there are two main classifications of RAM: static RAM (SRAM) and dynamic RAM (DRAM). SRAM is faster, but that speed comes at a price: it has a lower density and it is more expensive. Since main memory needs to be quite large and inexpensive, it is implemented with DRAM.

Could, however, the same relation that exists between main memory and a hard drive be realized between a small block of SRAM and a large main memory implemented in DRAM? Main memory improves the performance of the system by loading only the information that is currently in use from the hard drive. If a method could be developed where the code that is in immediate use could be stored in a small, fast SRAM while code that is not quite as active is left in the main memory, the system's performance could be improved again.

Due to the nature of programming, instructions that are executed within a short period of time tend to be clustered together. This is due primarily to the basic constructs of programming such as loops and subroutines that make it so that when one instruction is executed, the chances of it or its surrounding instructions being executed again in the near future are very good. Over a short period of time, a cluster of instructions may execute over and over again. This is referred to as the *principle of locality*. Data also behaves according to this principle due to the fact that related data is often defined in consecutive locations.

To take advantage of this principle, a small, fast SRAM is placed between the processor and main memory to hold the most recently used

code and data under the assumption that they will most likely be used again soon. This small, fast SRAM is called a **RAM cache**.



Figure 13-12 Cache Placement between Main Memory and Processor

The reason the SRAM of the cache needs to be small is that larger address decoder circuits are slower than small address decoder circuits. The larger the memory is, the more complex the address decoder circuit. The more complex the address decoder circuit is, the longer it takes to select a memory location based on the address it received. Therefore, making a memory smaller makes it faster.

It is possible to take this concept a step further by placing an even smaller SRAM between the cache and the processor thereby creating two levels of cache. This new cache is typically contained inside of the processor. By placing the new cache inside the processor, the wires that connect the two become very short, and the interface circuitry becomes more closely integrated with that of the processor. Both of these conditions along with the smaller decoder circuit result in even faster data access. When two caches are present, the one inside the processor is referred to as a level 1 or **L1 cache** while the one between the L1 cache and memory is referred to as a level 2 or **L2 cache**.



Figure 13-13 L1 and L2 Cache Placement

The **split cache** is another cache system that requires two caches. In this case, a processor will use one cache to store code and a second cache to store data. Typically, this is to support an advanced type of processor architecture such as pipelining where the mechanisms that the processor uses to handle code are so distinct from those used for

data that it does not make sense to put both types of information into the same cache.

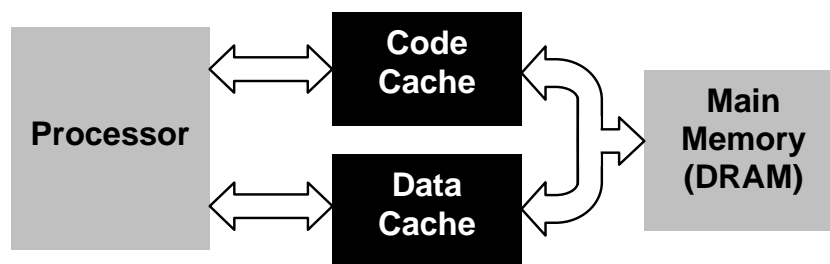


Figure 13-14 Split Cache Organization

13.4.1 Cache Organization

The success of caches is due primarily to the principle of locality. This suggests that when one data item is loaded into a cache, the items close to it in memory should be loaded too. For example, if a program enters a loop, most of the instructions that make up that loop will be executed multiple times. Therefore, when the first instruction of a loop is loaded into the cache, time will be saved if its neighboring instructions are loaded at the same time. That way the processor will not have to go back to main memory for subsequent instructions.

Because of this, caches are typically organized so that when one piece of data or code is loaded, the **block** of neighboring items is loaded too. Each block loaded into the cache is identified with a number called a **tag** that can be used to determine the original addresses of the data in main memory. This way, when the processor is looking for a piece of data or code (hereafter referred to as a word), it only needs to look at the tags to see if the word is contained in the cache.

The each block of words and its corresponding tag are combined in the cache to form a **line**. The lines are organized into a table much like that shown in Figure 13-15. It is important to note that when a word from within a block of words is needed from main memory, the whole block is moved into one of the lines of the cache along with the tag used to identify from where it came.

13.4.2 Dividing Memory into Blocks

Main memory stores all of its words in sequential addresses. The cache, however, has no sequential order. Therefore, it is the addressing scheme of main memory that is used to define the blocks of words and

the method for locating them. The definition of blocks in main memory is logical only; it has no effect on how the words are stored.

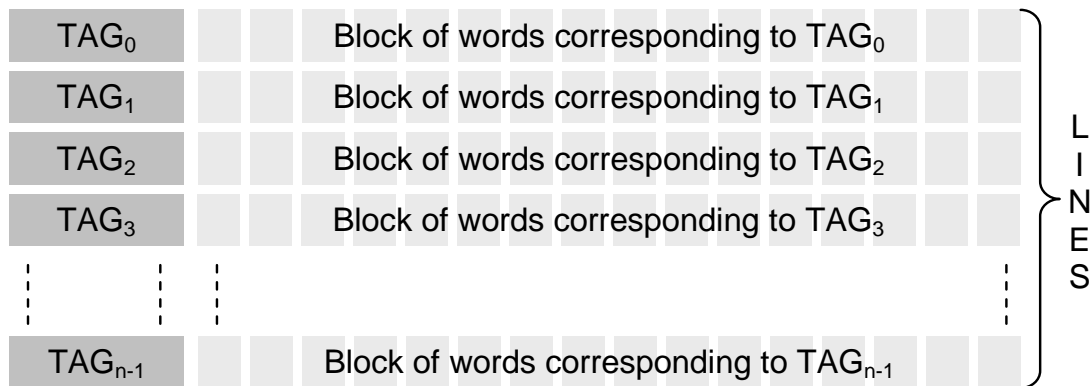


Figure 13-15 Organization of Cache into Lines

The full main memory address defines a specific memory location within memory. For example, a unique twenty-bit address such as $3E9D1_{16} = 0011\ 1110\ 1001\ 1101\ 0001_2$ points to exactly one memory location within a 1 Meg memory space.

If we "hide" the last bit of the address, i.e., that bit could be a one or a zero, then the resulting address could refer to one of two possible locations, $3E9D1_{16}$ ($0011\ 1110\ 1001\ 1101\ 0001_2$) or $3E9D0_{16}$ ($0011\ 1110\ 1001\ 1101\ 0000_2$). If we hide the last two bits, then the last two bits could be 00_2 , 01_2 , 10_2 , or 11_2 . Therefore, the address could be referring to one of the following four possible sequential locations:

$$\begin{aligned} 3E9D0_{16} &= 0011\ 1110\ 1001\ 1101\ 000\mathbf{0}_2 \\ 3E9D1_{16} &= 0011\ 1110\ 1001\ 1101\ 000\mathbf{1}_2 \\ 3E9D2_{16} &= 0011\ 1110\ 1001\ 1101\ 00\mathbf{10}_2 \\ 3E9D3_{16} &= 0011\ 1110\ 1001\ 1101\ 00\mathbf{11}_2 \end{aligned}$$

This is how a block is defined. By removing a small group of bits at the end of an address, the resulting identifier points to a group of memory locations rather than a specific address. Every additional bit that is removed doubles the size of the group. This group of memory locations is what is referred to as a block.

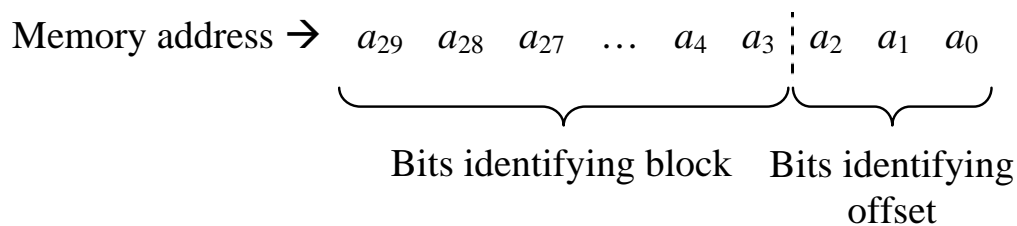
The number of words in a block is defined by the number of bits removed from the end of the address to create the block identifier. For example, when one bit is removed, a block contains two memory

Example

How many blocks of 8 words are there in a 1 Gig memory space?

Solution

Eight words require three bits to uniquely identify their position within a block. Therefore, the last three bits of the address represent the word's offset into the block. Since a 1 Gig (2^{30}) address space uses 30 address lines, there are $30 - 3 = 27$ remaining bits in the address. These bits are used to identify the block. Below is a diagram of the logical organization of the address.

*13.4.3 Cache Operation*

When the processor needs a word from memory, it first checks the cache. The circuits used to access the same word from main memory may be activated simultaneously so no time is lost in case the data is not available in the cache, a condition known as a *miss*. If the search of the cache is successful, then the processor will use the cache's word and disregard the results from main memory. This is referred to as a *hit*.

In the case of a miss, the entire block containing the requested word is loaded into a line of the cache, and the word is sent to the processor. Depending on the design of the cache/processor interface, the word is either loaded into the cache first and then delivered to the processor or it is loaded into the cache and sent to the processor at the same time. In the first case, the cache is in control of the memory interface and lies between memory and the processor. In the second case, the cache acts like an additional memory on the same bus with the main memory.

13.4.4 Cache Characteristics

The cache system used by a processor is defined by six traits:

- the size of the cache;
- the size of a block, which when combined with the size of the cache defines the number of lines;

- the number of caches (i.e., multiple levels or a split cache);
- the mapping function (the link between a block's address in memory and its location in the cache);
- the replacement algorithm (the method used to figure out which block to remove from the cache in order to free up a line); and
- the write policy (how the processor writes data to the cache so that main memory eventually gets updated).

As far as the size of a cache is concerned, designers need to perform a balancing act to determine the best size cache for a system. The larger a cache is, the more likely it is that the processor will find the word it needs in the cache. The problem is that as a cache gets larger, the address decoding circuits also get larger and therefore slower. In addition, more complicated logic is required to search a cache because of the seemingly random way that the blocks are stored in it. Larger caches are also more expensive.

There is also a relationship between size of a block and the performance of the cache. As the block size goes up, the possibility of getting a hit when looking for data could go up due to more words being available within a region of active code. For a fixed cache size, however, as the block size increases, the number of blocks that can be stored in a cache goes down thereby potentially reducing the number of hits. A typical size of a block is fairly low, between 4 and 8 words.

13.4.5 Cache Mapping Functions

There are three main methods used to map a line in the cache to an address in memory so that the processor can quickly find a word: direct mapping, full associative mapping, and set associative mapping. Let's begin with *direct mapping*.

Assume main memory is divided up into n blocks and the cache has room to contain exactly m blocks. Because of the nature of the cache, m is much smaller than n . If we divide m into n , we should get an integer which represents the number of times that the main memory could fill the cache with different blocks from its contents.

For example, if main memory is 128 Meg (2^{27}) and a block size is four words (2^2), then main memory contains $n = 2^{27-2} = 2^{25}$ blocks. If the cache for this system can hold 256 K (2^{18}) words, then $m = 2^{18-2} = 2^{16}$ blocks. Therefore, the main memory could fill the cache $n/m = 2^{25}/2^{16} = 2^{25-16} = 2^9 = 512$ times.

Another way of putting it is this: the memory is much larger than a cache, so each line in the cache is responsible for storing one of many blocks from main memory. In the case of our example above, each line of the cache is responsible for storing one of 512 different blocks from main memory at any one time.

Direct mapping is a method used to assign each memory block in main memory to a specific line in the cache. If a line is already filled with a memory block when a new block needs to be loaded, the old block is discarded from the cache. Figure 13-18 shows how multiple blocks from our example are mapped to each line in the cache.

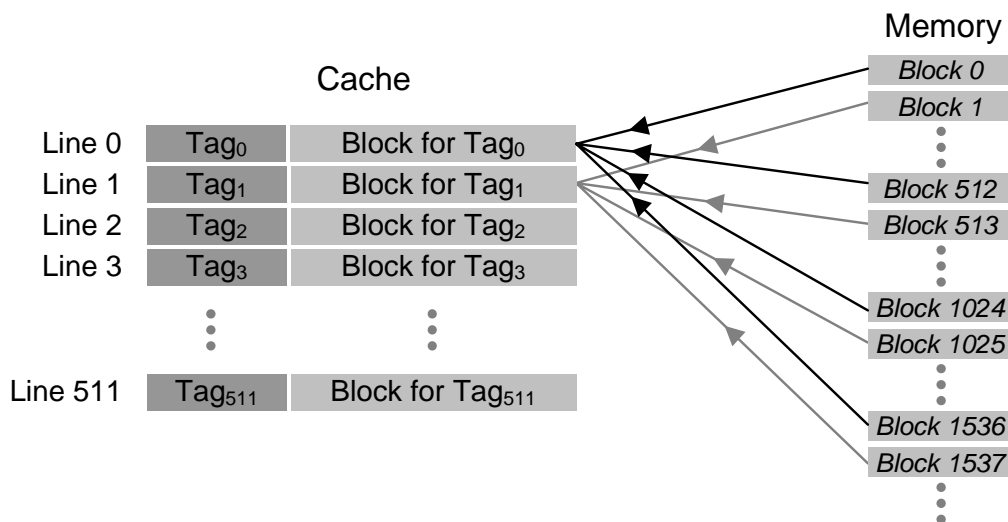


Figure 13-18 Direct Mapping of Main Memory to Cache

As with locating a word within a block, bits are taken from the main memory address to uniquely define the line in the cache where a block should be stored. For example, if a cache has $2^9 = 512$ lines, then a line would need 9 bits to be uniquely identified. Therefore, the nine bits of the address immediately to the left of the word identification bits would identify the line in the cache where the block is to be stored. The bits of the address not used for the word offset or the cache line would be used for the tag. Figure 13-19 presents this partitioning of the bits.

Once the block is stored in the line of the cache, the tag is copied to the tag location of the line. From the cache line number, the tag, and the word position within the block, the original address of the word can be reconstructed.

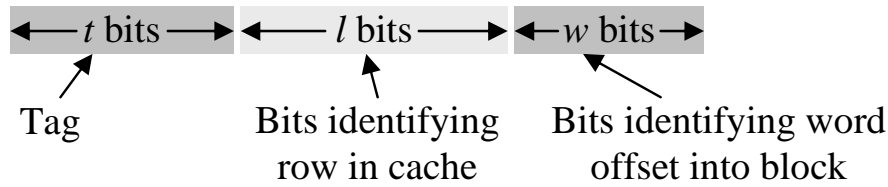


Figure 13-19 Direct Mapping Partitioning of Memory Address

In a nutshell, direct mapping breaks an address into three parts: t tag bits, l line bits, and w word bits. The word bits are the least significant bits identifying the specific word within a block of memory. The line bits are the next least significant identifying in which line of the cache the block will be stored. The remaining bits are stored with the block as the tag identifying where the block is located in main memory.

Example

Assume a cache system has been designed such that each block contains 4 words and the cache has 1024 lines, i.e., the cache can store up to 1024 blocks. What line of the cache is supposed to hold the block that contains the word from the twenty-bit address $3A456_{16}$? In addition, what is the tag number that will be stored with the block?

Solution

Start by dividing the address into its word id, line id, and tag bits. Since $4=2^2$, then the two least significant bits identify the word, i.e., $w = 2$. Since the cache has $1024=2^{10}$ lines, then the next 10 bits identify the line number where the data is supposed to be stored in the cache, i.e., $l = 10$. The remaining $t = 20 - w - l = 8$ bits are the tag bits. This partitions the address $3A456_{16} = 00111010010001010110_2$ as follows:

00111010	0100010101	10
tag bits	line id bits	word id bits

Therefore, the block from address $3A454_{16}$ to $3A457_{16}$ will be stored in line $0100010101_2 = 277_{10}$ of the cache with the tag 00111010_2 .

Example

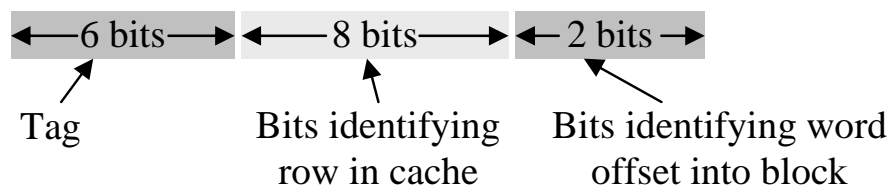
The first 10 lines of a 256 line cache are shown in the table below. Identify the address of the data that is shaded ($D8_{16}$). For this cache, a block contains 4 words. The tags are given in binary in the table.

Line #	Tag	word 00	word 01	word 10	word 11
0	110101	12	34	56	78
1	010101	54	32	6A	D3
2	000111	29	8C	ED	F3
3	001100	33	A2	2C	C8
4	110011	9A	BC	D8	F0
5	001101	33	44	55	66
6	010100	92	84	76	68
7	000100	FE	ED	00	ED
8	100000	00	11	22	33
9	101000	99	88	77	66

Solution

Start by finding the number of bits that represent each part of the address, i.e., the word id, the line id, and the tag. From the table, we can see that 2 bits represent the positions of each of the four words in a block and that 6 bits are used to represent the tag.

Since the cache has $256=2^8$ lines, then the line number in the cache is represented with 8 bits, and the address is partitioned as follows:



The shaded cell in the table has a tag number of 110011_2 . The line number is 4, which in 8 bit binary is 00000100_2 . Last of all, the word is in the third column which means that it is the 10_2 word within the block. (Remember to start counting from 00_2 .) Putting the tag, line id, and word id bits together gives us:

110011	00000100	10
tag bits	line id bits	word id bits

Therefore, the address that the shaded cell containing $D8_{16}$ came from is $1100\ 1100\ 0001\ 0010_2 = CC12_{16}$.

Example

Using the table from the previous example, determine if the data stored in main memory at address $101C_{16}$ is contained in this cache, and if it is, retrieve the data.

Solution

Converting $101C_{16}$ to binary gives us $0001\ 0000\ 0001\ 1100_2$. By using the breakdown of bits for the tag, line id, and word id, the binary value can be divided into its components.

000100	00000111	00
tag bits	line id bits	word id bits

From this we see that the line in the cache where this data should be stored is $00000111_2 = 7_{10}$. The tag currently stored in this line is 000100_2 which equals the tag from the above partitioned address. Therefore, the data from main memory address $101C_{16}$ is stored in this cache. If the stored tag did not match the tag pulled from the address, we would have known that the cache did not contain our address.

Lastly, we can find the data by looking at the offset 00_2 into the block at line 7. This gives us the value FE_{16} .

Example

Using the same table from the previous two examples, determine if the data from address 9827_{16} is in the cache.

Solution

Converting the hexadecimal address 9827_{16} to binary gives us $9827_{16} = 1001\ 1000\ 0010\ 0111_2$. By using the breakdown of bits for the tag, line id, and word id, we can divide this binary value into its components.

100110	00001001	11
tag bits	line id bits	word id bits

From this we see that the tag is 100110_2 , the line number is $00001001_2 = 9_{10}$, and the word offset into the block is 11_2 . Looking at line number 9 we see that the tag stored there equals 101000_2 . Since this does not equal 100110_2 , the data from that address is not contained in this cache, and we will have to get it from the main memory.

Fully associative mapping does not use line numbers at all. It divides the main memory address into two parts: the word id and a tag. In order to see if a block is stored in memory, the tag is pulled from the memory address and a search is performed through all of the lines of the cache to see if the block is present.

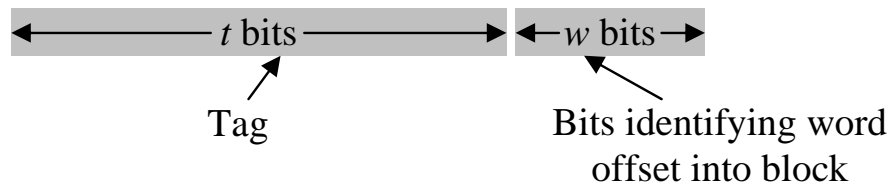


Figure 13-20 Fully Associative Partitioning of Memory Address

This method of searching for a block within a cache sounds like it might be a slow process, but it is not. Each line of the cache contains its own compare circuitry that is able to discern in an instant whether or not the block is contained at that line. With all of the lines performing this compare in parallel, the correct line is identified quickly.

This mapping algorithm is meant to solve a problem that occurs with direct mapping where two active blocks of memory map to the same line of the cache. When this happens, neither block of memory is allowed to stay in the cache long before it is replaced by the competing block. This results in a condition referred to as thrashing where a line in the cache goes back and forth between two or more blocks, usually replacing a block before the processor was through with it. Thrashing is avoided by allowing a block of memory to map to any line of the cache.

This benefit has a price, however. When a fully associative cache is full and the processor needs to load a new block from memory, a decision has to be made regarding which of the existing blocks is to be discarded. The selection method, known as a **replacement algorithm**, should have a goal of replacing the block least likely to be needed by the processor in the near future.

There are numerous replacement algorithms, no one of which is significantly better than the others. In an effort to realize the fastest operation, each of these algorithms is implemented in hardware.

- **Least Recently Used (LRU)** – This method replaces the block that hasn't been read by the processor in the longest period of time.
- **First In First Out (FIFO)** – This method replaces the block that has been in cache the longest.
- **Least Frequently Used (LFU)** – This method replaces the block which has had fewest hits since being loaded into the cache.
- **Random** – This method randomly selects a block to be replaced. It has only slightly lower performance than LRU, FIFO, or LFU.

Example

The table below represents five lines from a cache that uses fully associative mapping with a block size of eight. Identify the address of the shaded data ($C9_{16}$).

Tag	Word id bits (in binary)							
	000	001	010	011	100	101	110	111
0110110110010 ₂	16	36	66	28	A1	3B	D6	78
0100011010101 ₂	54	C9	6A	63	54	32	00	D3
0001000111011 ₂	29	8C	ED	FD	29	54	12	F3
0001111001100 ₂	39	FA	B5	C1	33	9E	33	C8
1001100101101 ₂	23	4C	D2	40	6A	76	A3	F0

Solution

The tag for $C9_{16}$ is 0100011010101₂. When combining this with the word id of 001₂, the address in main memory from which $C9_{16}$ was retrieved is 0100011010101001₂ = $46A9_{16}$.

Example

Is the data from memory address $1E65_{16}$ contained in the table from the previous example?

Solution

For this cache, the last three bits identify the word and the rest of the bits act as the tag. Since $1E65_{16} = 0001111001100101_2$, then 101₂ is the word id and 0001111001100₂ is the tag. Scanning the rows shows that

the fourth row contains this tag, and therefore the table contains the data in which we are interested. The word identified by 101_2 is $9E_{16}$.

The last mapping algorithm presented here is *set associative mapping*. Set associative mapping combines direct mapping with fully associative mapping by grouping together lines of a cache into sets. The sets are identified using a direct mapping scheme while the lines within each set are treated like a miniature fully associative cache where any block that is to be stored in the set can be stored to any line within the set. Figure 13-21 represents this arrangement with a sample cache that uses four lines to a set.

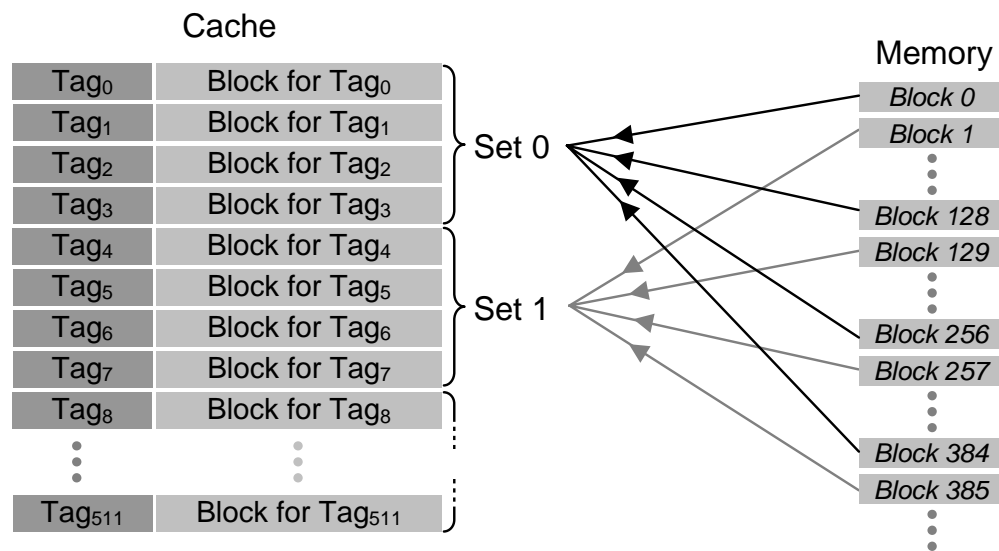


Figure 13-21 Set Associative Mapping of Main Memory to Cache

A set associative cache that has k lines per set is referred to as a k -way set associative cache. Since the mapping scheme uses the memory address just as direct mapping does, the number of lines contained in a set must be equal to an integer power of two, e.g., two, four, eight, sixteen, and so on.

Let's use an example to further explain set associative mapping. Assume that a system uses a cache with $2^9 = 512$ lines, a block of memory contains $2^3 = 8$ words, and the full memory space contains $2^{30} = 1$ Gig words. In a direct mapping scheme, this would leave $30 - 9 - 3 = 18$ bits for the tag. Note that the direct mapping method is equivalent to the set associative method where the set size is equal to one line.

By going from direct mapping to set associative with a set size of two lines per set, the number of sets is equal to half the number of lines.

In the case of the cache with 512 lines, that would give us 256 sets of two lines each which would require eight bits from the memory address to identify the set. This would leave $30 - 8 - 3 = 19$ bits for the tag. By going to four lines per set, the number of sets is reduced to 128 sets requiring seven bits to identify the set and twenty bits for the tag.

Figure 13-22 shows how each time the number of lines per set in the example is doubled, the number of bits used to identify the set is reduced by one thereby increasing the number of tag bits by one.

Tag bits	Set ID bits	Word ID bits	
18 bits	9 bits	3 bits	Direct mapping (1 line/set)
19 bits	8 bits	3 bits	2-way set associative (2^1 lines/set)
20 bits	7 bits	3 bits	4-way set associative (2^2 lines/set)
21 bits	6 bits	3 bits	8-way set associative (2^3 lines/set)
⋮	⋮	⋮	
25 bits	2 bits	3 bits	128-way set associative (2^7 lines/set)
26 bits	1 bit	3 bits	256-way set associative (2^8 lines/set)
27 bits		3 bits	Fully associative (1 big set)

Figure 13-22 Effect of Cache Set Size on Address Partitioning

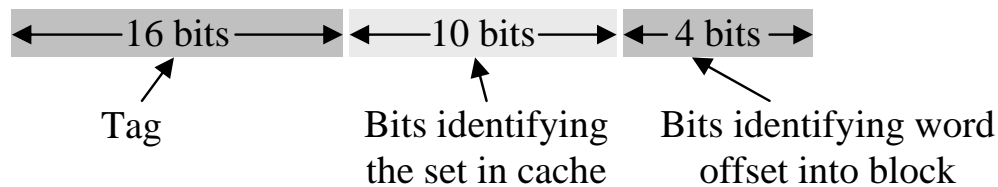
When a block from memory needs to be stored to a set in which all of the lines are already filled with other blocks, one of the replacement algorithms described for fully associative mapping is used. For a 2-way set associative cache, one of the easiest replacement algorithms to implement is the least recently used method. A single bit can be added to each set to identify which of the two lines was used last. If the bit contains a zero, then the first line was used last and the second line is the one that should be replaced with the new block from memory. If the bit contains a one, the first line should be replaced.

Example

Identify the set number where the block containing the address $29ABCDE8_{16}$ will be stored. In addition, identify the tag and the lower and upper addresses of the block. Assume the cache is a 4-way set associative cache with 4K lines, each block containing 16 words, with the main memory of size 1 G memory space.

Solution

First, we need to identify the partitioning of the bits in the memory address. A 1 Gig memory space requires 30 address lines. Four of those address lines will be used to identify one out of the 16 words within the block. Since the cache is a 4-way set associative cache, the number of sets equals 4K lines divided by four lines per set, i.e., $1K = 2^{10}$. Therefore, ten address lines will be needed to identify the set. The figure below represents the partitioning of the 30 bit address.



Converting $29ABCDE8_{16}$ to a 30-bit binary value gives us $00101001101010111100110111101000_2$. The first sixteen bits, 001010011010101111_2 , represent the tag. The next ten bits, $0011011110_2 = 222_{10}$, represent the set in which the block will be stored. The last four bits, $1000_2 = 8_{10}$, represent the word position within the block. The lowest address will be the one where word 0000_2 is stored and the highest address will be the one where the word 1111_2 is stored. Replacing the last four bits of $29ABCDE8_{16}$ with 0000_2 gives us a low address of $29ABCDE0_{16}$ while replacing them with 1111_2 gives us a high address of $29ABCDEF_{16}$.

13.4.6 Cache Write Policy

The last characteristic of caches discussed here is the **cache write policy**, i.e., the method used to determine how memory is updated when the cache is written to by the processor. There are a number of issues surrounding this topic, most of which apply to multi-processor systems which are beyond the scope of this text. Basically, when the cache is written to, the corresponding location in memory becomes obsolete.

One method for resolving this is to have the cache update memory every time the processor writes to the cache. This is called a **write through policy**. The problem with this is that it creates a great deal of memory bus traffic, some of which might be unnecessary if the same memory location is being updated often. This policy also slows the write process since both memories are being updated at the same time.

A second method is to update main memory only when a line of the cache that has been modified to is about to be replaced with a new block from memory. This is called a ***write back policy***. This method encounters problems when more than one processor such as an I/O processor is sharing memory. Solutions to this problem include making shared memory non-cacheable, adding an additional processor to watch all of the caches and update them when a write occurs to any one of them, or giving all of the processors the ability to check other caches for updates.

13.5 Registers

At the top of the memory hierarchy is a set of memory cells called ***registers***. A register is a group of latches that have been combined in order to perform a special purpose. This group of latches may be used to store an integer, store an address pointing to memory, configure an I/O device, or indicate the status of a process. Whatever the purpose of the register is, all of the bits are treated as a unit.

Registers are contained inside the processor and are integrated with the circuitry used to perform the processor's internal operations. This integration places registers within millionths of a meter of the action resulting in very quick access times. In addition, the typical processor contains fewer than a hundred registers making decoding very simple and very fast. These two features combine to make registers by far the fastest memory unit in the memory hierarchy.

Because of the integral part they play in computer architecture, the details and applications of registers are presented in Chapter 15.

13.6 What's Next?

This chapter presented the system of memory components that serve the processor. This system will be revisited in Chapter 15 where a detailed examination of the organization of the components inside of the processor will be introduced.

Chapter 14 presents another important component supporting the processor: serial communications. Up to this point, our discussion of the processor has used the parallel bus to transfer data. The parallel bus has some drawbacks though. These include higher expense, lack of adaptability, and lower reliability. Chapter 14 presents the basic structure of a serial communications system followed by a presentation of two serial protocols.

Problems

- Why is it important for hard drive substrates to be rigid?
- Why is it important for hard drive substrates to be lightweight?
- What is the advantage of a Winchester head, and how does it achieve this advantage?
- Sketch the pattern of magnetic polarity found using the RLL encoding of Figure 13-5 for the bit pattern 0110100110100110101.
- How many blocks of 16 words are there in a 256 Gig memory space? Draw the logical organization of the full address identifying the block ID portion and the word offset portion.
- Identify the line number, tag, and word position for each of the 30-bit addresses shown below if they are stored in a cache using the direct mapping method.
 - Address: $23D94EA6_{16}$ Lines in cache: 4K Block size: 2
 - Address: $1A54387F_6$ Lines in cache: 8K Block size: 4
 - Address: $3FE9704A_{16}$ Lines in cache: 16K Block size: 16
 - Address: $54381A5_{16}$ Lines in cache: 1K Block size: 8
- True or False: A block from main memory could possibly be stored in any line of a cache using fully associative mapping.
- What problem is the fully or set-associative mapping methods for caches supposed to solve over the direct mapping method?
- What is the easiest replacement algorithm to use with a 2-way set associative cache?
- The table below represents five lines from a cache that uses fully associative mapping with a block size of eight. Identify the address of the shaded data ($3B_{16}$).

Tag	Word id bits (in binary)							
	000	001	010	011	100	101	110	111
10011011011000101_2	10	65	BA	0F	C4	19	6E	C3
00111000011010101_2	21	76	CB	80	D5	2A	7F	B5
10111100010111001_2	32	87	DC	91	E6	3B	F0	A6
01110110001101011_2	43	98	ED	A2	F7	4C	E1	97
00111100100111000_2	54	9A	FE	B3	08	5D	D2	88

11. Using the table from the previous problem, identify the data value represented by each of the following addresses.
- a.) 76359_{16} b.) $386AF_{16}$ c.) $BC5CC_{16}$
12. Identify the set number, tag, and word position for each of the 30-bit addresses stored in an 8K line set associative cache.
- | | | |
|------------------------------|-------------|----------------|
| a.) Address: $23D94EA6_{16}$ | 2-way cache | Block size: 2 |
| b.) Address: $1A54387F_6$ | 2-way cache | Block size: 4 |
| c.) Address: $3FE9704A_{16}$ | 8-way cache | Block size: 16 |
| d.) Address: $54381A5_{16}$ | 4-way cache | Block size: 8 |
13. Using the C declarations below of a simulated 256 line cache and a 64K memory, create two functions. The first function, *bool requestMemoryAddress(unsigned int address)*, takes as its parameter a 16-bit value and checks to see if it exists in the cache. If it does, simply return a value of TRUE. If it doesn't, load the appropriate line of the cache with the requested block from memory[] and return a FALSE. The second function, *unsigned int getPercentageOfHits(void)*, should return an integer from 0 to 100 representing the percentage of successful hits in the cache.

```
typedef struct {
    int tag;
    char block[4];
}cache_line;

cache_line cache[256];

char memory[65536];
```