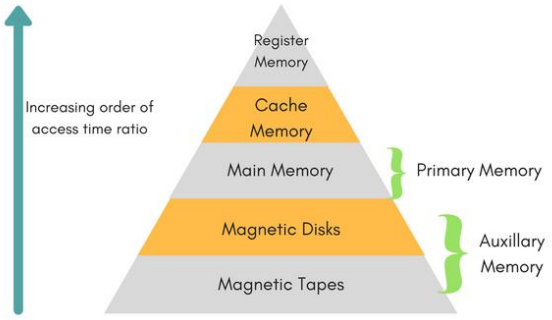
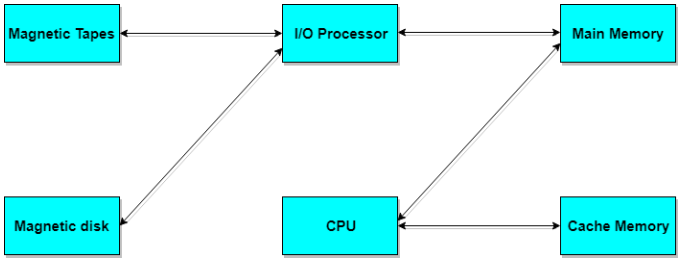
A memory unit is the collection of storage units or devices together. The memory unit stores the binary information in the form of bits. Generally, memory/storage is classified into 2 categories:

- **Volatile Memory**: This loses its data, when power is switched off.
- **Non-Volatile Memory**: This is a permanent storage and does not lose any data when power is switched off.

Memory Hierarchy



- The total memory capacity of a computer can be visualized by hierarchy of components. The memory hierarchy system consists of all storage devices contained in a computer system from the slow Auxiliary Memory to fast Main Memory and to smaller Cache memory.
- **Auxillary memory** access time is generally **1000 times** that of the main memory, hence it is at the bottom of the hierarchy.
- The **main memory** occupies the central position because it is equipped to communicate directly with the CPU and with auxiliary memory devices through Input/output processor (I/O).
- When the program not residing in main memory is needed by the CPU, they are brought in from auxiliary memory. Programs not currently needed in main memory are transferred into auxiliary memory to provide space in main memory for other programs that are currently in use.
- The **cache memory** is used to store program data which is currently being executed in the CPU. Approximate access time ratio between cache memory and main memory is about **1 to 7~10**



Memory Access Methods

Each memory type, is a collection of numerous memory locations. To access data from any memory, first it must be located and then the data is read from the memory location. Following are the methods to access information from memory locations:

1. **Random Access**: Main memories are random access memories, in which each memory location has a unique address. Using this unique address any memory location can be reached in the same amount of time in any order.
2. **Sequential Access**: This method allows memory access in a sequence or in order.
3. **Direct Access**: In this mode, information is stored in tracks, with each track having a separate read/write head.

Primary Memory (Main Memory):

Primary memory holds only those data and instructions on which the computer is currently working. It has a limited capacity and data is lost when power is switched off. It is generally made up of semiconductor device. These memories are not as fast as registers. The data and instruction required to be processed resides in the main memory. It is divided into two subcategories RAM and ROM.

Characteristics of Main Memory:

- These are semiconductor memories.
- It is known as the main memory.
- Usually volatile memory.
- Data is lost in case power is switched off.
- It is the working memory of the computer.
- Faster than secondary memories.
- A computer cannot run without the primary memory.

RAM (Random Access Memory) is the internal memory of the CPU for storing data, program, and program result. It is a read/write memory which stores data until the machine is working. As soon as the machine is switched off, data is erased.

Access time in RAM is independent of the address, that is, each storage location inside the memory is as easy to reach as other locations and takes the same amount of time. Data in the RAM can be accessed randomly but it is very expensive.

RAM is volatile, i.e. data stored in it is lost when we switch off the computer or if there is a power failure. Hence, a backup Uninterruptible Power System (UPS) is often used with computers. RAM is small, both in terms of its physical size and in the amount of data it can hold.

RAM is of two types −

- Static RAM (SRAM)
- Dynamic RAM (DRAM)

Static RAM (SRAM):

The word **static** indicates that the memory retains its contents as long as power is being supplied. However, data is lost when the power gets down due to volatile nature. SRAM chips use a matrix of 6-transistors and no capacitors. Transistors do not require power to prevent leakage, so SRAM need not be refreshed on a regular basis.

There is extra space in the matrix, hence SRAM uses more chips than DRAM for the same amount of storage space, making the manufacturing costs higher. SRAM is thus used as cache memory and has very fast access.

Characteristic of Static RAM

- Long life
- No need to refresh
- Faster
- Used as cache memory
- Large size
- Expensive
- High power consumption

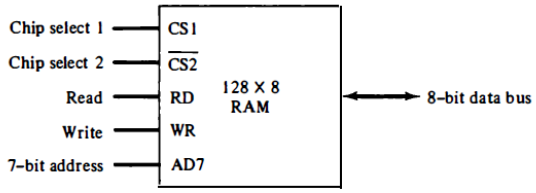
Dynamic RAM (DRAM):

DRAM, unlike SRAM, must be continually **refreshed** in order to maintain the data. This is done by placing the memory on a refresh circuit that rewrites the data several hundred times per second. DRAM is used for most system memory as it is cheap and small. All DRAMs are made up of memory cells, which are composed of one capacitor and one transistor.

Characteristics of Dynamic RAM

- Short data lifetime
- Needs to be refreshed continuously
- Slower as compared to SRAM
- Used as RAM
- Smaller in size
- Less expensive
- Less power consumption

Figure Typical RAM chip.



(a) Block diagram

CS1	$\overline{CS2}$	RD	WR	Memory function	State of data bus
0	0	×	×	Inhibit	High-impedance
0	1	×	×	Inhibit	High-impedance
1	0	0	0	Inhibit	High-impedance
1	0	0	1	Write	Input data to RAM
1	0	1	×	Read	Output data from RAM
1	1	×	×	Inhibit	High-impedance

(b) Function table

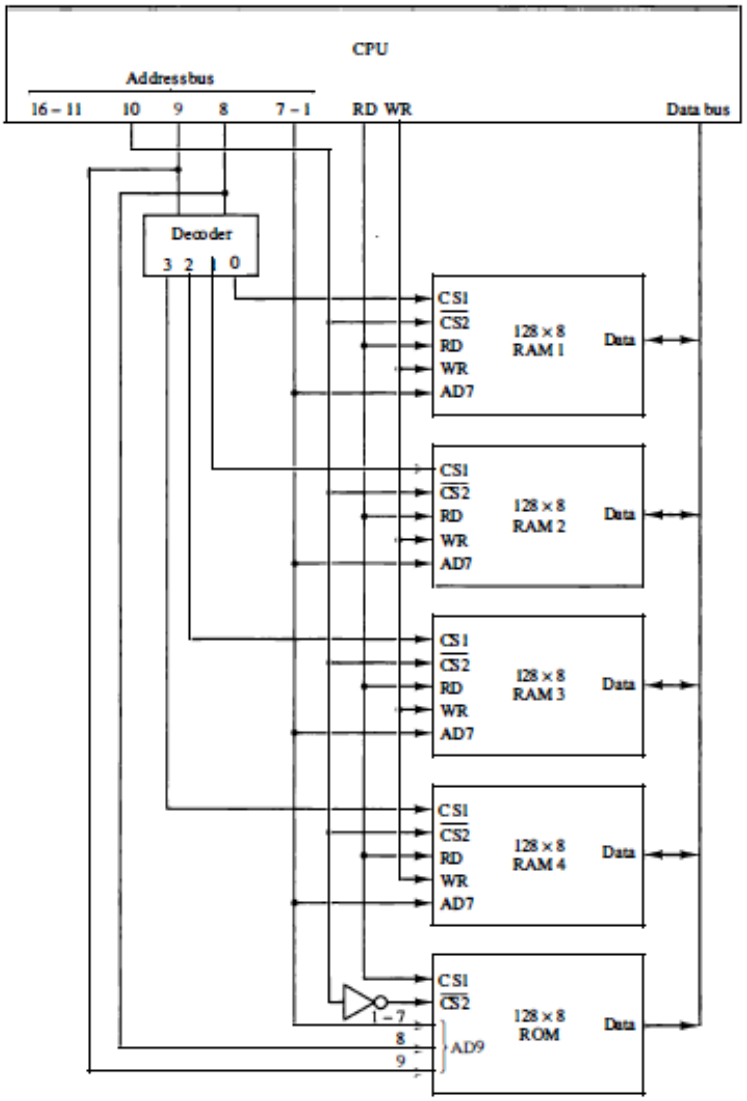
ROM stands for **Read Only Memory**. The memory from which we can only read but cannot write on it. This type of memory is non-volatile. The information is stored permanently in such memories during manufacture. A ROM stores such instructions that are required to start a computer. This operation is referred to as **bootstrap**. ROM chips are not only used in the computer but also in other electronic items like washing machine and microwave oven.

Let us now discuss the various types of ROMs and their characteristics.

- **MROM (Masked ROM)** - - - - The very first ROMs were hard-wired devices that contained a pre-programmed set of data or instructions. These kind of ROMs are known as masked ROMs, which are inexpensive.
- **PROM (Programmable Read Only Memory)** - - - - PROM is read-only memory that can be modified only once by a user. The user buys a blank PROM and enters the desired contents using a PROM program. Inside the PROM chip, there are small fuses which are burnt open during programming. It can be programmed only once and is not erasable.
- **EPROM (Erasable and Programmable Read Only Memory)** - - - - EPROM can be erased by exposing it to ultra-violet light for a duration of up to 40 minutes. Usually, an EPROM eraser achieves this function. During programming, an electrical charge is trapped in an insulated gate region. The charge is retained for more than 10 years because the charge has no leakage path. For erasing this charge, ultra-violet light is passed through a quartz crystal window (lid). This exposure to ultra-violet light dissipates the charge. During normal use, the quartz lid is sealed with a sticker.
- **EEPROM (Electrically Erasable and Programmable Read Only Memory)** - - - - EEPROM is programmed and erased electrically. It can be erased and reprogrammed about ten thousand times. Both erasing and programming take about 4 to 10 ms (millisecond). In EEPROM, any location can be selectively erased and programmed. EEPROMs can be erased one byte at a time, rather than erasing the entire chip. Hence, the process of reprogramming is flexible but slow.

The advantages of ROM are as follows −

- ✓ Non-volatile in nature
- ✓ Cannot be accidentally changed
- ✓ Cheaper than RAMs
- ✓ Easy to test
- ✓ More reliable than RAMs
- ✓ Static and do not require refreshing
- ✓ Contents are always known and can be verified



Auxiliary Memory:

Auxiliary memory is much larger in size than main memory but is slower. It normally stores system programs, instruction and data files. It is also known as secondary memory. It can also be used as an overflow/virtual memory in case the main memory capacity has been exceeded. Secondary memories cannot be accessed directly by a processor. First the data/information of auxiliary memory is transferred to the main memory and then that information can be accessed by the CPU. Characteristics of Auxiliary Memory are following

- **Non-volatile memory** − Data is not lost when power is cut off.
- **Reusable** − The data stays in the secondary storage on permanent basis until it is not overwritten or deleted by the user.
- **Reliable** − Data in secondary storage is safe because of high physical stability of secondary storage device.
- **Convenience** − With the help of a computer software, authorised people can locate and access the data quickly.
- **Capacity** − Secondary storage can store large volumes of data in sets of multiple disks.
- **Cost** − It is much lesser expensive to store data on a tape or disk than primary memory.

Magnetic Disks

A magnetic disk is a circular plate constructed of metal or plastic coated with magnetized material. Often both sides of the disk are used and several disks may be stacked on one spindle with read/write heads available on each surface. All disks rotate together at high speed and are not stopped or started for access purposes. Bits are stored in the magnetized surface in spots along concentric circles called tracks. The tracks are commonly divided into sections called sectors. In most systems, the minimum quantity of information which can be transferred is a sector. The subdivision of one disk surface into tracks and sectors

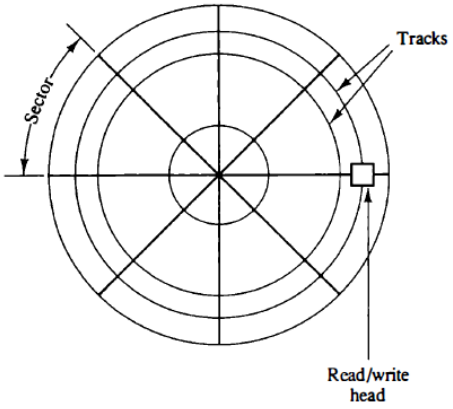


Figure Magnetic disk.

Magnetic Tape

A magnetic tape transport consists of the electrical, mechanical, and electronic components to provide the parts and control mechanism for a magnetic-tape unit. The tape itself is a strip of plastic coated with a magnetic recording content addressable memory medium. Bits are recorded as magnetic spots on the tape along several tracks. Usually, seven or nine bits are recorded simultaneously to form a character together with a parity bit. Read/write heads are mounted one in each track so that data can be recorded and read as a sequence of characters.

Associative Memory:

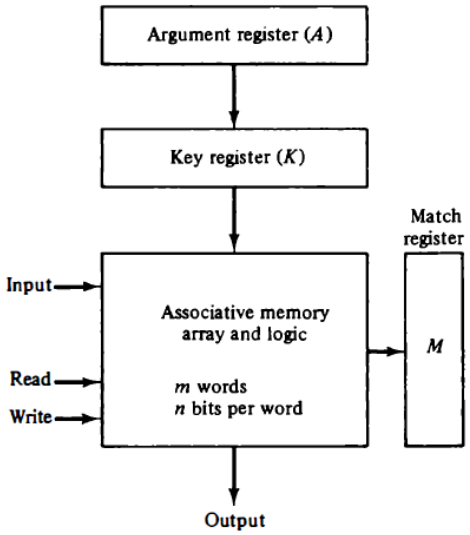
- Many data-processing applications require the search of items in a table stored in memory. An assembler program searches the symbol address table in order to extract the symbol's binary equivalent.
- Associative memory can also be called as Content addressable memory (CAM)
- CAM is accessed simultaneously and in parallel on the basis of data content rather than by specific address or location
- Associative memory is more expensive than a RAM because each cell must have storage capability as well as logic circuits
- Argument register – holds an external argument for content matching
- Key register – mask for choosing a particular field or key in the argument word

It consists of a memory array and logic for m words with n bits per word. The argument register A and key register K each have n bits, one for each bit of a word. The match register M has m bits, one for each memory word. Each word in memory is compared in parallel with the content of the argument register. The words that match the bits of the argument register

set a corresponding bit in the match register. After the matching process, those bits in the match register that have been set indicate the fact that their corresponding words have been matched. Reading is accomplished by a sequential access to memory for those words whose corresponding bits in the match register have been set.

The key register provides a mask for choosing a particular field or key in the argument word. The entire argument is compared with each memory word if the key register contains all l' s. Otherwise, only those bits in the argument that have l's in their corresponding position of the key register are compared. Thus the key provides a mask or identifying piece of information which specifies how the reference to memory is made. To illustrate with a numerical example, suppose that the argument register A and the key register K have the bit configuration shown below. Only the three leftmost bits of A are compared with memory words because K has 1's in these positions.

Figure Block diagram of associative memory.



Cache Memory:

As CPU has to fetch instruction from main memory speed of CPU depending on fetching speed from main memory. CPU contains register which has fastest access but they are limited in number as well as costly. Cache is cheaper so we can access cache. Cache memory is a very high speed memory that is placed between the CPU and main memory, to operate at the speed of the CPU.

It is used to reduce the average time to access data from the main memory. The cache is a smaller and faster memory which stores copies of the data from frequently used main memory locations. Most CPUs have different independent caches, including instruction and data.

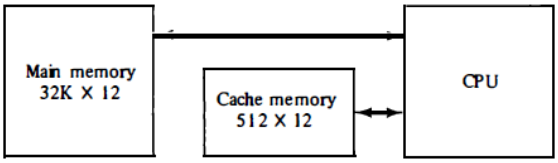


Figure 12-10 Example of cache memory.

Cache Mapping

The three different types of mapping used for the purpose of cache memory are as follow,

- Direct mapping
- Associative mapping,
- Set-Associative mapping.

Direct mapping: In direct mapping assigned each memory block to a specific line in the cache. If a line is previously taken up by a memory block when a new block needs to be loaded, the old block is trashed. An address space is split into two parts index field and tag field. The cache is used to store the tag field whereas the rest is stored in the main memory. Direct mapping`s performance is directly proportional to the Hit ratio.

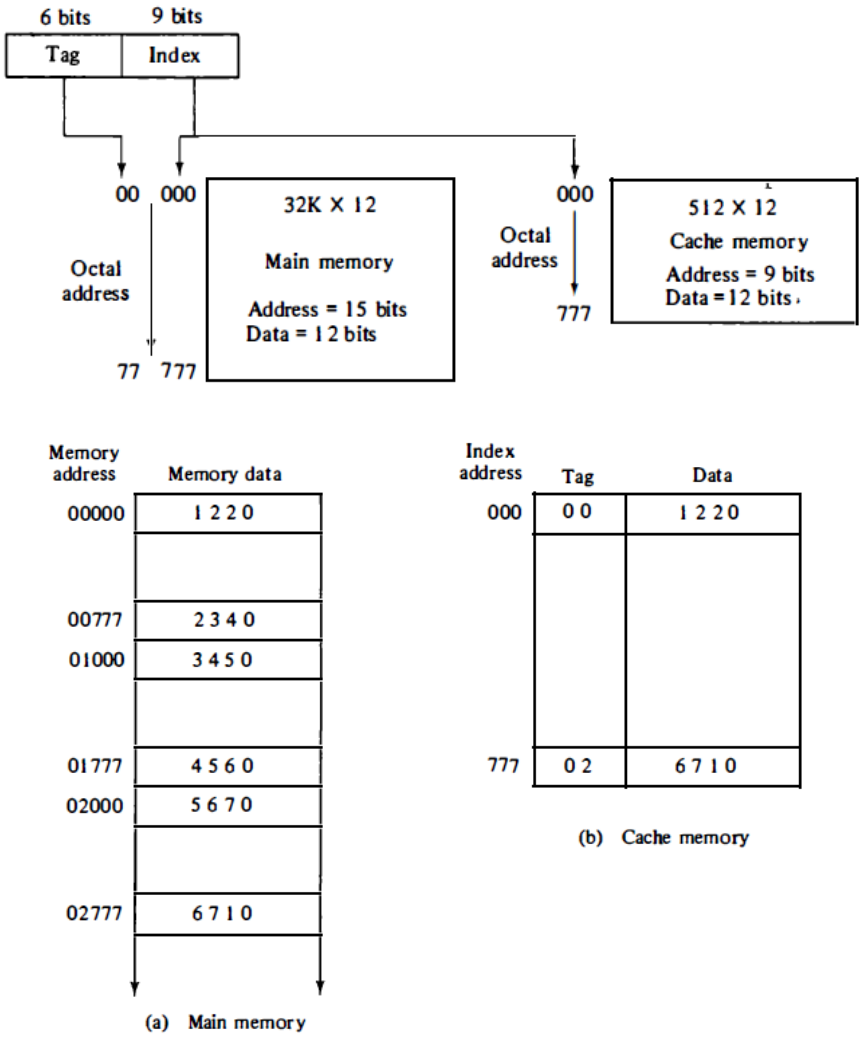
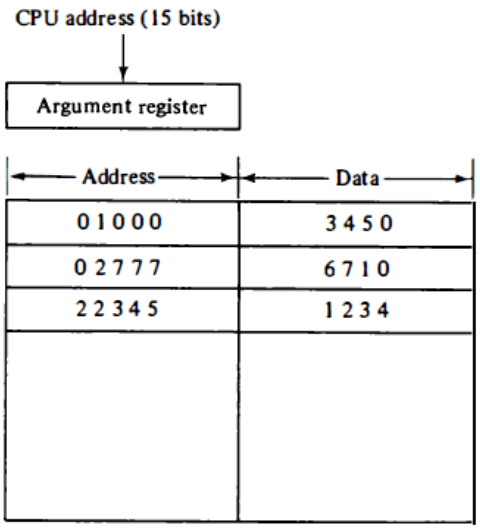


Figure 12-13 Direct mapping cache organization.

Associative mapping: In this type of mapping the associative memory is used to store content and addresses both of the memory word. Any block can go into any line of the cache. This means that the word id bits are used to identify which word in the block is needed, but the tag becomes all of the remaining bits. This enables the placement of the any word at any place in the cache memory. It is considered to be the fastest and the most flexible mapping form.



Set-associative mapping: This form of mapping is a enhanced form of the direct mapping where the drawbacks of direct mapping is removed. Set associative addresses the problem of possible thrashing in the direct mapping method. It does this by saying that instead of having exactly one line that a block can map to in the cache, we will group a few lines together creating a ***set***. Then a block in memory can map to any one of the lines of a specific set..Set-associative mapping allows that each word that is present in the cache can have two or more words in the main memory for the same index address. Set associative cache mapping combines the best of direct and associative cache mapping techniques.

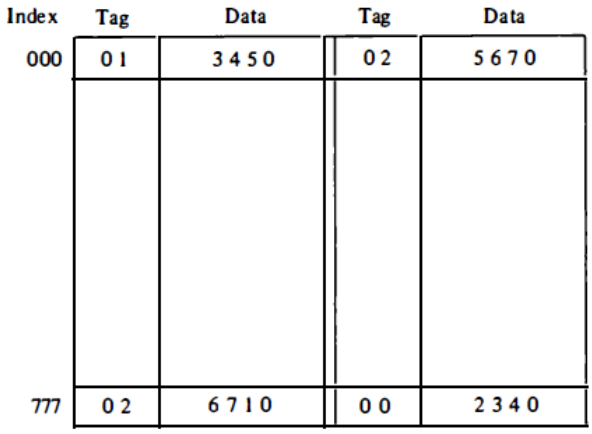


Figure 12-15 Two-way set-associative mapping cache.

Virtual Memory:

The concept of virtual memory in computer organization is allocating memory from the hard disk and making that part of the hard disk as a temporary RAM. In the earlier days, when the concept of virtual memory was not introduced, there was a big troubleshooting that when RAM is already full but program execution needs more space in RAM. The computers became unresponsive in such type of situation since processor forced the program to be in RAM but RAM can't hold them because it is already running out of space. To deal with this type problem the concept of virtual memory was introduced.

Virtual memory is used to give programmers the illusion that they have a very large memory even though the computer has a small main memory. It makes the task of programming easier because the programmer no longer needs to worry about the amount of physical memory available.

Working principle of virtual memory:

Now, let see the whole concept of virtual memory with a small example. Suppose the capacity of the main memory of a computer system is 32K while the secondary memory can store 1024K. That means the secondary memory can store data equal to the capacity of 32 main memory. If we denote address space by N and memory space by M, then we can have N = 1024K and M = 32K.

Here, 15 bits are required to specify each physical address since $32K = 2^{15}$ and 20 bits are required for each virtual address because, $1024K = 2^{20}$. So, here CPU is referring an address of 20-bit long for accessing the data from main memory but in reality, our main memory has the only 15-bit long address for accessing data. So, in this case, to access the data from main memory CPU has to perform a mapping of 20-bit virtual address to a 15-bit physical address.

Advantages and disadvantages of virtual memory:

The big advantage of virtual memory is that only a part of the program needs to be in memory for execution. So, more programs can run simultaneously at the same time interval. Virtual memory can increase CPU utilization and overall power of a system since large programmes can be run with real less primary memory.

The major disadvantage of virtual memory is when a system uses virtual memory, the application may run very slowly. So, CPU takes more times to switch between the applications.

Memory Management Hardware:

In a multiprogramming environment where many programs reside in memory it becomes necessary to move programs and data around the memory, to vary the amount of memory in use by a given program, and to prevent a program from changing other programs. The demands on computer memory brought about by multiprogramming have created the need for a memory management system. A memory management system is a collection of hardware and software procedures for managing the various programs residing in memory. The memory management software is part of an overall operating system available in many computers. Here we are concerned with the hardware unit associated with the memory management system.

The basic components of a memory management unit are:

1. A facility for dynamic storage relocation that maps logical memory references into physical memory addresses
2. A provision for sharing common programs stored in memory by different users.
3. Protection of information against unauthorized access between users and preventing users from changing operating system functions.