CIS410

LECTURE 5:
Data Storage Technology

CIS410/CIS510

Hardware and Software Architecture
Fall 2012

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Learning Objectives

- Describe the distinguishing characteristics of primary and secondary storage
- Describe the devices used to implement primary storage
- Describe memory allocation schemes
- Describe factors that determine storage device performance

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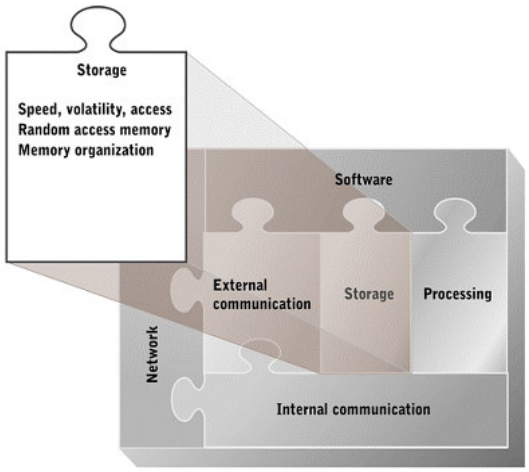
Lecture Topics



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Outline

- Primary And Secondary Storage
- Storage Device Characteristics
- Primary Storage Devices
- Memory Packaging
- Physical Memory Organization

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Storage

- Storage and retrieval of digital information is one of the most critical components of an IT system.
- Without storage, we would have no Web servers, electronic banking, e-mail, or almost any other digital application.

Hardware and Software Architecture

5

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Storage Devices

- Consist of a read/write mechanism and a storage medium
  - Storage medium: device or substance that actually holds data
  - Device controller provides interface between storage device and system bus.
- Primary storage devices
  - Support immediate execution of programs
- Secondary storage devices
  - Provide long-term storage of programs and data

Hardware and Software Architecture

6

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Access Storage

- Primary storage
  - directly accessible to the CPU
  - CPU continuously reads instructions stored there and executes them as required.
  - Any data actively operated on is also stored there in uniform manner.
- Secondary storage
  - not directly accessible by the CPU
  - The computer usually uses its input/output channels to access secondary storage and
  - transfers the desired data using intermediate area in primary storage.

7

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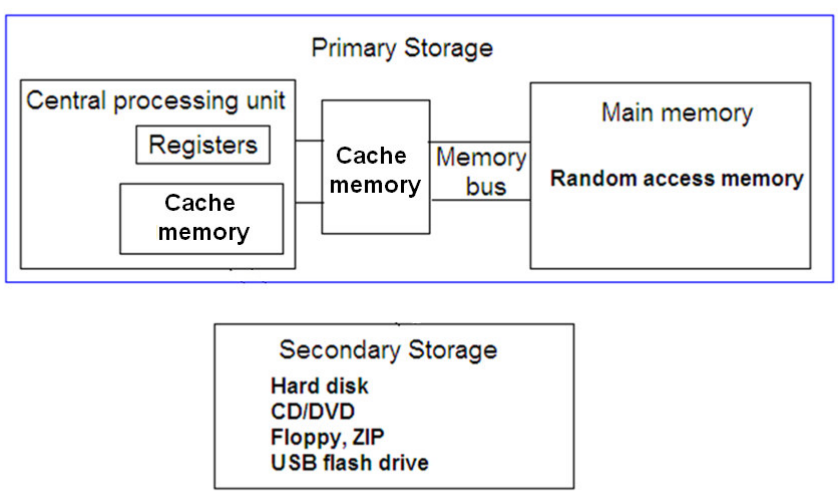
Various Forms of Storage



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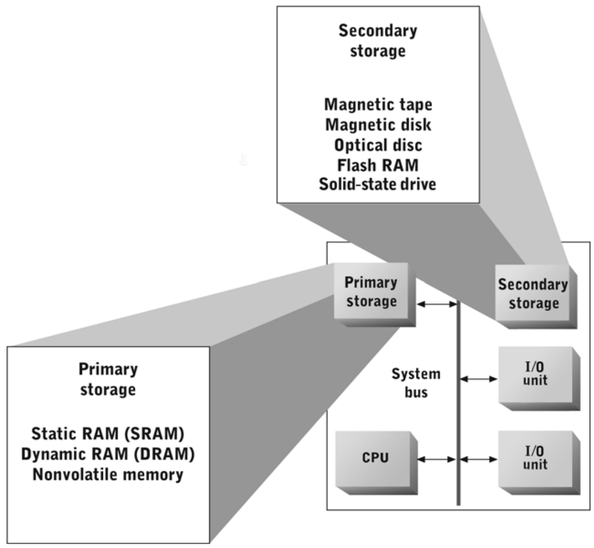
Primary and Secondary Storage



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Primary Storage

- Register
- Cache
- RAM
- ROM

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Secondary Storage Devices

- Disk storage: A read/write head passes over the spinning disk, reading or writing information as appropriate.
  - Magnetic disks: hard drives, Zip, floppy drives
  - Optical disks: CD, DVD (4.7GB per layer)
    - Compact disc-read only memory (**CD-ROM**)
    - Compact disc-recordable (**CD-R**)
    - Compact disc-rewritable (**CD-RW**)
    - Digital versatile disk-read only memory (**DVD-ROM**)
    - Digital versatile disk-recordable (**DVD-R**)
    - Digital versatile disk-rewritable (**DVD-RW**)
    - High-density optical disks: Blu-ray Disc (BD, 25GB per layer)

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Secondary Storage Devices (cont.)

- Electronic storage
  - also called semiconductor storage, has become an extremely effective technology for quick and efficient information storage.
  - Electronic storage lets users save data quickly without the relatively lengthy burn process required for optical media such as CDs and DVDs.
  - Electronic storage: Flash memory:
    - USB flash drive, memory cards (CompactFlash, Memory Stick, Memory Stick PRO**,** Secure Digital (SD), SDHC, xD)
  - Electronic storage: Solid-state drives
- Magnetic tape drives

Solid-State Drives (SSDs)

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- Expected to supplant magnetic disk like traditional hard disk drives (HDDs) as the dominant secondary storage technology.
- Mimics the behavior of a magnetic disk drive but uses flash RAM or other NVM (*Non-volatile memory)* devices as the storage medium and read/write mechanism.
- SSDs are distinguished from traditional HDDs, which are electromechanical devices containing spinning disks and movable read/write heads.

Solid-State Drives (SSDs) (cont.)

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- SSDs, in contrast, use microchips and data is retained in non-volatile memory chips and contain no moving parts.
- Compared to traditional HDDs, SSDs are typically less susceptible to physical shock and have lower access time and latency, lower power consumption.
- Currently implemented with the same physical size and interfaces as magnetic drives, thus easily replacing them in most applications.

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Comparing Various Types of Storage Media

- Hard disks provide very fast recording and access to information and can store large amounts of data.
- Because they can be written over and over again without encountering the limitations of CDs or DVDs, hard disks are currently the primary storage medium for computers.
- Optical disks are portable, lightweight, and can store information with greater stability than magnetic media.
- Optical disks are not affected by magnetic fields, so they are considered more robust than magnetic devices, which are prone to data loss over time.
- Electronic storage media are compact, fast, and versatile because they do not contain moving parts.

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Outline

Primary And Secondary Storage

Storage Device Characteristics

- Speed
- Volatility
- Access method
- Portability
- Cost and capacity

Memory Packaging

Physical Memory Organization

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Storage Device Characteristics

- Speed
- Volatility
- Access method
- Portability
- Cost and capacity

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Speed

- Most important characteristic differentiating primary and secondary storage.
  - CPU must be continuously supplied with instructions and data to keep it busy.
- Primary storage extends the limited capacity of CPU registers
  - Register's location enables zero wait states for access.
  - Before a program can be executed, its executable code is copied from secondary to primary storage.
  - CPU moves data and instructions continuously between registers and primary storage.

Speed (cont.)

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- Secondary storage speed also influences execution speed.
  - Many applications need access to large databases in the secondary storage to support ongoing processing.
  - Program response time in these systems depends on secondary storage access speed.

Speed (cont.)

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- Measured by access time and data transfer rate
  - Access time (or Latency): average time required to execute one complete read or write operation in nanoseconds
    - For memory read: the time required for a computer to process instruction/data from CPU and then retrieve the required data from the storage device.
  - Data transfer rate in *bps* (bit per second): amount of data that moves per second

$$\text{Data transfer rate} = \frac{1}{\text{access time}} \times \text{unit of data transfer}$$

Primary Storage Speed Vs. Secondary Storage Speed

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- Primary storage speed
  - Typically much faster than secondary storage speed
  - Expressed in nanoseconds (billionths of a second)
- Secondary storage speed
  - Expressed in milliseconds (thousandths of a second)

Typical Access Times of Storage

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Increasing storage capacity ↓

Device	Typical access times
CPU registers	0.25 nsec
Cache memory (SRAM)	1-10 nsec
Conventional memory (DRAM)	10-50 nsec
Flash memory	120 μsec
Magnetic disk drive	10-50 msec
Optical disk drive	100-500 msec
Magnetic tape	0.5 and up sec

Increasing access times ↓

1 nsec = 1 ns = 1 nanosecond = 10^{-9} seconds
1 μsec = 1 μs = 1 microsecond = 10^{-6} seconds
1 msec = 1 ms = 1 millisecond = 10^{-3} seconds

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Volatility

- **Non-volatile** storage device or medium retains its data when power is removed.
  - Secondary storage devices are generally non-volatile**.**
- **Volatile** storage device or medium loses its data when power is removed.
  - Primary storage devices are generally volatile**.**
    - Exception: ROM, Flash RAM

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Access Method

- Serial access (sequential, linear)
- Random access (direct access)
- Parallel access (simultaneous)

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Serial Access

- **Serial Access** (or sequential access, linear access)
- Stores and retrieves data items in a predetermined, ordered sequence.
  - Information can be accessed only after first getting past the intervening data.
  - For example, a magnetic tape must be rewound or fast-forwarded to get to the appropriate position.

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Random Access

- **Random Access** (or direct access)
- Access device is not restricted to any specific order when accessing data.
  - Consider the access data unit to be a byte or a word, RAM is a random access device.
  - Other devices include disk storage (hard disk, ZIP, floppy, CD/DVD), flash memory, and solid-state drives.
    - The read/write head of disk storage device can move directly to the information needed.

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Parallel Access

- **Parallel Access** (simultaneous access)
- A device that is capable of simultaneously accessing multiple storage locations.
  - Consider the access data unit to be a bit, RAM is also a parallel access device.

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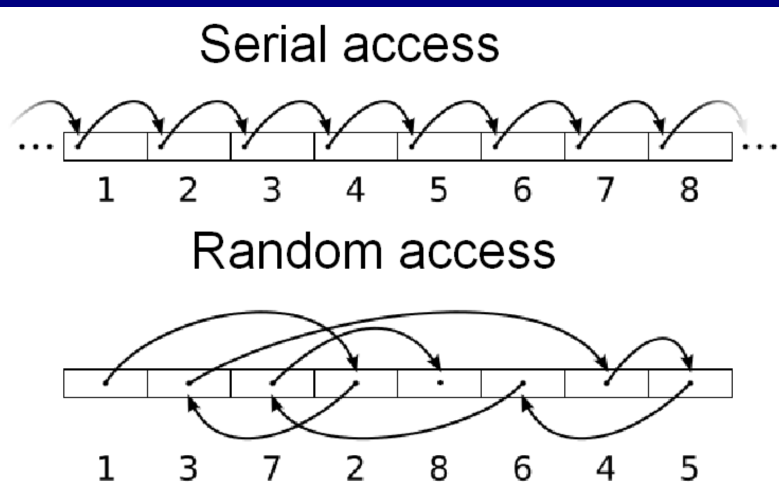
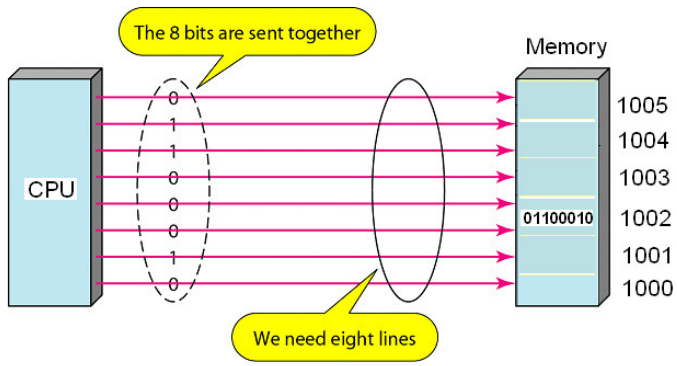
Serial Access vs. Random Access



RAM Parallel Access



CPU sends data n bits at a time instead of 1. In this example, data 01100010 will be stored in the memory unit with the address 1002.

Portability

- Data can be made portable by storing it on a removable storage medium or device.
- For example, CD/DVD, floppy disk, Zip disk, USB flash drive, and tape are portable because they are removable and have standardized storage formats.
- Typically implemented in two ways
- Entire storage device (USB flash drive)
- Storage medium can be removed (CDs, DVDs)
- Portable devices typically have slower access speed than permanently installed devices and those with non-removable media.

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Cost and Capacity

- Cost increases:
  - With improved speed, volatility, or portability
  - As access method moves from serial to random to parallel access method
- Primary storage - expensive (high speed and combination of parallel/random access methods)
- Capacity of secondary storage devices is greater than primary storage devices

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Characteristics Related to Cost

Characteristic	Description	Cost
Speed	Time required to read or write a bit, byte, or larger unit of data	Cost increases as speed increases.
Volatility	Capability to hold data indefinitely, particularly in the absence of external power	For devices of a similar type, cost decreases as volatility increases.
Access method	Can be serial, random, or parallel; parallel devices are also serial or random access	Serial is the least expensive; random is more expensive than serial; parallel is more expensive than nonparallel.
Portability	Capability to easily remove and re-install storage media from the device or the device from the computer	For devices of a similar type, portability increases cost, if all other characteristics are held constant.
Capacity	Maximum data quantity the device or storage medium holds	Cost usually increases in direct proportion to capacity.

Storage Hierarchy

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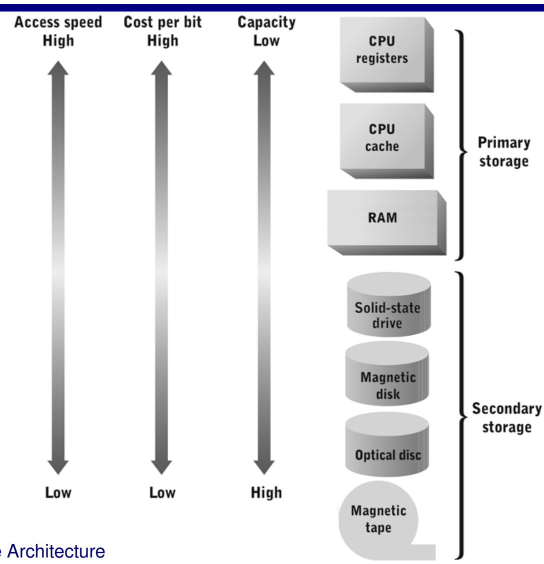

Outline

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Primary And Secondary Storage

Storage Device Characteristics

Primary Storage Devices

- Random access memory (RAM)
- Read-only memory (ROM)

Memory Packaging

Physical Memory Organization

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Primary Storage Devices

- Critical performance characteristics
  - Access speed
  - Data transfer unit size
- Must closely match CPU speed and word size to avoid wait states.
- Storing electrical signals.
- Types
  - Registers
  - Cache
  - Random Access Memory (RAM)
  - Read-Only Memory (ROM)

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Storing Electrical Signals

- Data is represented as electrical signals.
- Digital signals are used to transmit data to and from devices attached to the system bus.
- Storage devices must accept electrical signals as input and output.

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Outline

Primary And Secondary Storage

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RAM - Random Access Memory

- Characteristics
  - Microchip implementation using semiconductors
  - Ability to read and write with equal speed
  - Random access to stored bytes, words, or larger data units
- Saving information to RAM is referred to as “writing to RAM,” and retrieving RAM contents is called “reading the RAM”.

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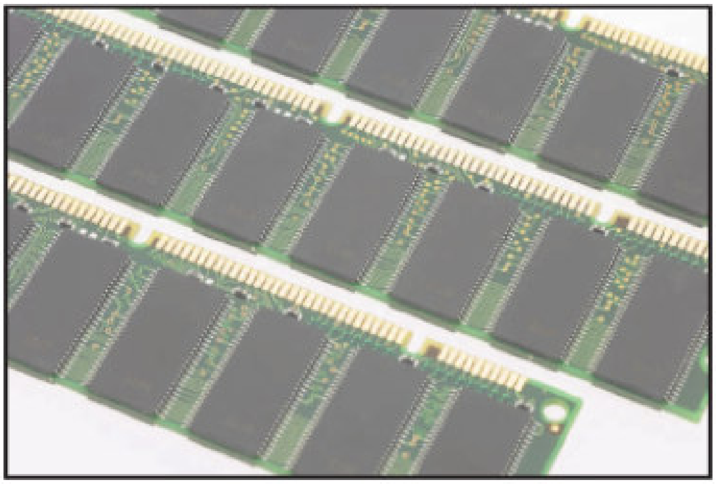
RAM Chips



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RAM Types

- Essentially, two types of RAM are used to store information as long as power is supplied to the computer: **static RAM** (SRAM) and **dynamic RAM** (DRAM).
- DRAMs include electronic components called *transistors* and *capacitors* that store electricity, whereas SRAMs are based on transistors.
- Memory chips that correspond to the main memory are mostly DRAM.
- Cache memory is typically SRAM
- Due to fundamental differences in how the two types of RAM are constructed, they differ in speed, size, and cost.

Content Refreshing

- The contents of DRAM must be refreshed several times per second, because the electrical charges representing the bits of DRAM leak out and must be replenished.
- There is no need to refresh the contents of SRAM.

DRAM (Dynamic RAM)

- Most common, cheap
- Volatile
- Although capacitors can store electricity, they cannot do so indefinitely
- Since electricity leaks out of capacitors, the information eventually fades unless the capacitor charge is refreshed periodically.
- DRAM must be **refreshed** (recharged with power) periodically to maintain its data.
  - So called *dynamic* memory

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DRAM (Dynamic RAM) (cont.)

- Only one transistor and a capacitor are required to store one bit information. This allows DRAM to reach very high density and to be used for *main memory*.
- Note: The term SDRAM, which stands for *synchronous DRAM*, should not be confused with SRAM.

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SRAM (Static RAM)

- More expensive than DRAM
- Faster (since use transistors only) and significantly less power usage than DRAM
- Used where either bandwidth or low power, or both, are principal considerations.
- Still volatile
- Due to a more complex internal structure (each bit is stored on four transistors), SRAM is less dense than DRAM and is therefore not used for high-capacity, low-cost applications such as the main memory.
- Small capacity, thus often used in registers and cache memory for high-speed access used.

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RAM Access Time

- Within the instruction fetch or execute cycle, the slowest steps are those that require memory access.
- Memory(e.g., memory clock at 266MHz) is slow compared to CPU processing speeds(e.g., 3.0GHz)!
- CPU must wait for the read/write operation to complete.
- A wait state is a CPU cycle spent waiting for a storage access or I/O operations to finish.

Memory access time <= CPU Fetch (or Execute) cycle time + CPU total wait stste time

where,

CPU total wait stste time = Numbe of CPU wait states x One wait state time

One wait state time = one CPU cycle time $= \dfrac{1}{\text{CPU clock rate}}$

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Bridging the Performance Gap Between Memory and CPU

- Read-ahead memory access
- Cache memory
- Synchronous read operations

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Read-ahead Memory Access

- Programs usually access instructions and data items sequentially, called *Spatial Locality*
  - If a particular memory location is referenced at a particular time, then it is likely that nearby memory locations will be referenced in the near future.
- Activating the read/write circuitry for location `n+1` while accessing to memory location `n`
  - e.g., traversing the elements in a one-dimensional array

```
for(index=0; index<=codes.length; index++)
        codes[index] = index*50;
```


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Cache Memory

- Take advantage of *Spatial Locality*
  - While requesting a word, this word and following words are retrieved.
  - The extra words are stored in a small amount of fast SRAM cache in anticipation of future sequential read requests.
- Also take advantage of *Temporal Locality*
  - If a data item is referenced, it will tend to be referenced again soon.
- Cache memory will be discussed in Lecture 7.

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Synchronous Read Operations

- Such RAM has a synchronous interface.
  - It waits for a system clock signal before transmitting data (reading or writing) and is therefore
  - synchronized with the computer's system bus.
- Example: SDRAM (Synchronous Dynamic RAM)
    - Only one word of data is read or written per system clock cycle (single data rate).

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SDRAM Latency

- SDRAM Latency (or Access time): refers to the delays incurred when a CPU tries to access data in SDRAM.
- SDRAM latency is often measured in memory clock speed.

$$\text{RAM clock speed in MHz} = \frac{1}{\text{RAM access time in nanoseconds (ns)}} \times 1000$$

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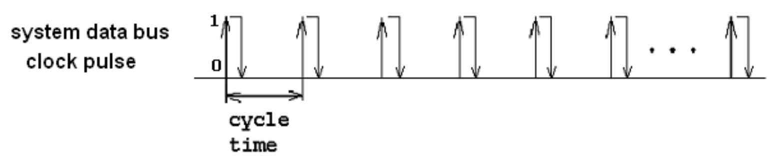
DDR SDRAM

- DDR (Double Data Rate) transfers data on both rising (0->1) and falling (1->0) edge of system data bus clock pulse.
  - i.e., reads or writes two words of data per clock cycle
- Theoretically it yields twice the data transfer rate of normal RAM or SDRAM.



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DDR SDRAM Example

- DDR266, for example, physically runs at 133MHz system data bus. As it transfers data twice on the same clock pulse, it's “virtually running” at 266MHz, or giving an effective data rate of 266MHz. I.e., 266 million data is transferred per second.

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DDR Standards

- Typical DDR SDRAM data bus clock rates are 133, 166 and 200 MHz.
- Thus they are generally described as DDR-266, DDR-333 and DDR-400.
  - E.g., DDR-400 means the data rate is 200M*2 or 400Million data transfers per second
- With data being transferred 64 bits (or 8 bytes) at a time, DDR RAM gives a transfer rate in Bytes per second (B/s):

  data rate (Million data transfers per second) × 8 (number of bytes per transfer)
- E.g., DDR400 gives a data transfer rate of 400*8, or 3200 MB/s. Thus it is also described as PC-3200.

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DDR SDRAM Modules

Standard name(Module name)	Data transfers per second
DDR266(PC-2100)	266 Million
DDR333(PC-2700)	333 Million
DDR400(PC-3200)	400 Million

- For example, for the module DDR333 (PC-2700)

  memory clock: 166 MHz
  system data bus clock: 166 MHz
  data transfers per second: 166 MT/s * 2 = 333 MT/s
  data transfer rate in B/s: 333MT/s * 8 B/T =2664 MB/s ->2700MB/s

- Note: PC-xxxx denotes theoretical bandwidth and it is often rounded up or down.
- DDR-SDRAM is not compatible with SDRAM memory.

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DDR2 SDRAM

- High-performance main memory.
- Over its predecessor, DDR-SDRAM, DDR2-SDRAM offers greater bandwidth and density in a smaller package along with a reduction in power consumption.
  - Adding an I/O buffer between the DDR2 and the data bus so that the data bus can be run at **twice the speed of the memory clock**.
  - Plus the double data rate of system bus, DDR2 achieves a total of **4 data transfers per memory clock cycle.**
- DDR2-SDRAM memory is not compatible with DDR-SDRAM memory.

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DDR2 SDRAM Modules

Standard name(Module name)	Data transfers per second
DDR2-400 (PC2-3200)	400 Million
DDR2-533 (PC2-4200)	533 Million
DDR2-667 (PC2-5300)	667 Million
DDR2-800 (PC2-6400)	800 Million
DDR2-1066 (PC2-8500)	1066 Million

- For example, for the module DDR2-800 (PC2-6400)

  memory clock: 200 MHz
  system data bus clock: 200 MHz*2 = 400 MHz
  data transfers per second: 400MT/s * 2 = 800 MT/s
  data transfer rate in B/s: 800MT/s * 8 B/T = 6400 MB/s.

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DDR3 SDRAM

- An improvement over its predecessor, DDR2 SDRAM.
- The primary benefit of DDR3 is the ability to transfer twice the data rate of DDR2, thus enabling higher bus rates and higher peak rates than earlier memory technologies.
  - Data bus can be run at **four times** of the speed of the memory clock.
  - DDR3 achieves a total of **8 data transfers per memory clock cycle**.
- DDR3 memory provides a reduction in power consumption compared to DDR2 modules.
- DDR3-SDRAM memory is not compatible with DDR2-SDRAM memory.

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DDR3 SDRAM Modules

Module	Data transfers per second
DDR3-800 (PC3-6400)	800 Million
DDR3-1066 (PC3-8500)	1066 Million
DDR3-1333 (PC3-10600)	1333 Million
DDR3-1600 (PC3-12800)	1600 Million

- For example, for the module DDR3-1600 (PC3-12800)

memory clock:	200 MHz
system data bus clock:	200MHz*4 = 800 MHz
data transfers per second:	800MT/s * 2 = 1600 MT/s
data transfer rate in B/s:	1600MT/s * 8 B/T = 12800 MB/s

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Outline

Primary And Secondary Storage

Storage Device Characteristics

Primary Storage Devices

- Random access memory (RAM)
- Read-only memory (ROM)

Memory Packaging

Physical Memory Organization

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Why the ROM is Needed?

- As RAM is volatile (cleared at start up), a computer containing only such storage would not have a source to read instructions from, in order to start the computer.
- Hence, non-volatile primary storage containing a small startup program (BIOS) is used to bootstrap the computer, that is, to read the larger programs from non-volatile secondary storage (such as hard disk) to RAM and start to execute them.
- The non-volatile primary storage used for this purpose is called ROM (read-only memory).

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ROM (Read Only Memory)

- *Non-volatile memory* (NVM) to hold software that is not expected to change over the life of the system
- The terminology of ROM may be somewhat confusing as most ROM types are also capable of rewriting for updating of held data and programs.
  - slower write speeds than DRAM and limited number of rewrites
- Modern types: EEPROM, Flash RAM (Flash ROM)

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EEPROM

- EEPROM
  - Electrically Erasable Programmable ROM
  - EEPROM can be programmed and erased electrically using field electron emission.
  - Slower and less flexible than Flash RAM

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Flash RAM

- Flash RAM (or Flash Memory, most common in use)
  - A special type of EEPROM
  - Faster than disk storages but more expensive
  - Competitive with DRAM in capacity and read performance
  - Slow rewrite time compared to RAM
  - Limited number of write cycles
    - Each write operation is mildly destructive, resulting in storage cell destruction after 100,000 or more write operations.
  - Used for firmware programs like BIOS
  - Also useful for nonvolatile portable computer storage
    - Memory cards for digital cameras, USB flash drive

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BIOS (Basic Input/Output System)

- Initial boot instructions and diagnostics
- Pronounced "bye-ose," BIOS is an acronym for basic input/output system.
- BIOS contains all the code required to control the keyboard, display screen, disk drives, serial communications, and a number of miscellaneous functions.
- BIOS was typically placed on a ROM chip (e.g., EEPROM) that comes with the computer.
- Most modern PCs have a flash BIOS recorded on a flash RAM (flash ROM) which can be updated if necessary.

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PnP BIOS

- PC BIOSes that can handle Plug-and-Play (PnP) devices are known as PnP BIOSes.
- Implemented with flash memory.
- When device details change, only BIOS needs to be changed.
- Sometimes this change can be made during the system setup.
- Neither the operating system or any using applications need to be changed.

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BIOS for System Booting-up

- When the computer is turned on, the CPU passes control to the BIOS program.
- When BIOS boots up (starts up) the computer, it first determines whether all of the attachments (devices) are in place and operational and then it loads the operating system (or key parts of it) into RAM from hard disk or diskette drive.
- Then the system control is passed to the operating system.

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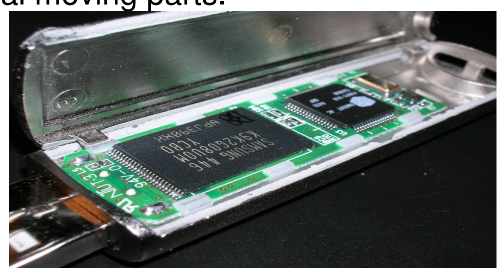
USB Flash Drive

- A small, portable flash memory card that plugs into a computer's USB port and functions as a portable hard drive with up to several GB of storage capacity.
- Easy-to-use as they are small enough to be carried in a pocket and can plug into any computer with a USB drive.
- Have less storage capacity than an external hard drive, but they are smaller and more durable because they do not contain any internal moving parts.

* The chip on the left is the flash memory. The microcontroller is on the right.



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New Nonvolatile Memory

- NVM technologies under development
  - Magnetoresistive RAM (MRAM)
  - Phase-change memory (PCM)

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Memory Packaging

- Dual in-line packages (DIPs)
  - Early RAM and ROM circuits
- Single in-line memory module (SIMM)
  - Standard RAM package in late 1980s
- Double in-line memory module (DIMM)
  - Newer packaging standard
  - A SIMM with independent electrical contacts on both sides of the module

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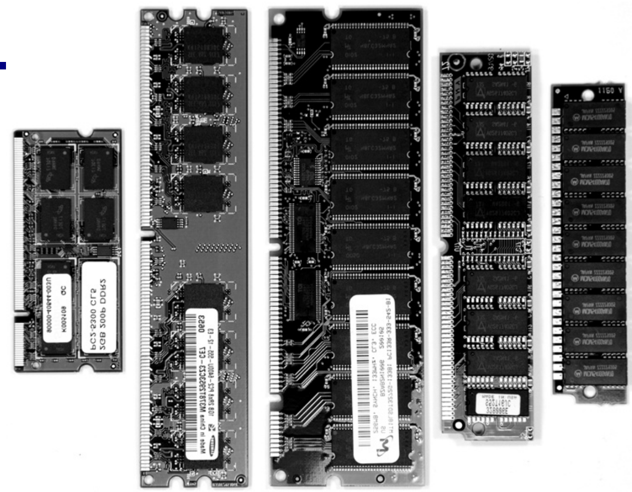

FIGURE 5.5 From left to right, 30-pin SIMM, 72-pin SIMM, DDR DIMM, DDR2 DIMM, and DDR2 DIMM for a laptop computer

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Outline

- Primary And Secondary Storage
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Physical Memory Organization

- Main memory can be regarded as a sequence of contiguous, or adjacent memory cells.
- Each memory location (cell) has a unique address.
- If a memory has n cells, they will have addresses 0 to n-1.

Physical Memory and Addressable Memory

- Physical memory
  - Actual number of memory bytes that physically are installed in the machine
- Addressable memory
  - Highest numbered storage byte that can be represented
- Physical memory is usually smaller than addressable memory.

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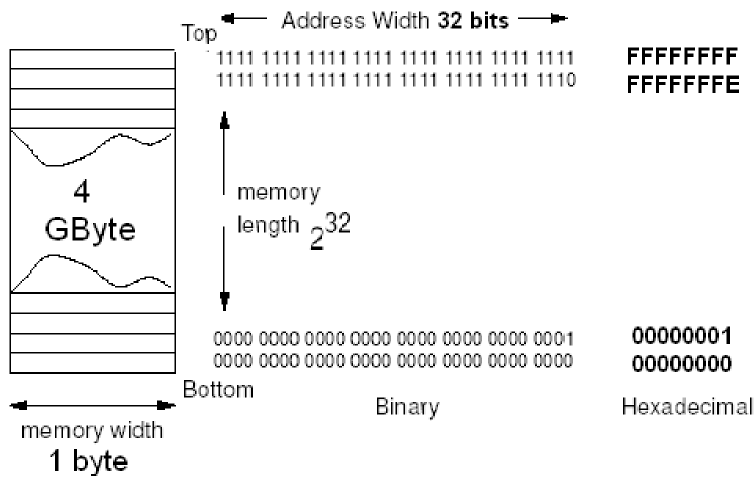
4GB Addressable Memory



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Address Width Determines Memory Length

16 bit addresses can access 2^{16}, or 65536, or 64K locations

20 bit addresses can access 2^{20}, or 1048576, or 1M locations

24 bit addresses can access 2^{24}, or 16777216, or 16M locations

32 bit addresses can access 2^{32}, or 4294967296, or 4G locations

64 bit addresses can access 2^{64}, or 4398046511104, or 4E locations

- For example, if 32 bits are used to represent a memory address, and one memory cell is 1 byte wide, then the addressable memory size is 2^{32} bytes, or 4,294,967,296 bytes, or 4GB

```
Memory size = number of cells * cell size
            = 2^32 * 1 byte
            = 2^2*2^30 * 1 byte
            = 4GB
```

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Endian-ness – Microsoft vs. Sun, or Intel vs. Motorola?

- Multi-byte data takes multiple memory cells to store.
- The agreement of items of multi-byte data in memory follows one of two conventions set independently by Intel and Motorola.
  - Big endian (Motorola): store the most significant byte (MSB) at the lowest memory address.
  - Little endian (Intel): store the least significant byte (LSB) at the lowest memory address.
- When transferring numeric data files from PC to Unix, they need to be converted.
  - Microsoft is tired to Intel processors.
  - Sun follows the Motorola convention.

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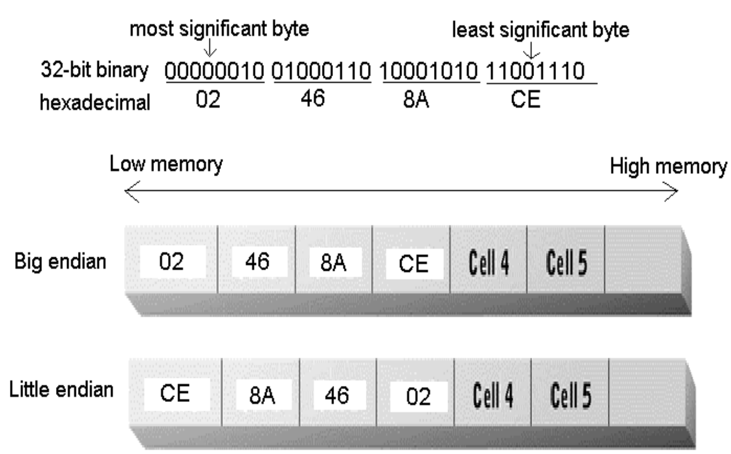
Store Bytes in Memory



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Which One Is Preferred?

- There are different applications.
- For example, little-endian representation can simplify hardware in multi-byte addition operation which starts at the least significant byte.
- While many network protocols use big-endian to send the most significant part first.

CIS410

Summary

- A typical computer system has primary and secondary storage devices.
- The critical performance characteristics of primary storage devices are their access speed and the number of bits that can be accessed in a single read or write operation.
- Programs generally are created as through they occupied contiguous primary storage locations starting at the first location.