香港中文大學
The Chinese University of Hong Kong

CENG3420

Lecture 07: Memory Organization

Bei Yu

byu@cse.cuhk.edu.hk

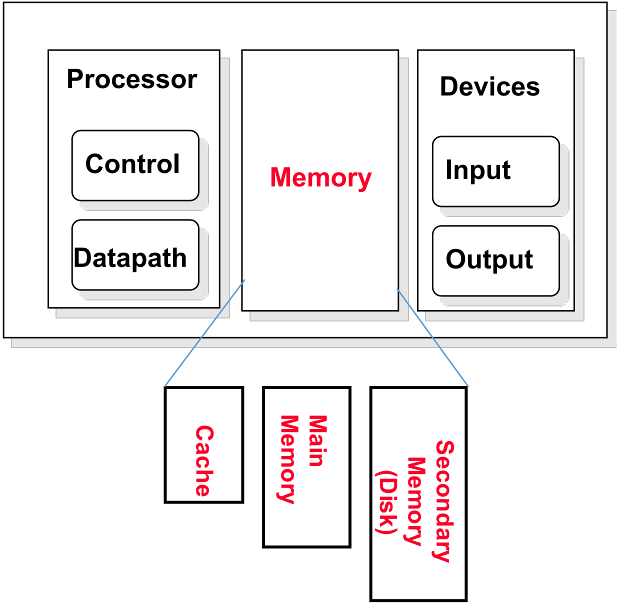
(Latest update: March 14, 2019)

Spring 2019

Overview

Overview

Review: Major Components of a Computer



Why We Need Memory?

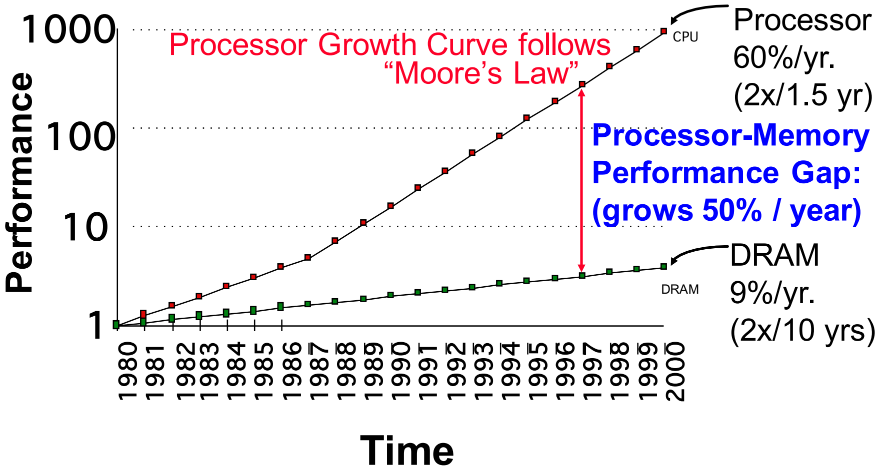
Combinational Circuit:

- Always gives the same output for a given set of inputs
- E.g., adders

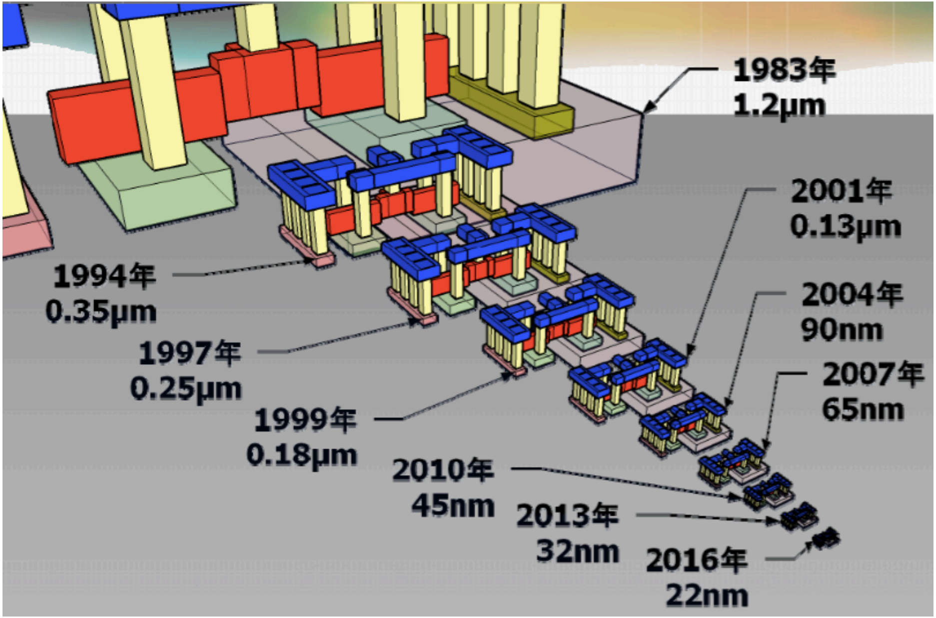
Sequential Circuit:

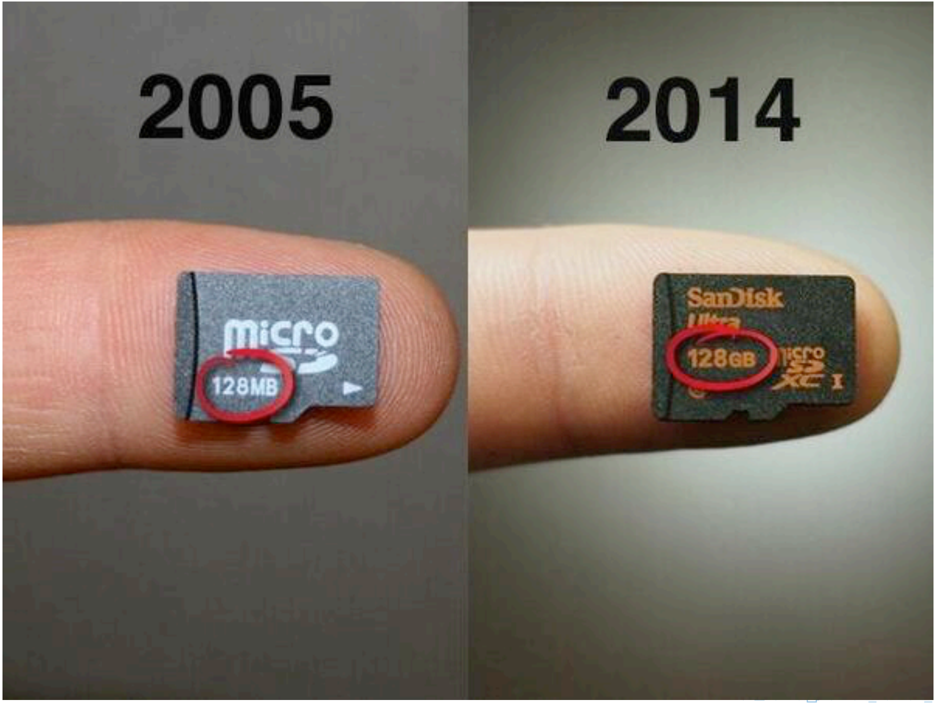
- Store information
- Output depends on stored information
- E.g., counter
- Need a storage element

Who Cares About the Memory Hierarchy?



Processor-DRAM Memory Performance Gap


1983年
1.2μm
2001年
0.13μm
2004年
90nm
2007年
65nm
1994年
0.35μm
1997年
0.25μm
1999年
0.18μm
2010年
45nm
2013年
32nm
2016年
22nm


2005
2014
micro
128MB
SanDisk
128GB
XC

Memory System Revisted

- Maximum size of memory is determined by addressing scheme

E.g.

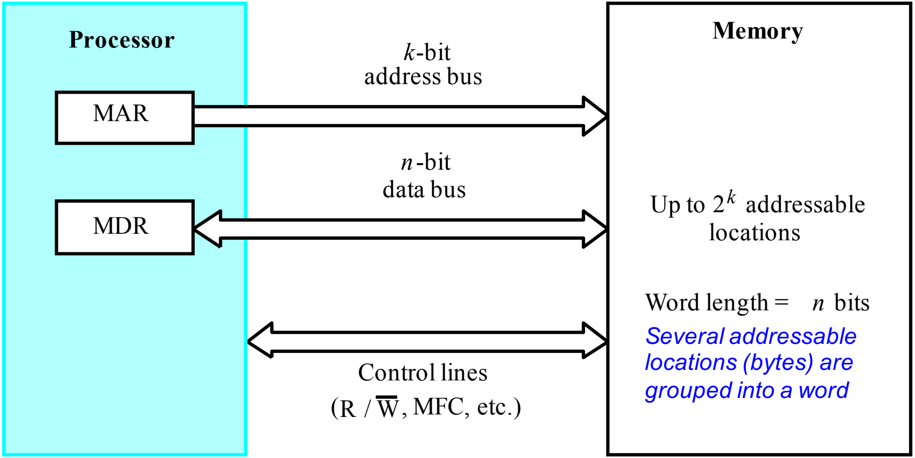
16-bit addresses can only address $2^{16} = 65536$ memory locations

- Most machines are byte-addressable
- each memory address location refers to a byte
- Most machines retrieve/store data in words
- Common abbreviations
  - 1k $\approx 2^{10}$ (kilo)
  - 1M $\approx 2^{20}$ (Mega)
  - 1G $\approx 2^{30}$ (Giga)
  - 1T $\approx 2^{40}$ (Tera)

Simplified View

Data transfer takes place through

- MAR: memory address register
- MDR: memory data register



Big Picture

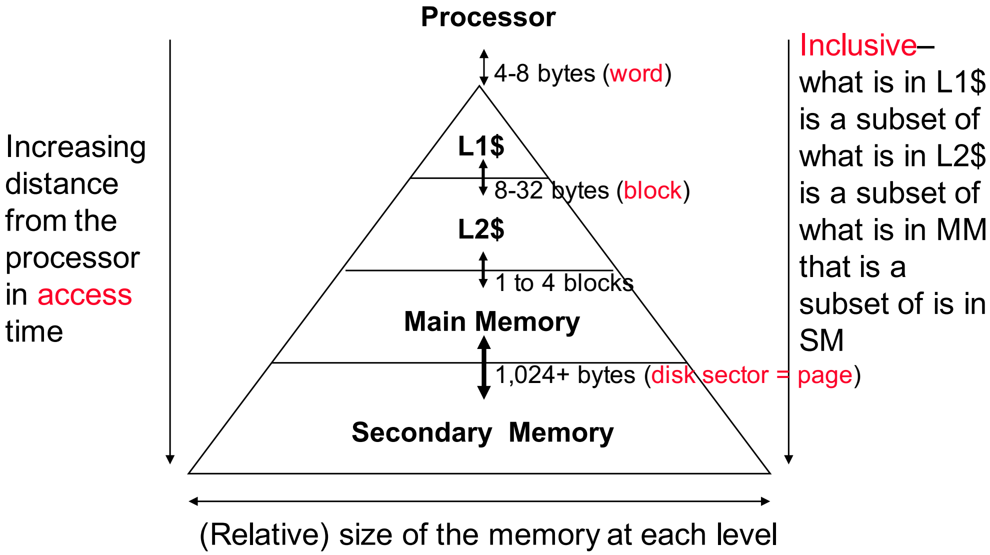
Processor usually runs much faster than main memory:

- Small memories are fast, large memories are slow.
- Use a cache memory to store data in the processor that is likely to be used.

Main memory is limited:

- Use virtual memory to increase the apparent size of physical memory by moving unused sections of memory to disk (automatically).
- A translation between virtual and physical addresses is done by a memory management unit (MMU)
- To be discussed in later lectures

Characteristics of the Memory Hierarchy



Memory Hierarchy: Why Does it Work?

Temporal Locality (locality in time)

If a memory location is referenced then it will tend to be referenced again soon

- Keep most recently accessed data items closer to the processor

Memory Hierarchy: Why Does it Work?

Temporal Locality (locality in time)

If a memory location is referenced then it will tend to be referenced again soon

- Keep most recently accessed data items closer to the processor

Spatial Locality (locality in space)

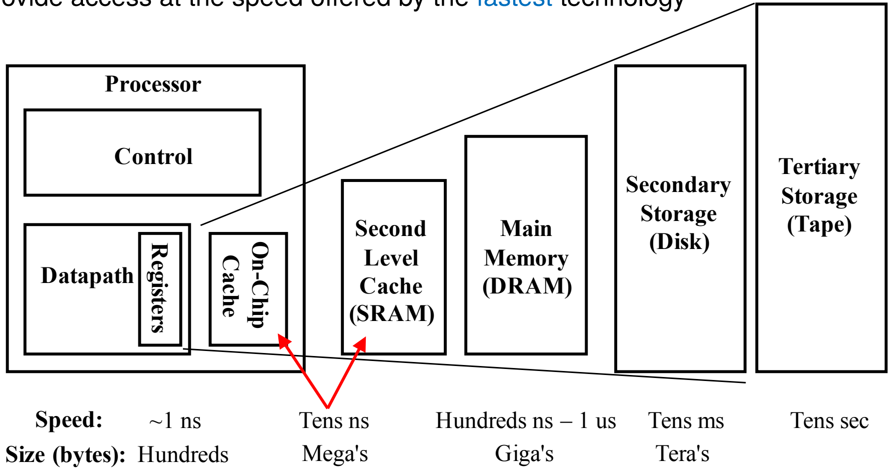
If a memory location is referenced, the locations with nearby addresses will tend to be referenced soon

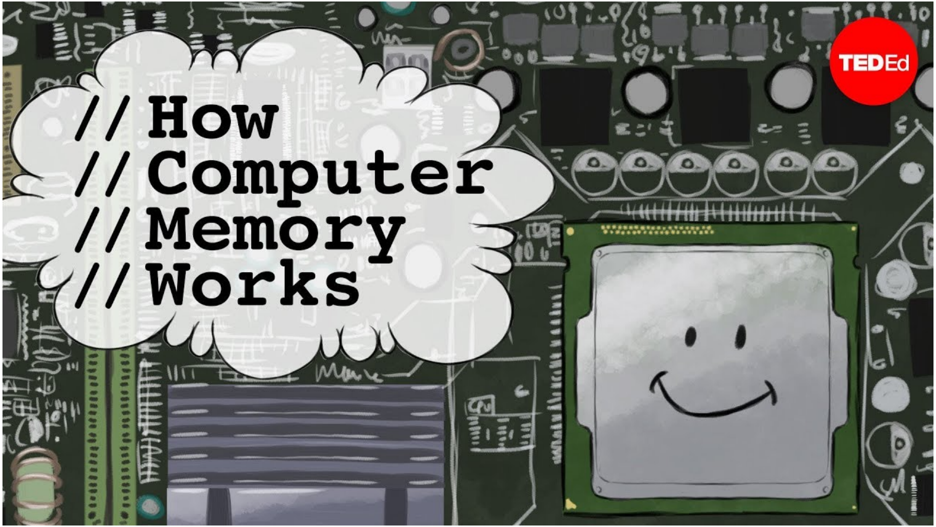
- Move blocks consisting of contiguous words closer to the processor

Memory Hierarchy

Taking advantage of the **principle of locality**:

- Present the user with as much memory as is available in the cheapest technology.
- Provide access at the speed offered by the fastest technology





https://youtu.be/p3q5zWCw8J4

Terminology

Random Access Memory (RAM)

Property: comparable access time for any memory locations

Block (or line)

the minimum unit of information that is present (or not) in a cache

Terminology

- Hit Rate: the fraction of memory accesses found in a level of the memory hierarchy
- Miss Rate: the fraction of memory accesses not found in a level of the memory hierarchy, i.e. 1 - (Hit Rate)

Hit Time

Time to access the block + Time to determine hit/miss

Miss Penalty

Time to replace a block in that level with the corresponding block from a lower level

Hit Time $<<$ Miss Penalty

Bandwidth v.s. Latency

Example

- Mary acts FAST but she's always LATE.
- Peter is always PUNCTUAL but he is SLOW.

Bandwidth v.s. Latency

Example

- Mary acts FAST but she's always LATE.
- Peter is always PUNCTUAL but he is SLOW.

Bandwidth:

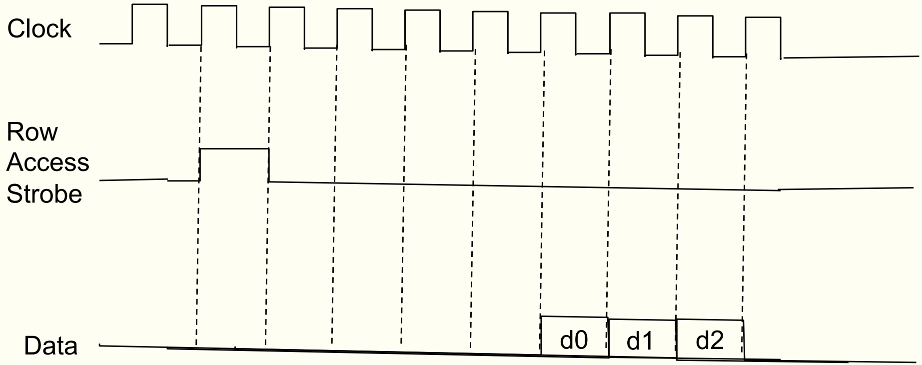
- talking about the "number of bits/bytes per second" when transferring a block of data steadily.

Latency:

- amount of time to transfer the first word of a block after issuing the access signal.
- Usually measure in "number of clock cycles" or in $ns/\mu s$.

Question:

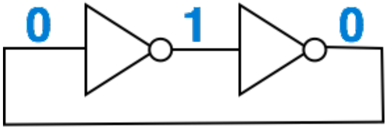
Suppose the clock rate is 500 MHz. What is the latency and what is the bandwidth, assuming that each data is 64 bits?



Overview

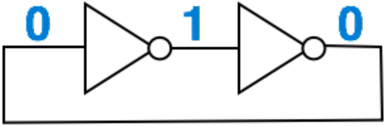
Storage based on Feedback

- What if we add feedback to a pair of inverters?

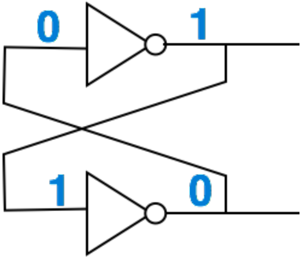


Storage based on Feedback

- What if we add feedback to a pair of inverters?

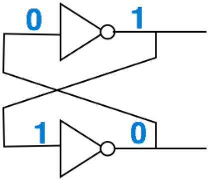


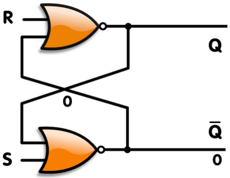
- Usually drawn as a ring of cross-coupled inverters
- Stable way to store one bit of information (w. power)



How to change the value stored?

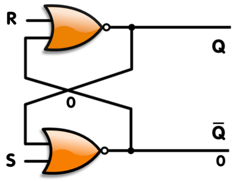
- Replace inverter with NOR gate
- **SR-Latch**





QUESTION:

What's the Q value based on different R, S inputs?

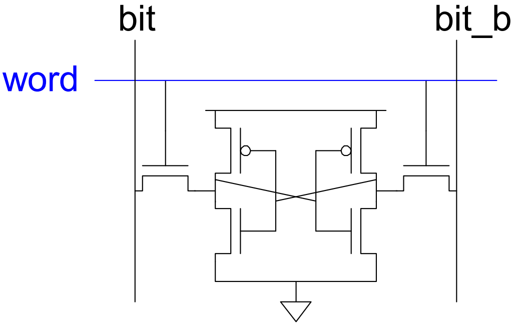


Input		Output
A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

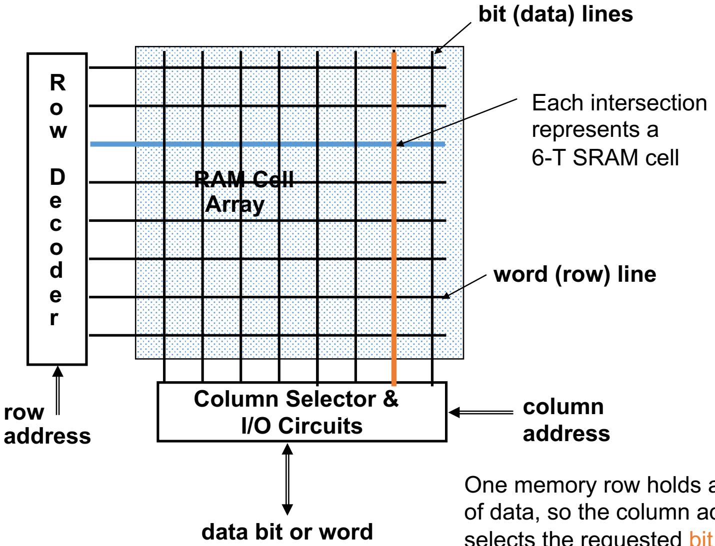
- R=S=1:
- S=0, R=1:
- S=1, R=0:
- R=S=0:

SRAM Cell

- At least 6 transistors (**6T**)
- Used in most commercial chips
- A pair of weak cross-coupled inverters
- Data stored in cross-coupled inverters



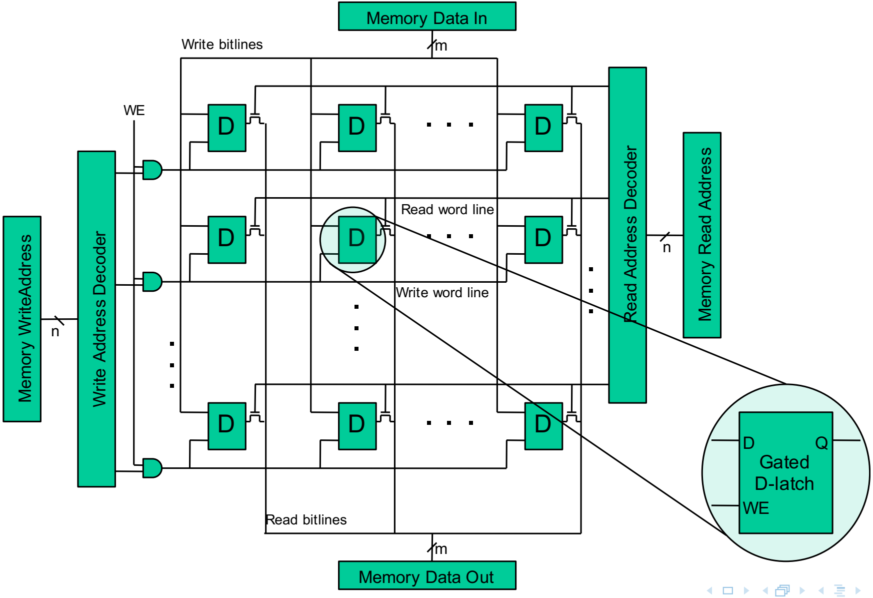
Classical SRAM Organization



One memory row holds a block of data, so the column address selects the requested bit or word from that block

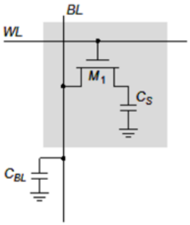
Classical SRAM Organization

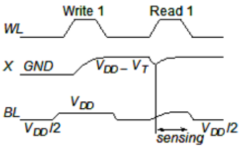
Latch based memory

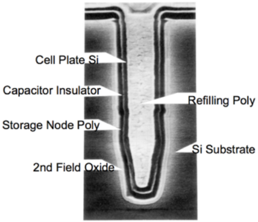


DRAM Cell

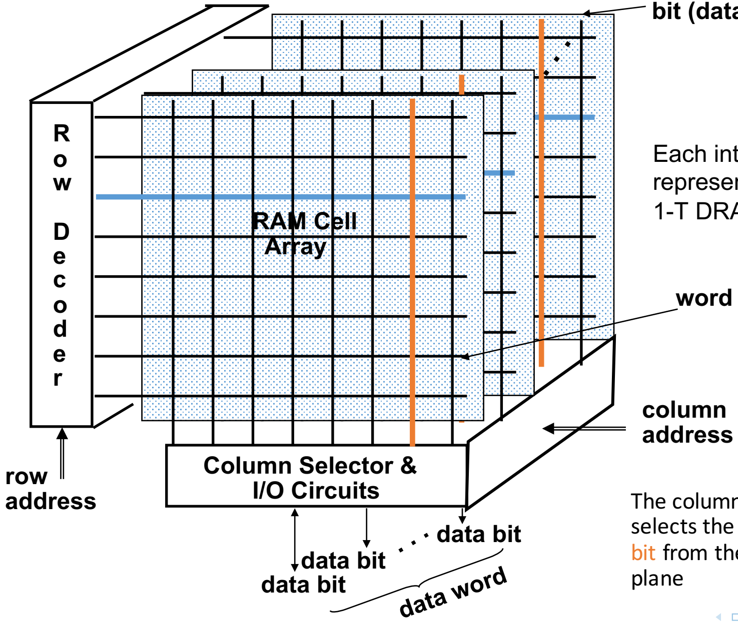
- 1 Transistor (**1T**)
- Requires presence of an extra capacitor
- Modifications in the manufacturing process.
- Higher density
- **Write**: Charged or discharged the capacitor (slow)
- **Read**: Charge redistribution takes place between bit line and storage capacitance







Classical DRAM Organization



Each intersection represents a 1-T DRAM cell

The column address selects the requested bit from the row in each plane

Synchronous DRAM (SDRAM)

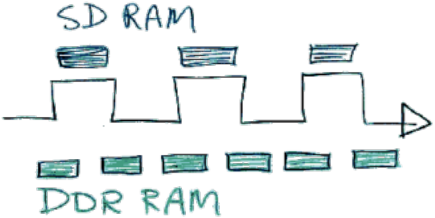
- The common type used today as it uses a clock to synchronize the operation.
- The refresh operation becomes transparent to the users.
- All control signals needed are generated inside the chip.
- The initial commercial SDRAM in the1990s were designed for clock speed of up to 133MHz.
- Today's SDRAM chips operate with clock speeds exceeding 1 GHz.

Memory modules are used to hold several SDRAM chips and are the standard type used in a computer's motherboard, of size like 4GB or more.

Double Data Rate (DDR) SDRAM

- normal SDRAMs only operate once per clock cycle
- Double Data Rate (DDR) SDRAM transfers data on both clock edges
- DDR-2 (4x basic memory clock) and DDR-3 (8x basic memory clock) are in the market.
- They offer increased storage capacity, lower power and faster clock speeds.
- For example, DDR2 can operate at clock frequencies of 400 and 800 MHz. Therefore, they can transfer data at effective clock speed of 800 and 1600 MHz.

Performance of SDRAM



1 Hertz
1 Cycle per second

RAM Type	Theoretical Maximum Bandwidth
SDRAM 100 MHz (PC100)	100 MHz X 64 bit/ cycle = 800 MByte/sec
SDRAM 133 MHz (PC133)	133 MHz X 64 bit/ cycle = 1064 MByte/sec
DDR SDRAM 200 MHz (PC1600)	2 X 100 MHz X 64 bit/ cycle ~= 1600 MByte/sec
DDR SDRAM 266 MHz (PC2100)	2 X 133 MHz X 64 bit/ cycle ~= 2100 MByte/sec
DDR SDRAM 333 MHz (PC2600)	2 X 166 MHz X 64 bit/ cycle ~= 2600 MByte/sec
DDR-2 SDRAM 667 MHz (PC2-5400)	2 X 2 X 166 MHz X 64 bit/ cycle ~= 5400 MByte/sec
DDR-2 SDRAM 800 MHz (PC2-6400)	2 X 2 X 200 MHz X 64 bit/ cycle ~= 6400 MByte/sec

Bandwidth comparison. However, due to latencies, SDRAM does not perform as good as the figures shown.

SRAM v.s. DRAM

Static RAM (SRAM)

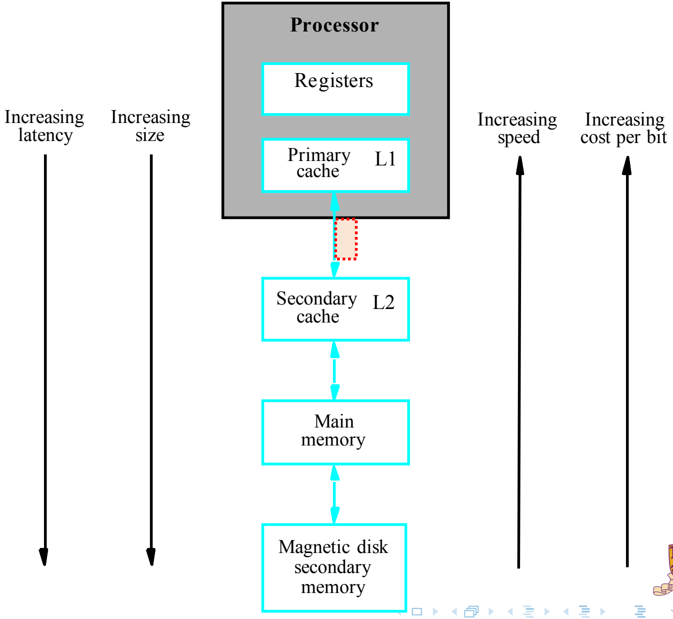
- Capable of retaining the state as long as power is applied.
- They are fast, low power (current flows only when accessing the cells) but costly (require several transistors), so the capacity is small.
- They are the Level 1 cache and Level 2 cache inside a processor, of size 3 MB or more.

Dynamic RAM (DRAM)

- store data as electric charge on a capacitor.
- Charge leaks away with time, so DRAMs must be refreshed.
- In return for this trouble, much higher density (simpler cells).

Memory Hierarchy

- **Aim**: to produce fast, big and cheap memory
- L1, L2 cache are usually SRAM
- Main memory is DRAM
- Relies on locality of reference



Mix-and-Match: Best of Both

By taking advantages of the principle of locality:

- Present the user with as much memory as is available in the cheapest technology.
- Provide access at the speed offered by the fastest technology.

DRAM is slow but cheap and dense:

- Good choice for presenting the user with a BIG memory system – main memory

SRAM is fast but expensive and not very dense:

- Good choice for providing the user FAST access time – L1 and L2 cache

Overview

Introduction

Random Access Memory (RAM)

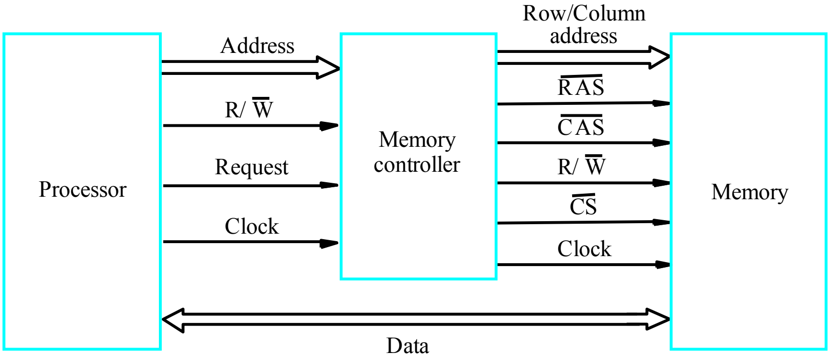
Interleaving

Secondary Memory

Conclusion

Memory Controller

- A memory controller is normally used to interface between the memory and the processor.
- DRAMs have a slightly more complex interface as they need refreshing and they usually have time-multiplex signals to reduce pin number.
- SRAM interfaces are simpler and may not need a memory controller.



RAS (CAS) = Row (Column) Address Strobe; CS = Chip Select

Memory Controller

- The memory controller accepts a complete address and the R/W signal from the processor.
- The controller generates the RAS (Row Access Strobe) and CAS (Column Access Strobe) signals.

Memory Controller

- The memory controller accepts a complete address and the R/W signal from the processor.
- The controller generates the RAS (Row Access Strobe) and CAS (Column Access Strobe) signals.
- The high-order address bits, which select a row in the cell array, are provided first under the control of the RAS (Row Access Strobe) signal.
- Then the low-order address bits, which select a column, are provided on the same address pins under the control of the CAS (Column Access Strobe) signal.

Memory Controller

- The memory controller accepts a complete address and the R/W signal from the processor.
- The controller generates the RAS (Row Access Strobe) and CAS (Column Access Strobe) signals.
- The high-order address bits, which select a row in the cell array, are provided first under the control of the RAS (Row Access Strobe) signal.
- Then the low-order address bits, which select a column, are provided on the same address pins under the control of the CAS (Column Access Strobe) signal.
- The right memory module will be selected based on the address. Data lines are connected directly between the processor and the memory.
- SDRAM needs refresh, but the refresh overhead is only less than 1 percent of the total time available to access the memory.

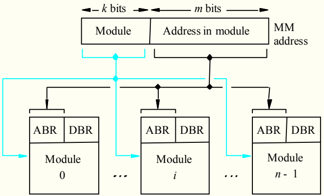
Memory Module Interleaving

- Processor and cache are fast, main memory is slow.
- Try to hide access latency by interleaving memory accesses across several memory modules.
- Each memory module has own Address Buffer Register (ABR) and Data Buffer Register (DBR)

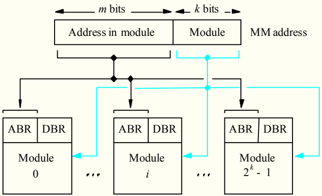
Memory Module Interleaving

- Processor and cache are fast, main memory is slow.
- Try to hide access latency by interleaving memory accesses across several memory modules.
- Each memory module has own Address Buffer Register (ABR) and Data Buffer Register (DBR)

Which scheme below can be better interleaved?



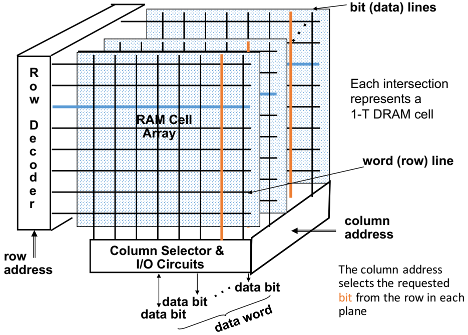
(a) Consecutive words in a module



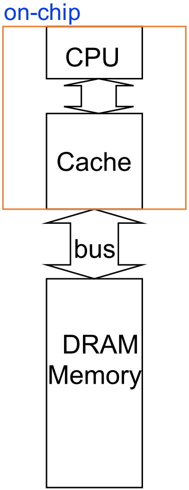
(b) Consecutive words in different modules

Memory Module Interleaving

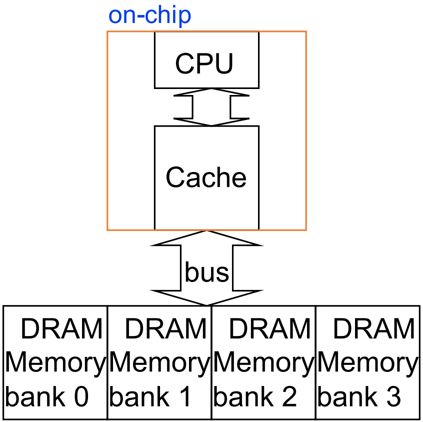
- Two or more compatible (identical the best) memory modules are used.
- Within a memory module, several chips are used in "parallel".
- E.g. 8 modules, and within each module 8 chips are used in "parallel'. Achieve a $8 \times 8 = 64$-bit memory bus.
- Memory interleaving can be realized in technology such as "Dual Channel Memory Architecture".



Non-Interleaving v.s. Interleaving



(a) Non-Interleaving



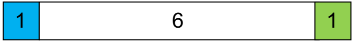
(b) Interleaving

Example

- Suppose we have a cache read miss and need to load from main memory
- Assume cache with 8-word block, i.e., cache line size = 8 words (bytes)
- Assume it takes one clock to send address to DRAM memory and one clock to send data back.
- In addition, DRAM has 6 cycle latency for first word
- Good that each of subsequent words in same row takes only 4 cycles

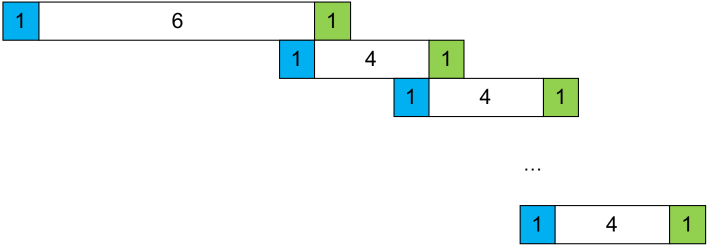
Single Memory Read: 1 + 6 + 1 = 8 Cycles

Example: Non-Interleaving



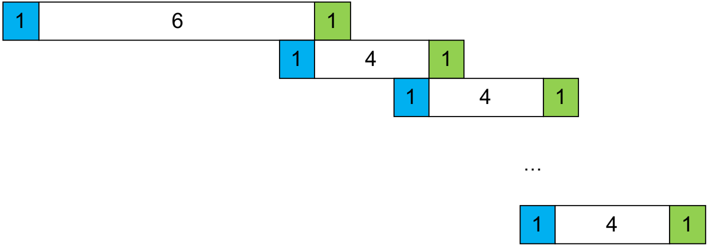
- First byte DRAM needs 6 cycle (same as single memory read)

Example: Non-Interleaving



- First byte DRAM needs 6 cycle (same as single memory read)
- All subsequent words DRAM needs 4 cycle
- Non-overlappings in cache access
- Assumption: all words are in the same row

Example: Non-Interleaving

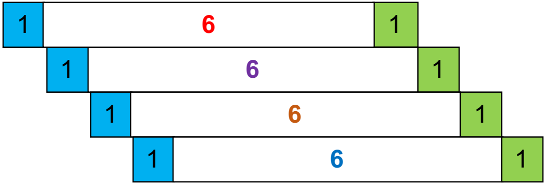


- First byte DRAM needs 6 cycle (same as single memory read)
- All subsequent words DRAM needs 4 cycle
- Non-overlappings in cache access
- Assumption: all words are in the same row

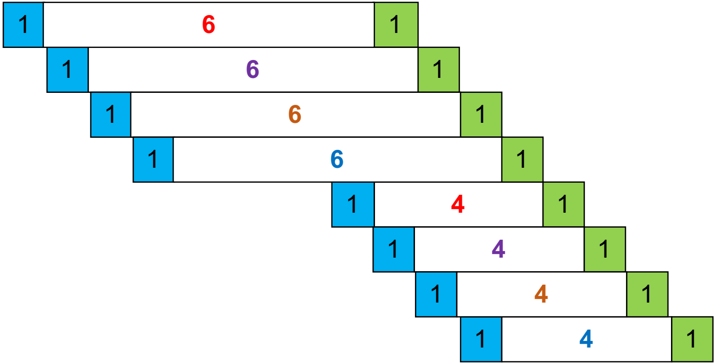
Non-Interleaving Cycle#

$$1 + 1 \times 6 + 7 \times 4 + 1 = 36$$

Example: Four Module Interleaving



Example: Four Module Interleaving



Interleaving Cycle#

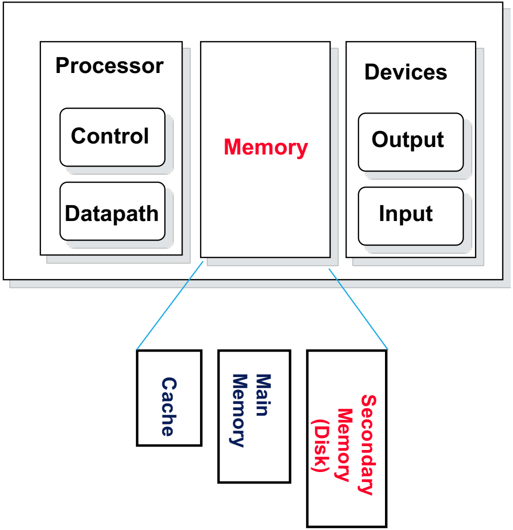
$$1 + 6 + 1 \times 8 = 15$$

Question:

To transfer 8 bytes, what is the cycle# if just have TWO-module interleaved?

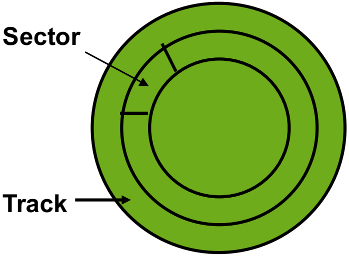
Overview

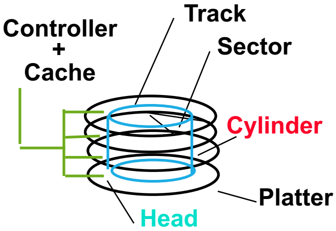
Major Components of A Computer



Magnetic Disk

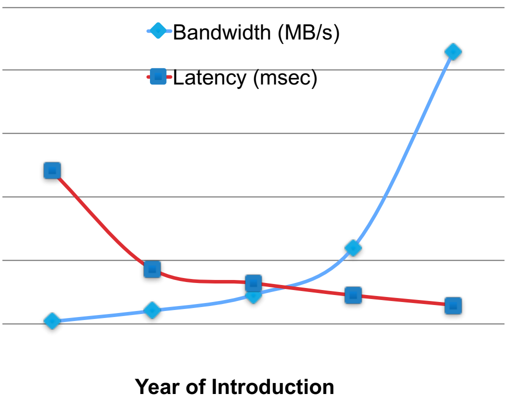
- Long term, nonvolatile storage
- Lowest level memory: slow; large; inexpensive
- A rotating platter coated with a magnetic surface
- A moveable read/write head to access the information





Magnetic Disk (cont.)

- Latency: average seek time plus the rotational latency
- Bandwidth: peak transfer time of formatted data from the media (not from the cache)



- In the time the bandwidth doubles, latency improves by a factor of only around 1.2

Read-Only Memory (ROM)

- Memory content fixed and cannot be changed easily.
- Useful to bootstrap a computer since RAM is volatile (i.e. lost memory) when power removed.
- We need to store a small program in such a memory, to be used to start the process of loading the OS from a hard disk into the main memory.

PROM/EPROM/EEPROM

Flash Storage

- First credible challenger to disks
- Nonvolatile, and $100\times - 1000\times$ faster than disks
- Wear leveling to overcome wear out problem

FLASH Memory

- Flash devices have greater density, higher capacity and lower cost per bit.
- Can be read and written
- This is normally used for non-volatile storage
- Typical applications include cell phones, digital cameras, MP3 players, etc.

FLASH Cards

- Flash cards are made from FLASH chips
- Flash cards with standard interface are usable in a variety of products.
- Flash cards with USB interface are widely used – memory keys.
- Larger cards may hold 32GB. A minute of music can be stored in about 1MB of memory, hence 32GB can hold 500 hours of music.

Overview

Conclusion

- Processor usually runs much faster than main memory
- Common RAM types:
  SRAM, DRAM, SDRAM, DDR SDRAM
- Principle of locality: Temporal and Spatial
  - Present the user with as much memory as is available in the cheapest technology.
  - Provide access at the speed offered by the fastest technology.
- Memory hierarchy:
  - Register $\rightarrow$ Cache $\rightarrow$ Main Memory $\rightarrow$ Disk $\rightarrow$ Tape