CHAPTER 6

Memory

6.1 Introduction 351
6.2 Types of Memory 351
6.3 The Memory Hierarchy 353
   6.3.1 Locality of Reference 356
6.4 Cache Memory 356
   6.4.1 Cache Mapping Schemes 359
   6.4.2 Replacement Policies 374
   6.4.3 Effective Access Time and Hit Ratio 377
   6.4.4 When Does Caching Break Down? 378
   6.4.5 Cache Write Policies 379
   6.4.6 Instruction and Data Caches 379
   6.4.7 Levels of Cache 382
6.5 Virtual Memory 383
   6.5.1 Paging 384
   6.5.2 Effective Access Time Using Paging 392
   6.5.3 Putting It All Together: Using Cache, TLBs, and Paging 393
   6.5.4 Advantages and Disadvantages of Paging and Virtual Memory 395
   6.5.5 Segmentation 396
   6.5.6 Paging Combined with Segmentation 397
6.6 Real-World Examples of Memory Management 397
Chapter Summary 399
6.1 Introduction

- In this chapter, we examine the various types of memory and how each is part of memory hierarchy system.
- We then look at cache memory (a special high-speed memory) and a method that utilizes memory to its fullest by means of virtual memory implemented via paging.

6.2 Types of Memory

- There are two kinds of main memory: random access memory, RAM, and read-only memory, ROM.
- There are two general types of RAM, dynamic RAM (DRAM) and static RAM (SRAM).
- DRAM
  - Dynamic RAM consists of capacitors that slowly leak their charge over time. Thus they must be refreshed every few milliseconds to prevent data loss.
  - DRAM is “cheap” memory owing to its simple design.
  - It is used to build main memory.
- SRAM
  - SRAM consists of circuits similar to the D flip-flop.
  - SRAM is very fast memory and it doesn’t need to be refreshed like DRAM does.
  - It is used to build cache memory.
- ROM
  - ROM also does not need to be refreshed, either. In fact, it needs very little charge to retain its memory.
  - ROM is used to store permanent or semi-permanent data that persists even while the system is turned off.
- Types of DRAM (Basic operations of all DRAM memories are the same)
  - MDRAM (Multibank DRAM)
  - FPM RAM (Fast-Page Mode DRAM)
  - SDRAM (Synchronous DRAM)
  - DDR SDRAM (Double Data Rate Synchronous DRAM)
  - RDRAM (Rambus DRAM)
  - DRDRAM (Direct Rambus DRAM)
- Types of ROMs
  - ROM (Read-Only Memory)
  - PROM (Programmable Read-Only Memory)
  - EPROM (Erasable PROM)
  - EEPROM (Electrically Erasable PROM)
6.3 The Memory Hierarchy 353

- Generally speaking, faster memory is more expensive than slower memory.
- To provide the best performance at the lowest cost, memory is organized in a hierarchical fashion.
- Small, fast storage elements are kept in the CPU, larger, slower main memory is accessed through the data bus.
- Larger, (almost) permanent storage in the form of disk and tape drives is still further from the CPU.

![FIGURE 6.1 The Memory Hierarchy]

- We are most interested in the memory hierarchy that involves registers, cache, main memory, and virtual memory.
- Registers are storage locations available on the processor itself.
- Virtual memory is typically implemented using a hard drive; it extends the address space from RAM to the hard drive.
- Virtual memory provides more space: Cache memory provides speed.
- To access a particular piece of data, the CPU first sends a request to its nearest memory, usually cache. If the data is not in cache, then main memory is queried. If the data is not in main memory, then the request goes to disk. Once the data is located, then the data, and a number of its nearby data elements are fetched into cache memory.
- This leads us to some definitions.
  - **Hit** – The requested data is found at a given memory level.
  - **Miss** – The requested data is not found at a given memory level.
  - **Hit Rate** – The percentage of time data is found at a given memory level.
o **Miss Rate** – The percentage of time it is not found at a given memory level. Note: Miss rate = 1 - Hit Rate.

o **Hit Time** – The time required to access data at a given memory level.

o **Miss Penalty** – The time required to process a miss, including the time that it takes to replace a block of memory plus the time it takes to deliver the data to the processor.

### 6.3.1 Locality of Reference 356

- An entire block of data is copied after a hit because the *principle of locality* tells us that once a byte is accessed, it is likely that a nearby data element will be needed soon.

- There are three forms of *locality*:
  - *Temporal locality*: Recently-accessed data elements tend to be accessed *again* in the *near future*.
  - *Spatial locality* - Accesses tend to be *clustered* in the address space (for example, as in *array* or *loops*).
  - *Sequential locality* - *Instructions* tend to be accessed *sequentially*. 
6.4 Cache Memory

- The purpose of cache memory is to speed up accesses by storing recently used data closer to the CPU, instead of storing it in main memory.
- Although cache is much smaller than main memory, its access time is a fraction of that of main memory.
- The computer uses the locality principle and transfers an entire block from main memory into cache whenever it has to make a main memory access.
- Unlike main memory, which is accessed by address, cache is typically accessed by content; hence, it is often called content addressable memory or CAM.
- A single large cache memory isn’t always desirable-- it takes longer to search.

6.4.1 Cache Mapping Schemes

- The CPU uses a specific mapping scheme that “converts” the main memory address into a cache location.
- Many blocks of main memory map to a single block of cache.
- **Direct Mapped Cache**
  - In a direct mapped cache consisting of \( N \) blocks of cache, block \( X \) of main memory maps to cache block \( Y = X \mod N \).
  - Thus, if we have 10 blocks of cache, block 7 of cache may hold blocks 7, 17, 27, 37, . . . of main memory.

![FIGURE 6.2 Direct Mapping of Main Memory Blocks to Cache Blocks](image)
To perform direct mapping, the binary main memory address is partitioned into the fields shown below.
   ▪ The offset field uniquely identifies an address within a specific block.
   ▪ The block field selects a unique block of cache.
   ▪ The tag field is whatever is left over.

The sizes of these fields are determined by characteristics of both memory and cache.

FIGURE 6.3 The Format of a Main Memory Address Using Direct Mapping

EXAMPLE 6.1 Consider a byte-addressable main memory consisting of 4 blocks, and a cache with 2 blocks, where each block is 4 bytes.
   ▪ This means Block 0 and 2 of main memory map to Block 0 of cache, and Blocks 1 and 3 of main memory map to Block 1 of cache.
   ▪ Using the tag, block, and offset fields, we can see how main memory maps to cache as follows.
   ▪ First, we need to determine the address format for mapping. Each block is 4 bytes, so the offset field must contain 2 bits; there are 2 blocks in cache, so the block field must contain 1 bit; this leaves 1 bit for the tag (as a main memory address has 4 bits because there are a total of $2^4=16$ bytes).
Suppose we need to access main memory address 0x03 (0011 in binary). If we partition 0011 using the address format from Figure 6.4a, we get Figure 6.4b. Thus, the main memory address 0011 maps to cache block 0. Figure 6.4c shows this mapping, along with the tag that is also stored with the data.

Suppose we need to access main memory address 0x0A (1010 in binary). If we partition 1010 using the address format from Figure 6.4a, we get Figure 6.4d. Thus, the main memory address 0011 maps to cache block 0. Figure 6.4e shows this mapping, along with the tag that is also stored with the data.

FIGURE 6.4 Diagrams for Example 6.1
EXAMPLE 6.2 Assume a byte-addressable memory consists of $2^{14}$ bytes, cache has 16 blocks, and each block has 8 bytes.
- The number of memory blocks are: $2^{14} / 2^3 = 2^{11}$
- Each main memory address requires 14 bits. Of this 14-bit address field, the rightmost 3 bits reflect the offset field
- We need 4 bits to select a specific block in cache, so the block field consists of the middle 4 bits.
- The remaining 7 bits make up the tag field.

![Figure 6.5](image)

**FIGURE 6.5** The Main Memory Address Format for Example 6.2

- In summary, direct mapped cache maps main memory blocks in a modular fashion to cache blocks. The mapping depends on:
  - The number of bits in the main memory address (how many addresses exist in main memory)
  - The number of blocks are in cache (which determines the size of the block field)
  - How many addresses (either bytes or words) are in a block (which determines the size of the offset field)

**Fully Associative Cache**
- Instead of placing memory blocks in specific cache locations based on memory address, we could allow a block to go anywhere in cache.
- In this way, cache would have to fill up before any blocks are evicted.
- A memory address is partitioned into only two fields: the tag and the offset.
- Suppose, as before, we have 14-bit memory addresses and a cache with 16 blocks, each block of size 8 bytes. The field format of a memory reference is:

![Figure 6.10](image)

**FIGURE 6.10** The Main Memory Address Format for Associative Mapping

- The tag must be stored with each block in cache.
- When the cache is searched, all tags are searched in parallel to retrieve the data quickly. This requires special, costly hardware.
- You will recall that direct mapped cache evicts a block whenever another memory reference needs that block.
- With fully associative cache, we have no such mapping, thus we must devise an algorithm to determine which block to evict from the cache.
- The block that is evicted is the victim block.
- **Set-Associative Cache**
  - Set associative cache **combines** the ideas of direct mapped cache and fully associative cache.
  - An $N$-way set associative cache mapping is like direct mapped cache in that a memory reference maps to a particular location in cache.
  - Unlike direct mapped cache, a memory reference maps to a set of several cache blocks, similar to the way in which fully associative cache works.
  - Instead of mapping anywhere in the entire cache, a memory reference can map **only** to the **subset** of cache slots.
  - The number of cache blocks per set in set associative cache varies according to overall system design.
    - For example, a **2-way set associative cache** can be conceptualized as shown in the schematic below.
    - Each set contains two different memory blocks.

![Logical View of 2-Way Set Associative Cache](image1)

![Linear View of 2-Way Set Associative Cache](image2)

**FIGURE 6.11 A 2-Way Set Associative Cache**
EXAMPLE 6.5 Suppose we have a main memory of \(2^{14}\) bytes. This memory is mapped to a 2-way set associative cache having 16 blocks where each block contains 8 bytes.
- Since this is a 2-way cache, cache has a total of 16 blocks and each set consists of 2 blocks, then there are 8 sets.
- Thus, we need 3 bits for the set, 3 bits for the offset, giving 8 leftover bits for the tag:

![FIGURE 6.12 Format for Set-Associative Mapping for Example 6.5](image)

Example 6.6: Suppose a byte-addressable memory contains 1MB and cache consists of 32 blocks, where each block contains 16 bytes. Using direct mapping, fully associative mapping, and a 4-way set associative mapping, determine where the main memory address 0x326A0 maps to in cache.
- First note that a main memory address has 20 bits. The main memory address for **direct mapped** cache is shown below.

![FIGURE](image)

- If we represent our main memory address 0x326A0 in binary and place the bits into the format, we get:

![FIGURE](image)

- So this address (0x326A0) maps to cache block 01010 (or block 10).
- If we are using **fully associative** cache, we have:

![FIGURE](image)

- But because it is fully associative, it could map anywhere.
- If we are using **4-way set associative** cache, we have:

![FIGURE](image)

- If we divide the main memory address into these fields, we get:

![FIGURE](image)

- So this address (0x326A0) maps to cache set 010 (or set 2).
6.4.2 Replacement Policies 374

- The existing block is kicked out of cache to make room for the new block. This process is called replacement.
- With direct mapping, there is no need for a replacement policy.
- LRU
  - A least recently used (LRU) algorithm keeps track of the last time that a block was assessed and evicts the block that has been unused for the longest period of time.
  - The disadvantage of this approach is its complexity: LRU has to maintain an access history for each block, which ultimately slows down the cache.
- FIFO
  - First-in, first-out (FIFO) is a popular cache replacement policy.
  - In FIFO, the block that has been in the cache the longest, regardless of when it was last used.
- Random
  - A random replacement policy does what its name implies: It picks a block at random and replaces it with a new block.
  - Random replacement can certainly evict a block that will be needed often or needed soon, but it never thrashes (constantly throw out a block, then bring it back, then throw out it out, then bring it back, repeatedly).

6.4.3 Effective Access Time and Hit Ratio 377

- The performance of hierarchical memory is measured by its effective access time (EAT).
- EAT is a weighted average that takes into account the hit ratio and relative access times of successive levels of memory.
  - The EAT for a two-level memory is given by:
    \[
    \text{EAT} = H \times \text{Access}_C + (1-H) \times \text{Access}_MM
    \]
    
    where \(H\) is the cache hit rate and \(\text{Access}_C\) and \(\text{Access}_MM\) are the access times for cache and main memory, respectively.
- For example, consider a system with a main memory access time of 200ns supported by a cache having a 10ns access time and a hit rate of 99%.
  - The EAT is:
    \[
    0.99(10\text{ns}) + 0.01(200\text{ns}) = 9.9\text{ns} + 2\text{ns} = 11.9\text{ns}.
    \]
6.4.4 When Does Caching Break Down? 378

- In particular, object-oriented programming can cause programs to exhibit less than optimal locality.
- Another example of bad locality can be seen in two dimensional array access. Arrays are typically stored in row-major order.
  - 5 X 4 array. If a program accesses the array in row-major order. So 5 X 4 array would produce 5 misses and 15 hits over 20 accesses.
  - If a program accesses the array in column-major order. So 5 X 4 array would produce 20 misses on 20 accesses.
- A third example would be a program that loops through a linear array that does not fit in cache. There would be a significant reduction in the locality when memory is used in this fashion.

6.4.5 Cache Write Policies 379

- Cache replacement policies must also take into account dirty blocks, those blocks that have been updated while they were in the cache.
- Dirty blocks must be written back to memory. A write policy determines how this will be done.
- There are two types of write policies, write through and write back.
  - Write through updates cache and main memory simultaneously on every write.
  - Write back (also called copyback) updates memory only when the block is selected for replacement.
- The disadvantage of write through is that memory must be updated with each cache write, which slows down the access time on updates. This slowdown is usually negligible, because the majority of accesses tend to be reads, not writes.
- The advantage of write back is that memory traffic is minimized, but its disadvantage is that memory does not always agree with the value in cache, causing problems in systems with many concurrent users.
6.4.6 Instruction and Data Caches 379

- The cache we have been discussing is called a unified or integrated cache where both instructions and data are cached.
- Harvard cache: Many modern systems employ separate caches for data and instructions.
- The separation of data from instructions provides better locality, at the cost of greater complexity.
- Cache performance can also be improved by adding a small associative cache to hold blocks that have been evicted recently. This is called a victim cache.
- A trace cache is a variant of an instruction cache that holds decoded instructions for program branches, giving the illusion that noncontiguous instructions are really contiguous.

6.4.7 Levels of Cache 382

- Most of today’s small systems employ multilevel cache hierarchies.
- The levels of cache form their own small memory hierarchy.
- Level1 cache (8KB to 64KB) is situated on the processor itself.
  - Access time is typically about 4ns.
- Level 2 cache (64KB to 2MB) is typically located external to the processor, may be on the motherboard, or on an expansion card.
  - Access time is usually around 15 - 20ns.
- In systems that employ three levels of cache, the Level 2 cache is placed on the same die as the CPU (reducing access time to about 10ns)
- Accordingly, the Level 3 cache (2MB to 256MB) refers to cache that is situated between the processor and main memory.
- Once the number of cache levels is determined, the next thing to consider is whether data (or instructions) can exist in more than one cache level.
- If the cache system used an inclusive cache, the same data may be present at multiple levels of cache. For example, in the Intel Pentium family, data found in L1 may also exist in L2
- Strictly inclusive caches guarantee that all data in a smaller cache also exists at the next higher level.
- Exclusive caches permit only one copy of the data.
- Separate data and instruction caches: For example, the Intel Celeron uses two separate L1 caches, one for instructions and one for data.
6.5 Virtual Memory 383

- Cache memory enhances performance by providing faster memory access speed.
- Virtual memory enhances performance by providing greater memory capacity, without the expense of adding main memory.
- Instead, a portion of a disk drive serves as an extension of main memory.
- If a system uses paging, virtual memory partitions main memory into individually managed page frames that are written (or paged) to disk when they are not immediately needed.
- Virtual address: The logical or program address that the process uses. Whenever the CPU generates an address, it is always in terms of virtual address space.
- Physical address: The real address in physical memory.
- Mapping: The mechanism by which virtual addresses are translated into physical ones.
- Page frames: The equal-size chunks or blocks into which main memory (physical memory) is divided.
- Pages: The chunks or blocks into which virtual memory (the logical address) is divided, each equal in size to a page frame.
- Paging: The process of copying a virtual page from disk to a page frame in main memory.
- Fragmentation: Memory that becomes unusable.
- Page fault: An event that occurs when a requested page is not in main memory and must be copied into memory from disk.
- We need not have all of the process in main memory at once. The entire address space required by a process need not be in memory at once. Some parts can be on disk, while others are in main memory.
6.5.1 Paging 384

- The basic idea behind paging is quite simple: Allocate physical memory to processes in fixed size chunks (page frames) and keep track of where various pages of the process reside by recording information in a page table.
- Every process has its own page table that typically resides in main memory.
- If the page is in main memory the valid bit is set to 1.
- Process memory is divided into these fixed size pages, resulting in potential internal fragmentation when the last page is copied into memory.
- The operating system must dynamically translate this virtual address into the physical address in memory at which the data actually resides.
- The newly retrieved page can be placed in any of those free frames.
- EXAMPLE 6.8
  - Suppose we have a virtual address space of $2^8$ bytes (addresses range 0x00 to 0xFF, which is 0 to 255 in base 10) for a given process, and physical memory of 4 page frames.
  - Assume also that pages are 32 bytes in length ($2^8/2^5 = 2^3$, or 8 pages).
  - Virtual addresses contain 8 bits, and physical addresses contain 7 bits (4 frames of 32 bytes each is 128 bytes, or $2^7$).

![FIGURE 6.18 Current State Using Paging and the Associated Page](image)

![FIGURE 6.19 Format for an 8-Bit Virtual Address with $2^5 = 32$ Byte Page Size.](image)

![FIGURE 6.20 Format for Virtual Address 00001101₂ = 0x0D](image)

![FIGURE 6.21 Format for Physical address 1001101₂ = 0x4D](image)
6.5.2 Effective Access Time Using Paging

- We said earlier that effective access time (EAT) takes all levels of memory into consideration.
- Thus, virtual memory is also a factor in the calculation, and we also have to consider page table access time.
- Suppose a main memory access takes 200ns, the page fault rate is 1%, and it takes 10ms to load a page from disk. We have:

  \[ EAT = 0.99(200\text{ns} + 200\text{ns}) + 0.01(10\text{ms}) = 1,396\text{ns} \]

- Even if we had no page faults, the EAT would be 400ns because memory is always read twice: First to access the page table (the page itself is stored in main memory), and second to load the page from memory.
- Because page tables are read constantly, it makes sense to keep them in a special cache called a translation look-aside buffer (TLB).
- Typically, the TLB is a special associative cache that stores the mapping of virtual pages to physical pages.

<table>
<thead>
<tr>
<th>Virtual Page Number</th>
<th>Physical Page Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

**FIGURE 6.26 Current State of the TLB for Figure 6.23**
6.5.3 Putting It All Together: Using Cache, TLBs, and Paging 393

FIGURE 6.27 Using the TLB
6.5.4 Advantages and Disadvantages of Paging and Virtual Memory 395

- Programs are no longer restricted by the amount of physical memory that is available. Virtual address space is larger than physical memory.
- Because each program requires less physical memory, virtual memory also permits us to run more programs at the same time.
- Increase in CPU utilization and system throughput.

6.5.5 Segmentation 396

- Instead of dividing memory into equal-sized pages, virtual address space is divided into variable-length segments, often under the control of the programmer.
- A segment is located through its entry in a segment table, which contains the segment’s memory location and a bounds limit that indicates its size.
- This segment table is simply a collection of the base/bounds pairs for each segment.
- Both paging and segmentation can cause fragmentation.
  - Paging is subject to internal fragmentation because a process may not need the entire range of addresses contained within the page. Thus, there may be many pages containing unused fragments of memory.
  - Segmentation is subject to external fragmentation, which occurs when contiguous chunks of memory become broken up as segments are allocated and deallocated over time.
  - To combat external fragmentation, system use some sort of garbage collection.
6.5.6 Paging Combined with Segmentation 397

- Paging and segmentation can be combined to take advantage of the best features of both by assigning fixed-size pages within variable-sized segments.
- Pages are typically smaller than segments.
- Each segment has a page table, which means every program has multiple page tables.
  This means that a memory address will have three fields:
  - The first field is the segment field, which points the system to the appropriate page table.
  - The second field is the page number, which is used as an offset into this page table.
  - The third field is the offset within the page
6.6 Real-World Examples of Memory Management 397

- The Pentium architecture allows for **32-bit** virtual addresses and 32-bit physical addresses.
- It uses either **4KB or 4MB** page size, when using paging.
- The Pentium architecture supports **both** paging and segmentation, and they can be used in various combinations including unpaged unsegmented, segmented unpaged, and unsegmented paged.
- The processor supports two levels of cache (L1 and L2), both having a block size of **32** bytes.
- The L1 cache is next to the processor, and the L2 cache sits between the processor and memory.
- The L1 cache is in two parts: an instruction cache (I-cache) and a data cache (D-cache).

![Pentium Memory Hierarchy](image)

**FIGURE 6.29** Pentium Memory Hierarchy
Chapter Summary 399

- Computer memory is organized in a hierarchy, with the smallest, fastest memory at the top and the largest, slowest memory at the bottom.
- Cache memory gives faster access to main memory, while virtual memory uses disk storage to give the illusion of having a large main memory.
- Cache maps blocks of main memory to blocks of cache memory. Virtual memory maps page frames to virtual pages.
- There are three general types of cache: Direct mapped, fully associative and set associative. With fully associative and set associative cache, as well as with virtual memory, replacement policies must be established.
- All virtual memory must deal with fragmentation, internal for paged memory, external for segmented memory.
- Replacement policies include LRU, FIFO, or some other placement policy to determine the block to remove from cache to make room for a new block, if cache is full.
- Virtual memory allows us to run programs whose virtual address is larger than physical memory. It also allows more processes to run concurrently.
- TLB is a cache
- Cache improves the effective access time to main memory whereas paging extends the size of memory.