Chapter 8: Main Memory
Chapter 8: Memory Management

- Background
- Swapping
- Contiguous Memory Allocation
- Segmentation
- Paging
- Structure of the Page Table
- Example: The Intel 32 and 64-bit Architectures
- Example: ARM Architecture
Objectives

- To provide a detailed description of various ways of organizing memory hardware
- To discuss various memory-management techniques, including paging and segmentation
- To provide a detailed description of the Intel Pentium, which supports both pure segmentation and segmentation with paging
Background

- Program must be brought (from disk) into memory and placed within a process for it to be run
- Main memory and registers are the only storage CPU can access directly
- Memory unit only sees a stream of addresses + read-requests, or address + data and write-requests
- Register can be accessed in **one** CPU clock (or less)
- Main memory access can take many cycles, causing a **stall**
- **Cache** sits between main memory and CPU registers, typically on CPU chip
- Protection of memory required to ensure correct operation
  - between processes from OS and users, and between processes from users
  - provided by hardware support, otherwise too costly to involve OS
A pair of base and limit registers define the logical address space

- these registers are loaded only by OS in kernel mode, with privileged instructions

CPU must check every memory access generated in user mode to be sure it is between the base and limit for that user

OS can access any OS and user's memory, in order to complete its tasks
Hardware Address Protection with Base and Limit Registers

CPU

address

≥

yes

no

<

no

yes

trap to operating system
monitor—addressing error

memory
Address Binding

- Programs on disk, ready to be brought into memory to execute, form an input queue
  - Without support, must be loaded into address 0000
- Inconvenient to have first user process physical address always at 0000
- Addresses represented in different ways at different stages of a program’s life
  - Source code addresses usually symbolic (variable name)
  - Compiled code addresses bind to relocatable addresses
    - i.e. “14 bytes from beginning of this module”
  - Linker or loader will bind relocatable addresses to absolute addresses
    - i.e. 74014
  - Each binding maps one address space to another
Address binding of instructions and data to memory addresses can happen at three different stages

- **Compile time**: If memory location known a priori, absolute code can be generated and binding is done when compiling; must recompile code if starting location changes
- **Load time**: Compiler must generate relocatable code if memory location is not known at compile time, and binding is done when loading; must reload if starting location changes
- **Execution time**: Binding delayed until run time if the process can be moved during its execution from one memory segment to another
  - Need hardware support for address maps (e.g., base and limit registers)
Multistep Processing of a User Program

- Source program
- Compiler or assembler
- Object module
- Linkage editor
- Load module
- Loader
- In-memory binary image
- System library
- Dynamically loaded system library
- Dynamic linking
- Compile time
- Load time
- Execution time (run time)
Logical vs. Physical Address Space

- The concept of a logical address space that is bound to a separate physical address space is central to proper memory management
  - Logical address – generated by the CPU; also referred to as virtual address
  - Physical address – address seen by the memory unit (MMU)

- Logical and physical addresses are the same in compile-time and load-time address-binding schemes
- Logical (virtual) and physical addresses differ in execution-time address-binding scheme

- Logical address space is the set of all logical addresses generated by a program
- Physical address space is the set of all physical addresses generated by a program
Memory-Management Unit (MMU)

- Hardware device that at runtime maps virtual to physical address

- Many methods possible, covered in the rest of this chapter

- To start, consider a simple scheme where the value in the relocation register is added to every address generated by a user process at the time it is sent to memory
  - Base register now called relocation register
  - MS-DOS on Intel 80x86 used 4 relocation registers

- The user program deals with logical addresses; it never sees the real physical addresses
  - Execution-time binding occurs when reference is made to location in memory
  - Logical address bound to physical addresses
Dynamic Relocation Using a Relocation Register

- Routine is not loaded until it is called
- Better memory-space utilization; unused routine is never loaded
- All routines kept on disk in relocatable load format
- When called, routine is checked if not in memory, and if so, it is loaded. The program address tables are updated, and control is passed to the newly loaded routine
- Useful when large amounts of code are needed to handle infrequently occurring cases
- No special support from the operating system is required
  - Implemented through program design
  - OS can help by providing libraries to implement dynamic loading

![Diagram showing dynamic relocation using a relocation register](image)
Dynamic Linking

- Static linking – system libraries and program code combined by the loader into the binary program image
  - some OSes support only static linking
- Dynamic linking – linking postponed until execution time
- Small piece of code, stub, used to locate the appropriate memory-resident library routine
- Stub replaces itself with the address of the routine, and executes the routine
- Operating system checks if routine is in processes’ memory address
  - If not in address space, add to address space
- Dynamic linking is particularly useful for libraries
- System also known as shared libraries
- Consider applicability to patching system libraries
  - Versioning may be needed
- OS needs to support if the processes can access the shared library in the same memory space (more later...)
Swapping

A process can be **swapped** temporarily out of memory to a backing store, and then brought back into memory for continued execution

- Total physical memory space of processes can exceed physical memory

**Backing store** – fast disk large enough to accommodate copies of all memory images for all users; must provide direct access to these memory images

**Roll out, roll in** – swapping variant used for priority-based scheduling algorithms

- lower-priority process is swapped out so higher-priority process can be loaded and executed

Major part of swap time is transfer time; total transfer time is directly proportional to the amount of memory swapped

System maintains a **ready queue** of ready-to-run processes which have memory images on disk

Does the swapped out process need to swap back in to same physical addresses?

- Depends on address binding method
- Plus consider pending I/O to / from process memory space

Modified versions of swapping are found on many systems (i.e., UNIX, Linux, and Windows)

- Swapping normally disabled
- Started if more than threshold amount of memory allocated
- Disabled again once memory demand reduced below threshold
Schematic View of Swapping

1. swap out

2. swap in
Context Switch Time including Swapping

- If next processes to be put on CPU is not in memory, need to swap out a process and swap in target process
- Context switch time can then be very high
- 100MB process swapping to hard disk with transfer rate of 50MB/sec
  - Swap out time of 2000 ms
  - Plus swap in of same sized process
  - Total context switch swapping component time of 4000ms (4 seconds)
- Can reduce if reduce size of memory swapped – by knowing how much memory really being used
  - System calls to inform OS of memory use via request_memory() and release_memory()
- Other constraints as well on swapping
  - Pending I/O – cannot swap out as I/O would occur to wrong process
  - Or always transfer I/O to kernel space, then to I/O device
    - Known as double buffering, adds overhead
- Standard swapping not used in modern operating systems
  - But modified version common
    - Swap only when free memory extremely low
Swapping on Mobile Systems

- Not typically supported
  - Flash memory based
    - Small amount of space
    - Limited number of write cycles
    - Poor throughput between flash memory and CPU on mobile platform

- Instead use other methods to free memory if low
  - iOS *asks* apps to voluntarily relinquish allocated memory
    - Read-only data thrown out and reloaded from flash if needed
    - Failure to free can result in termination of a given process
  - Android terminates apps if low free memory, but first writes *application state* to flash for fast restart
  - Both OSes support paging as discussed below
**Contiguous Allocation**

- Main memory must support both OS and user processes
- Limited resource, must allocate efficiently
- Contiguous allocation is one early method

- Main memory usually into two **partitions**:
  - Resident operating system, usually held in low memory with interrupt vector
  - User processes then held in high memory
  - Each process contained in single contiguous section of memory

- Relocation registers used to protect user processes from each other, and from changing operating-system code and data
  - Base register contains value of smallest physical address
  - Limit register contains range of logical addresses – each logical address must be less than the limit register
  - MMU maps logical address **dynamically**
  - Can then allow actions such as kernel code being **transient** and kernel changing size
Hardware Support for Relocation and Limit Registers

![Diagram showing the process of logical to physical address conversion using limit and relocation registers.](Diagram)

- The CPU provides a logical address to the system.
- The limit register is checked to determine if the address is valid. If yes, the physical address is calculated by adding the relocation register.
- If the address is not valid (no), a trap is signaled indicating an addressing error.

**Figure:** 8.19

---

Operating System Concepts – 9th Edition

Silberschatz, Galvin and Gagne ©2013
Contiguous Allocation (cont.)

- Multiple-partition allocation
  - With fixed-size partitions, degree of multiprogramming limited by number of partitions
  - **Variable-partition** sizes for efficiency (sized to a given process’ needs)
  - **Hole** – block of available memory; holes of various sizes are scattered throughout memory
  - When a process arrives, it is allocated memory from a hole large enough to accommodate it
  - Process exiting frees its partition, adjacent free partitions are combined
  - Operating system maintains information about:
    a) allocated partitions
    b) free partitions (hole)

---

<table>
<thead>
<tr>
<th>OS</th>
<th>OS</th>
<th>OS</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>process 5</td>
<td>process 5</td>
<td>process 5</td>
<td>process 5</td>
</tr>
<tr>
<td>process 8</td>
<td>process 2</td>
<td>process 9</td>
<td>process 10</td>
</tr>
<tr>
<td>process 2</td>
<td>process 2</td>
<td>process 2</td>
<td>process 2</td>
</tr>
</tbody>
</table>
Dynamic Storage-Allocation Problem

How to satisfy a request of size $n$ from a list of free holes?

- **First-fit**: Allocate the *first* hole that is big enough; can search from current location
- **Best-fit**: Allocate the *smallest* hole that is big enough; must search entire list, unless ordered by size
  - Produces the smallest leftover hole
- **Worst-fit**: Allocate the *largest* hole; must also search entire list
  - Produces the largest leftover hole

First-fit and best-fit are better than worst-fit in terms of speed and storage utilization
Fragmentation

- **External Fragmentation** – total memory space exists to satisfy a request, but it is not contiguous

- **Internal Fragmentation** – allocated memory may be slightly larger than requested memory; this size difference is memory internal to a partition, but not being used

- First fit analysis reveals that given $N$ blocks allocated, $0.5 \times N$ blocks are lost to fragmentation
  - $1/3$ may be unusable -> **50-percent rule**
Fragmentation (cont.)

- Reduce external fragmentation by compaction
  - Shuffle memory contents to place all free memory together in one large block
  - Compaction is possible only if relocation is dynamic, and is done at execution time
  - I/O problem
    - Latch job in memory while it is involved in I/O
    - Do I/O only into OS buffers

- Now consider that backing store has same fragmentation problems (general to storage problems)
Segmentation

- Memory-management scheme that supports user view of memory

- A program is a collection of segments
  - A segment is a logical unit such as:
    - main program
    - procedure
    - function
    - method
    - object
    - local variables, global variables
    - common block
    - stack
    - symbol table
    - arrays
User's View of a Program

- subroutine
- stack
- symbol table
- main program

logical address
Logical View of Segmentation

user space

physical memory space

1
4
2
3
Segmentation Architecture

- Logical address consists of a two tuple:
  \(<\text{segment-number}, \text{offset}>\)

- **Segment table** – maps two-dimensional physical addresses; each table entry has:
  - **base** – contains the starting physical address where the segments reside in memory
  - **limit** – specifies the length of the segment

- **Segment-table base register (STBR)** points to the segment table’s location in memory

- **Segment-table length register (STLR)** indicates number of segments used by a program;
  segment number \(s\) is legal if \(s < \text{STLR}\)
Protection
- With each entry in segment table associate:
  - validation bit = 0 $\Rightarrow$ illegal segment
  - read/write/execute privileges

Protection bits associated with segments; code sharing occurs at segment level

Since segments vary in length, memory allocation is a dynamic storage-allocation problem

A segmentation example is shown in the following diagram
Segmentation Hardware

CPU

\[ s \{ \text{limit, base} \} \]

segment table

\(<\]

yes

no

+\]

trap: addressing error

physical memory
Paging

- Physical address space of a process can be noncontiguous; process is allocated physical memory whenever the latter is available
  - Avoids external fragmentation
  - Avoids problem of varying sized memory chunks

- Divide physical memory into fixed-sized blocks called frames
  - Size is power of 2, between 512 bytes and 16 Mbytes

- Divide logical memory into blocks of same size called pages

- Keep track of all free frames

- To run a program of size $N$ pages, need to find $N$ free frames and load program

- Set up a page table to translate logical to physical addresses

- Backing store likewise split into pages

- Still have Internal fragmentation
Address Translation Scheme

- Address generated by CPU is divided into:
  - **Page number** $(p)$ – used as an index into a page table which contains base address of each page in physical memory
  - **Page offset** $(d)$ – combined with base address to define the physical memory address that is sent to the memory unit

<table>
<thead>
<tr>
<th>page number</th>
<th>page offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$d$</td>
</tr>
</tbody>
</table>

$(m - n)$ bits   $n$ bits

- For given logical address space $2^m$ and page size $2^n$
Paging Hardware

The diagram illustrates the process of converting a logical address from the CPU to a physical address in memory using a page table. The logical address is broken down into page (p) and directory (d) parts, which are used to look up the page frame number (f) in the page table. The page frame number is then concatenated with the directory part to form the physical address for accessing memory.
Paging Model of Logical and Physical Memory

logical memory

page 0
page 1
page 2
page 3

page table

0 1
1 4
2 3
3 7

physical memory

frame number

0 page 0
1 page 0
2 page 2
3 page 2
4 page 1
5 page 1
6
7 page 3
Paging Example

\( n = 2 \) and \( m = 4 \)  
32-byte memory and 4-byte pages
Calculating internal fragmentation
- Page size = 2,048 bytes
- Process size = 72,766 bytes
- 35 pages + 1,086 bytes
- Internal fragmentation of 2,048 - 1,086 = 962 bytes
- Worst case fragmentation = 1 frame + 1 byte
- On average fragmentation = 1 / 2 frame size
- So small frame sizes desirable?
- But each page table entry takes memory to track
- Page sizes growing over time
  - Solaris supports two page sizes – 8 KB and 4 MB

Process view and physical memory now very different

By implementation, a process can only access its own memory
Free Frames

Before allocation

After allocation
Implementation of Page Table

- Page table is kept in *main memory*
- **Page-table base register** (PTBR) points to the page table
- **Page-table length register** (PTLR) indicates size of the page table
- In this scheme every data/instruction access requires two memory accesses
  - One for the page table and one for the data / instruction
- The two memory access problem can be solved by the use of a special fast-lookup *hardware cache* called *associative memory* or *translation look-aside buffers* (TLBs)
- Some TLBs store **address-space identifiers** (ASIDs) in each TLB entry – uniquely identifies each process to provide address-space protection for that process
  - Otherwise need to flush at every context switch
- TLBs typically small (64 to 1024 entries)
- On a TLB miss, value is loaded into the TLB for faster access next time
  - Replacement policies must be considered (LRU, RR, etc.)
  - Some entries can be **wired down** for permanent fast access
Associative Memory

- Associative memory – parallel search

<table>
<thead>
<tr>
<th>Page #</th>
<th>Frame #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Address translation \((p, d)\)
  - If \(p\) is in associative register, get frame # out
  - Otherwise get frame # from page table in memory
Paging Hardware with TLB

- CPU
- Logical address
- Page number
- Frame number
- TLB
- TLB hit
- TLB miss
- Page table
- Physical memory
- Logical address
- Page number
- Frame number
- TLB
- TLB hit
- Physical address
- Page table
- Physical memory
Effective Access Time

- Associative Lookup = $\varepsilon$ time unit
  - Can be < 10% of memory access time

- Hit ratio = $\alpha$
  - Hit ratio – percentage of times that a page number is found in the associative registers; ratio related to number of associative registers

- Consider $\alpha = 80\%$, $\varepsilon = 20$ns for TLB search, $m=100$ns for memory access

- **Effective Access Time (EAT)**
  \[
  EAT = (\varepsilon + 1m) \alpha + (\varepsilon + 2m)(1 - \alpha) \\
  = 2m + \varepsilon - m \alpha
  \]

- Consider $\alpha = 80\%$, $\varepsilon = 20$ns for TLB search, 100ns for memory access
  - EAT = $0.80 \times (20+100) + 0.20 \times (20+200) = 140$ns

- Consider more realistic hit ratio -> $\alpha = 99\%$, $\varepsilon = 20$ns for TLB search, 100ns for memory access
  - EAT = $0.99 \times (20+100) + 0.01 \times (20+200) = 121$ns
Memory Protection

- Memory protection implemented by associating protection bit with each frame to indicate if read-only or read-write access is allowed
  - Can also add more bits to indicate page execute-only, and so on

- Two methods to indicate valid entries in page table:
  - **Valid-invalid** bit attached to each entry in the page table:
    - “valid” indicates that the associated page is in the process’ logical address space, and is thus a legal page
    - “invalid” indicates that the page is not in the process’ logical address space
  - OR use **page-table length register (PTLR)**
    - this method wastes less memory for the page table

- Any violations result in a trap to the kernel
Valid (v) or Invalid (i) Bit in a Page Table

- Page 0: Valid (v)
- Page 1: Valid (v)
- Page 2: Valid (v)
- Page 3: Valid (v)
- Page 4: Valid (v)
- Page 5: Invalid (i)

Frame numbers:
0: Page 0
1: Page 1
2: Page 2
3: Page 3
4: Page 4
5: Page 5
6: Page 3
7: Page 4
8: Page 5
9: Page n

Page table entries:
0
2: v
3: v
4: v
7: v
8: v
9: v
6: i
7: i
Shared Pages

- **Shared code**
  - One copy of read-only *(reentrant)* code shared among processes (i.e., text editors, compilers, window systems)
  - Similar to multiple threads sharing the same process space
  - Also useful for interprocess communication if sharing of read-write pages is allowed

- **Private code and data**
  - Each process keeps a separate copy of the code and data
  - The pages for the private code and data can appear anywhere in the logical address space
Shared Pages Example

Shared code of editor that is used by all three processes.
Structure of the Page Table

- Memory structures for paging can get huge using straight-forward methods
  - Consider a 32-bit logical address space as on modern computers
  - Page size of 4 KB ($2^{12}$)
  - Page table would have more than 1 million entries ($2^{32} / 2^{12}$)
  - If each entry is 4 bytes, it amounts to 4 MB of physical address space / memory for page table alone
    - That amount of memory used to cost a lot
    - Do not want to allocate that contiguously in main memory

- Hierarchical Paging

- Hashed Page Tables

- Inverted Page Tables
Hierarchical Page Tables

- Break up the logical address space into multiple page tables
- A simple technique is a two-level page table
- We then page the page table
Two-Level Page-Table Scheme
Two-Level Paging Example

A logical address (on 32-bit machine with 1 KB page size) is divided into:
- a page number consisting of 22 bits
- a page offset consisting of 10 bits

Since the page table is paged, the page number is further divided into:
- a 12-bit page number
- a 10-bit page offset

Thus, a logical address is as follows:

<table>
<thead>
<tr>
<th>page number</th>
<th>page offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_1 )</td>
<td>( p_2 )</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>

where \( p_1 \) is an index into the outer page table, and \( p_2 \) is the displacement within the page of the inner page table

Known as forward-mapped page table
Address-Translation Scheme

logical address

\[ p_1 \quad p_2 \quad d \]

\[
\begin{array}{c}
\text{p}_1 \\
\end{array}
\]

\[
\begin{array}{c}
\text{outer page table} \\
\end{array}
\]

\[
\begin{array}{c}
p_2 \\
\end{array}
\]

\[
\begin{array}{c}
\text{page of page table} \\
\end{array}
\]

\[
\begin{array}{c}
d \\
\end{array}
\]
64-bit Logical Address Space

- Even two-level paging scheme not sufficient for a 64-bit machine
- If page size is 4 KB (2^{12})
  - Then page table has 2^{52} entries
  - If two-level scheme, with an inner page table that could be 2^{10} x 4-byte entries
  - Address would look like

<table>
<thead>
<tr>
<th>outer page</th>
<th>inner page</th>
<th>page offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>p₁</td>
<td>p₂</td>
<td>d</td>
</tr>
<tr>
<td>42</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

- Outer page table has 2^{42} entries or 2^{44} bytes
- One solution is to add a 2^{nd} outer page table
- But in the following example the 2^{nd} outer page table is still 2^{34} bytes in size
  - And possibly 4 memory access to get to one physical memory location
Three-level Paging Scheme

<table>
<thead>
<tr>
<th>outer page</th>
<th>inner page</th>
<th>offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>$p_2$</td>
<td>$d$</td>
</tr>
<tr>
<td>42</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2nd outer page</th>
<th>outer page</th>
<th>inner page</th>
<th>offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>$p_2$</td>
<td>$p_3$</td>
<td>$d$</td>
</tr>
<tr>
<td>32</td>
<td>10</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>
Hashed Page Tables

- Common in address spaces > 32 bits

- The virtual page number is hashed into a page table
  - This page table contains a chain of elements hashing to the same location

- Each element contains
  - (1) the virtual page number
  - (2) the value of the mapped page frame
  - (3) a pointer to the next element

- Virtual page numbers are compared in this chain, searching for a match
  - If a match is found, the corresponding physical frame is extracted

- Variation for 64-bit addresses is **clustered page tables**
  - Similar to hashed but each entry refers to several pages (such as 16) rather than 1
  - Especially useful for **sparse** address spaces (where memory references are non-contiguous and scattered)
Hashed Page Table

The diagram illustrates the process of mapping a logical address to a physical address using a hashed page table. The logical address consists of two parts, p and d, which are used to calculate a hash function. The hash function then maps the hash to a position in the hash table. Each entry in the hash table contains a physical address, r and d, which is used to access the corresponding page in physical memory.
Inverted Page Table

- Rather than each process having a page table and keeping track of all possible logical pages, track all physical pages.

- One entry for each real page of memory.

- Entry consists of the virtual address of the page stored in that real memory location, with information about the process that owns that page.

- Decreases memory needed to store each page table, but increases time needed to search the table when a page reference occurs.

- Use hash table to limit the search to one — or at most a few — page-table entries.
  - TLB can accelerate access.

- But how to implement shared memory?
  - One mapping of a virtual address to the shared physical address.
Inverted Page Table Architecture
Oracle SPARC Solaris

- Consider modern, 64-bit operating system example with tightly integrated hardware
  - Goals are efficiency, low overhead
- Based on hashing, but more complex
- Two hash tables
  - One for kernel processes and one for all user processes
  - Each maps memory addresses from virtual to physical memory
  - Each entry represents a contiguous area of mapped virtual memory
    - More efficient than having a separate hash-table entry for each page
  - Each entry has base address and span (indicating the number of pages the entry represents)
- TLB holds translation table entries (TTEs) for fast hardware lookups
  - A cache of TTEs reside in a translation storage buffer (TSB)
    - Includes an entry per recently accessed page
- Virtual address reference causes TLB search
  - If miss, hardware walks the in-memory TSB looking for the TTE corresponding to the address
    - If match found, the CPU copies the TSB entry into the TLB and translation completes
    - If no match found, kernel interrupted to search the hash table
      - The kernel then creates a TTE from the appropriate hash table and stores it in the TSB, Interrupt handler returns control to the MMU, which completes the address translation.
Example: The Intel 32- and 64-bit Architectures

- Dominant industry chips
- Pentium CPUs are 32-bit and called IA-32 architecture
- Current Intel CPUs are 64-bit and called IA-64 architecture
- Many variations in the chips, cover the main ideas here
Example: The Intel IA-32 Architecture

- Supports both segmentation and segmentation with paging
  - Each segment can be 4 GB
  - Up to 16 K segments per process
  - Divided into two partitions
    - First partition of up to 8 K segments are private to process (kept in local descriptor table (LDT))
    - Second partition of up to 8K segments shared among all processes (kept in global descriptor table (GDT))

- CPU generates logical address
  - Selector given to segmentation unit
    - Which produces linear addresses
  - Linear address given to paging unit
    - Which generates physical address in main memory
    - Paging units form equivalent of MMU
    - Pages sizes can be 4 KB or 4 MB
Logical to Physical Address Translation in IA-32

CPU \rightarrow \text{segmentation unit} \rightarrow \text{paging unit} \rightarrow \text{physical memory}

\begin{align*}
\text{page number} & \quad \text{page offset} \\
\begin{array}{ccc}
p_1 & p_2 & d \\
10 & 10 & 12
\end{array}
\end{align*}
Intel IA-32 Segmentation

logical address

selector

offset

descriptor table

segment descriptor

32-bit linear address
Intel IA-32 Paging Architecture

One bit in the page directory indicates if (up) an index to a 4 KB offset or (below) a 4 MB offset.
Intel IA-32 Page Address Extensions

- 32-bit address limits led Intel to create page address extension (PAE), allowing 32-bit apps access to more than 4GB of memory space
  - Paging went to a 3-level scheme
  - Top two bits refer to a page directory pointer table
  - Page-directory and page-table entries moved to 64-bits in size
  - Net effect is increasing address space to 36 bits – 64GB of physical memory
Current generation Intel x86 architecture

- 64 bits is ginormous (> 16 exabytes)
- In practice only implement 48 bit addressing
  - Page sizes of 4 KB, 2 MB, 1 GB
  - Four levels of paging hierarchy
- Can also use PAE so virtual addresses are 48 bits and physical addresses are 52 bits
Example: ARM Architecture

- Dominant mobile platform chip (Apple iOS and Google Android devices for example)
- Modern, energy efficient, 32-bit CPU
- 4 KB and 16 KB pages
- 1 MB and 16 MB pages (termed sections)
- One-level paging for sections, two-level for smaller pages
- Two levels of TLBs
  - Outer level has two micro TLBs (one data, one instruction)
  - Inner is single main TLB
  - First inner is checked, on missouters are checked, and on miss page table walk performed by CPU
End of Chapter 8