Chapter 8: Memory Management

肖 卿 俊

办公室：计算机楼212室
电邮：csqjxiao@seu.edu.cn
主页：http://cse.seu.edu.cn/PersonalPage/csqjxiao
电话：025-52091022
Chapter 8: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Background for Memory Hierarchy

- Main memory and registers are the only storage CPU can access directly.
- Register access in one CPU clock (or less).
- Main memory can take many cycles.
- **L1/L2/L3 Cache** sits between main memory and CPU registers.
- Protection of memory required to ensure correct operation.
- Program must be brought into main memory and placed within a process for it to be run.
Background on Multistep Processing of a User Program

1. Source program
2. Compiler or assembler
3. Object module
4. Linkage editor
5. Load module
6. Loader
7. In-memory binary memory image
8. Execution time (run time)
9. Load time
10. Compile time

Other object modules
System library
Dynamically loaded system library
Dynamic linking
Binding of Instructions and Data to Physical Memory Addresses

■ Compile time
  - If memory location of running a program is known a priori, absolute code can be generated by compiler; must recompile code if starting location changes.

■ Load time
  - Must generate relocatable code if memory location is not known at compile time.

■ 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 mappings.

Most general-purpose operating systems use the execution-time address binding.
The concept of a *logical address space* that is bound to a separate *physical address space* is central to the proper memory management.

- *Logical address* – generated by the CPU; also referred to as *virtual address*.
- *Physical address* – address seen by memory unit.
Logical Address Space vs. Physical Address Space (cont.)

- Logical and physical addresses are the same in compile-time and load-time address-binding schemes.

- Logical and physical addresses differ in execution-time address-binding scheme.
  - In this case, logical address is also referred to as virtual address. (Logical = Virtual in this course)
Memory-Management Unit (MMU)

- Hardware device that maps virtual to physical address.

- In MMU scheme, the value in the relocation register is added to every address generated by a user process at the time it is sent to memory.

- The user program deals with *logical* addresses; it never sees the *real* physical addresses.
Revisit the Simple Memory Management: Base + Limit Registers

A pair of **base** and **limit** registers define the logical address space.

![Diagram showing base and limit registers with corresponding memory allocation](image-url)
Hardware Address Protection

- CPU
- address
- $\geq$
- yes
- no
- base
- base + limit
- $<$
- yes
- no
- trap to operating system monitor—addressing error
- memory
Applications only know logical addresses, so use a relocation register instead of a base register.
Memory Protection

- Relocation-register scheme used to protect user processes from each other, and from changing operating-system code and data.

- Relocation register contains value of the smallest physical address

- Limit register contains range of logical addresses – each logical address must be less than the limit register.
Hardware Support for Relocation and Limit Registers

- CPU
- logical address
- limit register
  - <
  - yes
  - physical address
  - +
  - no
  - trap; addressing error
- relocation register
- memory
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Swapping

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

Backin store – fast disk large enough to hold 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.
Schematic View of Swapping

1. swap out
2. swap in
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Contiguous Allocation

Monoprogramming systems usually have two partitions:

- Resident operating system, usually held in low memory with interrupt vector.
- User processes then held in high memory.

Multiprogramming Systems:

- Fixed partitions
- Variable partitions
Fixed Partitions

- Main memory is divided into $n$ partitions.
- Partitioning can be done at the startup time and altered later on.
- Each partition may have a job queue. Or, all partitions share the same job queue.
Variable Partitions

- **Hole** – block of available memory; holes of various size are scattered throughout memory.

- When a process arrives, it is allocated memory from a hole large enough to accommodate it.

- Thus, partition sizes are not fixed, the number of partitions also varies.

- Operating system maintains information about:
  a) allocated partitions  
  b) free partitions (hole)
### Variable Partitions (Cont.)

<table>
<thead>
<tr>
<th>OS</th>
<th>A</th>
<th>Free</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>A</td>
<td>Free</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>A</td>
<td>Free</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>A</td>
<td>Free</td>
</tr>
</tbody>
</table>

- Free space is indicated by the red background.
Dynamic Storage-Allocation Problem

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

- **First-fit (首次适配):** Allocate the *first* hole that is big enough.

- **Best-fit (最佳适配):** Allocate the *smallest* hole that is big enough; must search entire list, unless ordered by size. Produces the smallest leftover hole.

- **Worst-fit (最差适配):** Allocate the *largest* hole; must also search entire list. Produces the largest leftover hole.
Dynamic Storage-Allocation Problem

- If the hole is larger than the requested size, it is cut into two. The one of the requested size is given to the process, the remaining one becomes a new hole.

- When a process returns a memory block, it becomes a hole and must be combined with its neighbors.
Fragmentation (内存碎片)

- Processes are loaded and removed from memory, eventually the memory will be cut into small holes that are not large enough to run any incoming process.

- Free memory holes between allocated ones are called *external fragmentation*.

- It is unwise to allocate exactly the requested amount of memory to a process, because of the minimum requirement for memory management.

- Thus, memory that is allocated to a partition, but is not used, are called *internal fragmentation*. 
Fragment (Cont.)

- **External fragmentation**: More available space than the smallest program (the space gap between two consecutive used areas).
- **Internal fragmentation**: More available space than the individual program (the space gap between two consecutive used areas).

```
used
free
used
used
used
free
used
```

```
allocated partition
used
un-used
```


Compaction for External Fragmentation

- Shuffle memory contents to place all free memory together in one large block.

- Compaction is possible *only* if program relocation is dynamic, and is done at execution time.

- Compaction scheme can be expensive
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
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
A Previously Used Example

//main.cpp
int a = 0;    // 数据段，全局变量
char *p1;    // 数据段，全局变量
main()
{
    int b;    // 栈段，局部变量
    char s[] = "abc";    // 栈段，局部变量
    char *p2;    // 栈段，局部变量
    char *p3 = "123456";    // 栈段，局部变量
    p1 = (char *)malloc(10);    // 堆段
    p2 = (char *)malloc(20);    // 堆段
}
User’s View of a Program

logical address space

- subroutine
- stack
- symbol table
- main program

Sqrt
Logical View of Segmentation

user space

physical memory space
Segmentation Architecture

- Logical address consists of a two tuple: `<segment-number, 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.
Segmentation Hardware

CPU -> s -> limit, base

segment table

s < limit -> yes

trap; addressing error

physical memory

s ≥ limit -> no

+
Segmentation Architecture (Cont.)

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

- **Segment-table length register (STLR)** indicates the number of segments used by a program; segment number $s$ is legal if $s < STLR$. 
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.
Example of Segmentation

Logical address space:
- Segment 0: subroutine
- Segment 1: Sqrt
- Segment 2: main program
- Segment 3: stack
- Segment 4: symbol table

Segment table:

<table>
<thead>
<tr>
<th>limit</th>
<th>base</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1400</td>
</tr>
<tr>
<td>1</td>
<td>6300</td>
</tr>
<tr>
<td>2</td>
<td>4300</td>
</tr>
<tr>
<td>3</td>
<td>3200</td>
</tr>
<tr>
<td>4</td>
<td>4700</td>
</tr>
</tbody>
</table>

Physical memory:
- Segment 0: 1400
- Segment 1: 3200
- Segment 2: 4300
- Segment 3: 4700
- Segment 4: 5700
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Paging

Contiguous memory allocation method suffers from the external fragmentation problem.

Paging method allows logical address space of a process to be noncontiguous; a process is allocated physical memory whenever the latter is available.

How?

- Divide physical memory into fixed-sized blocks called frames (帧) (size is power of 2, between 512 bytes and 8192 bytes).
- Divide logical memory into blocks of same size called pages (页).
Paging (Cont.)

- 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.

- 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.
logical address \(<1, d>\) translates to physical address \(<2, d>\)
Address Translation Architecture
Paging Example

logical memory

page 0
page 1
page 2
page 3

page table

0  1
1  4
2  3
3  7

frame number

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

physical memory
### Paging Example

#### Logical Memory

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>i</td>
<td>j</td>
<td>k</td>
<td>l</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>m</td>
<td>n</td>
<td>o</td>
<td>p</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Page Table

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Physical Memory

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>i</td>
<td>j</td>
<td>k</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>l</td>
</tr>
<tr>
<td>8</td>
<td>m</td>
<td>n</td>
<td>o</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>p</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>24</td>
<td>e</td>
<td>f</td>
<td>g</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Free Frames

(a) Before allocation

(b) After allocation
Implementation of Page Table

- Page table must be kept in main memory.

**Question**: Why is a page table hard to entirely fit into L2 cache? What will be the size of a page table, if assuming 32 bits virtual address, 4GB physical memory and 4KB page/frame size?

- **20 bits required for frame number.**
  - 4 GB of Physical Memory = \(2^{32}\) bytes.
  - \(2^{32}\) bytes of memory/\(2^{12}\) bytes per frame = \(2^{20}\) frames

- So each page table entry is approximately **4 bytes**.
  - (20 bits frame number is roughly 3 bytes and access control contributes 1 byte)

- **Page table size = \(2^{20} \text{ entries} \times 4\text{ bytes/entry} = 4M\text{ bytes}\)**
Implementation of Page Table

- **Page-table base register (PTBR)** points to the page table existing in main memory.

- 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)*.
Paging Hardware With TLB

Translation of virtual address \((p, d)\)

- If an entry with the key \(p\) can be found in the TLB or associative memory, returns the value of frame \(f\)
- Otherwise, get the frame \(f\) value from the page table that exists in memory
### TLB based on Associative Memory

**Associative memory – parallel search**

<table>
<thead>
<tr>
<th>MAPPING from KEY → VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page #</td>
</tr>
<tr>
<td>Entry 1</td>
</tr>
<tr>
<td>Entry 2</td>
</tr>
<tr>
<td>Entry 3</td>
</tr>
<tr>
<td>Entry 4</td>
</tr>
</tbody>
</table>

**Parallel Search**

**An Example**

![Parallel Search Diagram](chart)

- For page 123, frame 79
- For page 374, frame 199
- For page 767, frame 100
- For page 23, frame 946

When page 767 is accessed, frame 100 is output.

*p (page #)*

*valid*
Effective Access Time

- Associative Lookup = $\varepsilon$ time unit
- Assume memory cycle time is 1 time unit
- Hit ratio – percentage of times that a page number is found in the associative registers.
- Hit ratio is related to the number of associative registers.
- Hit ratio = $\alpha$
- Effective Access Time (EAT)

\[
EAT = (1 + \varepsilon) \alpha + (2 + \varepsilon)(1 - \alpha)
\]

\[
= 2 + \varepsilon - \alpha
\]
A Quiz

■ **Q1**: What will be the size of a page table, if assuming 32 bits virtual address, 4GB physical memory, 8KB page size, and 4KB frame size?

■ **Q2**: What if the page size is increased to 2MB?

■ **Q3**: What are the pros & cons of larger page size?
Memory Protection

- Memory protection implemented by associating protection bit with each frame.

- 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.
### Valid (v) or Invalid (i) Bit in a Page Table Entry

<table>
<thead>
<tr>
<th>Frame Number</th>
<th>Valid-Invalid Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>v</td>
</tr>
<tr>
<td>1</td>
<td>v</td>
</tr>
<tr>
<td>2</td>
<td>v</td>
</tr>
<tr>
<td>3</td>
<td>v</td>
</tr>
<tr>
<td>4</td>
<td>v</td>
</tr>
<tr>
<td>5</td>
<td>v</td>
</tr>
<tr>
<td>6</td>
<td>i</td>
</tr>
<tr>
<td>7</td>
<td>i</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame Number</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Page 0</td>
</tr>
<tr>
<td>1</td>
<td>Page 1</td>
</tr>
<tr>
<td>2</td>
<td>Page 2</td>
</tr>
<tr>
<td>3</td>
<td>Page 3</td>
</tr>
<tr>
<td>4</td>
<td>Page 4</td>
</tr>
<tr>
<td>5</td>
<td>Page 5</td>
</tr>
<tr>
<td>6</td>
<td>Page 5</td>
</tr>
<tr>
<td>7</td>
<td>Page 5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>Page n</td>
</tr>
</tbody>
</table>
Memory Protection (Cont.)

- We can use a page table length register (PTLR) that stores the length of a process’s page table. In this way, a process cannot access the memory beyond its region. Compare this with the base/limit register pair.

- We can also add read-only, read-write, or execute bits in page table to enforce r-w-e permission.
Advantage of Paging Method: Shared Pages

■ Shared code
  ◆ One copy of read-only (reentrant) code shared among processes (i.e., text editors, compilers, window systems).

■ 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
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Advanced Page Table Structure

- Hierarchical Paging
- Hashed Page Tables
- Inverted Page Tables
Hierarchical Page Tables

Why it needs the multiple-level page table?

**Answer:** A single-level page table may become too big to fit into the physical memory of a commodity machine.

- Assume we have a 64-bit computer (which means **64 bit virtual address space**), which has **4KB pages** and **4 GB** of physical memory.
- In the single-level page table, \(2^{64}\) addressable bytes / \(2^{12}\) bytes per page = \(2^{52}\) page entries.
- One page table entry contains: Access control bits (like Page present, RW) + Physical page #.

http://en.wikipedia.org/wiki/Page_table#Multilevel_page_table
Hierarchical Page Tables

- 20 bits required for physical page number.
  - 4 GB of Physical Memory = \(2^{32}\) bytes.
  - \(2^{32}\) bytes of memory/\(2^{12}\) bytes per page
    = \(2^{20}\) physical pages

- So each page table entry is approximately 4 bytes. (20 bits physical page number is roughly 3 bytes and access control contributes 1 byte)

- Now page table size = \(2^{52} \times 4\) bytes = \(2^{54}\) bytes

Hence, the size of single-level page table is \(2^{54}\) bytes (16 petabytes) per process, which is a very huge amount of memory.
Hierarchical Page Tables

■ A Solution: Break up the logical address space into multiple page tables.

■ If we page the page table too, we can magically bring down the memory required

◆ The first-level page table contains $2^{52}$ page entries

◆ If we page the first-level page table, then one page contains $4\text{KB} / 4 \text{ bytes per entry} = 1024 = 2^{10}$ entries

◆ So the second-level page table needs $2^{42}$ entries

◆ ……

◆ The fifth-level page table only needs $2^{12}$ page entries, as low as four pages, just $16 \text{ KB}$ memory
Two-Level Paging Example for 32-bit Operating Systems

A logical address (on 32-bit machine with 4K page size) is divided into:

- a page number consisting of 20 bits, and
- a page offset consisting of 12 bits.

Since the page table itself is also paged, the page number is further divided into:

- a 10-bit page number, and
- a 10-bit page offset.

Thus, a logical address is as follows:

\[
\begin{array}{c|c|c}
\text{page number} & \text{page offset} \\
\hline
p_i & p_2 & d \\
10 & 10 & 12
\end{array}
\]

where \( p_i \) is an index into the outer page table, and \( p_2 \) is the displacement within the page of outer page table.
Address-Translation Scheme

- Address-translation scheme for a two-level 32-bit paging architecture
Two-Level Page-Table Scheme

outer-page table

page of page table

page table

memory

1

500

100

708

929

900

1

100

500

708

900

929
### Three-level Paging Scheme for 64-bit Operating System

<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>

- The 2\textsuperscript{nd} outer page table still needs 16GB memory, since $2^{32}$ number of table entries $\times$ 4 bytes per table entry = $2^{34}$ bytes memory.
### Intel x86-64

- Current generation Intel x86 architecture
- 64 bits address space is ginormous (> 16 exabytes)

- In practice only implement 48 bit addressing
  - Four levels of paging hierarchy

<table>
<thead>
<tr>
<th>9 bits</th>
<th>9 bits</th>
<th>9 bits</th>
<th>9 bits</th>
<th>12 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>unused</td>
<td>page map</td>
<td>page directory</td>
<td>page directory</td>
<td>offset</td>
</tr>
<tr>
<td>63</td>
<td>48 47</td>
<td>39 38</td>
<td>30 29</td>
<td>21 20</td>
</tr>
<tr>
<td></td>
<td>level 4</td>
<td>pointer table</td>
<td></td>
<td>12 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

- Multiple page sizes of 4 KB, 2 MB, 1 GB
Hashed Page Tables

- Common in address spaces > 32 bits.

**Motivation**

- On a 64-bit operating system, the third-level page table is still too large to fit in main memory.
- In a 32-bit or 64-bit address space of a process, most part of it is unused.

**Solution** base on Chained Hash Table

- The virtual page number is hashed into a page table. This page table contains a chain of elements hashing to the same location.
- Virtual page numbers are compared in this chain searching for a match. If a match is found, the corresponding physical frame is extracted.
Hashed Page Tables

logical address

hash function

hash table

physical address

physical memory
Inverted Page Table

- **Motivation**: All the previous schemes need to maintain a page table for each process.
- One entry for each real page of memory (frame)
- Entry consists of the virtual address of the page stored in that real memory location, with information about the process owning 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.
Inverted Page Table Architecture

The diagram illustrates the inverted page table architecture in an operating system. It shows how the logical address is translated into a physical address through the page table and page directory. The diagram includes:

- CPU
- Logical address space
- Page table
- Physical memory
- Physical address

The process involves:

1. The CPU generates a logical address.
2. The logical address is used to search the page table.
3. If the page table entry is found, the physical address is retrieved.
4. The physical address is used to access the physical memory.

This architecture optimizes memory access by minimizing the number of page table lookups.
Chapter 9: Memory Management

- Background
- Swapping
- Contiguous Allocation
- Segmentation
- Paging
- Advanced Page Table Structure
- Segmentation with Paging
Example: The Intel Pentium

- 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
The Intel IA-32 Architecture

- Supports segmentation with paging

- CPU generates logical address
  - Selector given to segmentation unit
    - Which produces linear addresses
    - Up to 16K segments per process
  - Linear address given to paging unit
    - Which generates physical address in main memory
    - Paging units form equivalent of MMU

s: segment number

g: whether in GDT or LDT

p: protection bits

http://en.wikipedia.org/wiki/Memory_segmentation#Segmentation_with_paging
Intel IA-32 Segmentation with Paging

Support two-level page table
Pages sizes can be either 4 KB or 4 MB
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 (page address extension) 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
Example: ARM Architecture (Cont.)

- Two levels of TLBs
  - Outer level has two micro TLBs (one data, one instruction)
  - Inner is single main TLB
  - Firstly, inner is checked, on miss outers are checked, and on miss page table walk performed by CPU
OS creates, for each process, an illusion of continuous memory address space, based on the paging/segmentation mechanism.

**Question:** Why the mainstream CPU chips organize the page#-to-frame# mapping table in a hierarchical way, instead of using hashed page table or inverted page table?
Dynamic Linking

■ **Static linking** – system libraries and program code combined by the loader into the binary program image

■ **Dynamic linking** – linking postponed until run 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