Recall: Paging

Virtual memory view

1111 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000

Page Table

1111 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000

Physical memory view

1111 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000
1110 1111
1110 0000

What happens if stack grows to 1110 0000?

Allocate new pages where room!
**Page Table Discussion**

- What needs to be switched on a context switch?
  - Page table pointer and limit

- Analysis
  - Pros
    » Simple memory allocation
    » Easy to share
  - Cons: What if address space is sparse?
    » E.g., on UNIX, code starts at 0, stack starts at \((2^{31}-1)\)
    » With 1K pages, need 2 million page table entries!
  - Cons: What if table really big?
    » Not all pages used all the time ⇒ would be nice to have working set of page table in memory

- How about multi-level paging or combining paging and segmentation?

---

**Fix for sparse address space: The two-level page table**

- Tree of Page Tables
- Tables fixed size (1024 entries)
- Valid bits on Page Table Entries
  - Don’t need every 2nd-level table
  - Even when exist, 2nd-level tables can reside on disk if not in use

---

**Summary: Two-Level Paging**

Virtual memory view

- stack
- heap
- code
- data

Page Tables

- (level 1)

Physical memory view

- stack
- heap
- data

---

**Summary: Two-Level Paging**

Virtual memory view

- stack
- heap
- code
- data

Page Tables

- (level 2)

Physical memory view

- stack
- heap
- code
Multi-level Translation: Segments + Pages

- What about a tree of tables?
  - Lowest level page table \( \Rightarrow \) memory still allocated with bitmap
  - Higher levels often segmented
- Could have any number of levels. Example (top segment):

<table>
<thead>
<tr>
<th>Virtual Address</th>
<th>Virtual Seg #</th>
<th>Virtual Page #</th>
<th>Offset</th>
<th>Physical Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base0 Limit0</td>
<td>page #0</td>
<td>VR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base1 Limit1</td>
<td>page #1</td>
<td>VR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base2 Limit2</td>
<td>page #2</td>
<td>VR,W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base3 Limit3</td>
<td>page #3</td>
<td>VR,W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base4 Limit4</td>
<td>page #4</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base5 Limit5</td>
<td>page #5</td>
<td>VR,W</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- What must be saved/restored on context switch?
  - Contents of top-level segment registers (for this example)
  - Pointer to top-level table (page table)

What about Sharing (Complete Segment)?

Process A:

<table>
<thead>
<tr>
<th>Virtual Seg #</th>
<th>Virtual Page #</th>
<th>Offset</th>
<th>Page #0</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base0 Limit0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base1 Limit1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base2 Limit2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base3 Limit3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base4 Limit4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base5 Limit5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base6 Limit6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base7 Limit7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Process B:

<table>
<thead>
<tr>
<th>Virtual Seg #</th>
<th>Virtual Page #</th>
<th>Offset</th>
<th>Page #0</th>
<th>VR,W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base0 Limit0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base1 Limit1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base2 Limit2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base3 Limit3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base4 Limit4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base5 Limit5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base6 Limit6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base7 Limit7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multi-level Translation Analysis

- Pros:
  - Only need to allocate as many page table entries as we need for application
    - In other words, sparse address spaces are easy
  - Easy memory allocation
  - Easy Sharing
    - Share at segment or page level (need additional reference counting)
- Cons:
  - One pointer per page (typically 4K – 16K pages today)
  - Page tables need to be contiguous
    - However, previous example keeps tables to exactly one page in size
  - Two (or more, if >2 levels) lookups per reference
    - Seems very expensive!

What is in a Page Table Entry

- What is in a Page Table Entry (or PTE)?
  - Pointer to next-level page table or to actual page
  - Permission bits: valid, read-only, read-write, write-only
- Example: Intel x86 architecture PTE:
  - Address same format previous slide (10, 10, 12-bit offset)
  - Intermediate page tables called “Directories”

<table>
<thead>
<tr>
<th>Page Frame Number (Physical Page Number)</th>
<th>Free (OS)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-12</td>
<td></td>
<td>11</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

P: Present (same as “valid” bit in other architectures)
W: Writeable
U: User accessible
PWT: Page write transparent: external cache write-through
PCD: Page cache disabled (page cannot be cached)
A: Accessed: page has been accessed recently
D: Dirty (PTE only): page has been modified recently
L: L\(\Rightarrow\) 4MB page (directory only).
  - Bottom 22 bits of virtual address serve as offset
How is the Translation Accomplished?

• What, exactly happens inside MMU?
• One possibility: Hardware Tree Traversal
  – For each virtual address traverses the page table in hardware
  – Generates a “Page Fault” if it encounters invalid PTE
    » Fault handler will decide what to do
    » More on this next lecture
  – Pros: Relatively fast (but still many memory accesses!)
  – Cons: Inflexible, Complex hardware
• Another possibility: Software
  – Each traversal done in software
  – Pros: Very flexible
  – Cons: Every translation must invoke Fault!
• In fact, need way to cache translations for either case!

Recall: Dual-Mode Operation (1/2)

• Can a process modify its own translation tables?
  – NO!
  – If it could, could get access to all of physical memory
  – Has to be restricted somehow

• To Assist with Protection, hardware provides at least two modes (Dual-Mode Operation):
  – “Kernel” mode (or “supervisor” or “protected”)
  – “User” mode (Normal program mode)
  – Mode set with bits in special control register only accessible in kernel-mode

Recall: Dual-Mode Operation (2/2)

• Intel processor actually has four “rings” of protection:
  – PL (Privilege Level) from 0 – 3
    » PL0 has full access, PL3 has least
  – Privilege Level set in code segment descriptor (CS)
  – Mirrored “IOPL” bits in condition register gives permission to programs to use the I/O instructions
  – Typical OS kernels on Intel processors only use PL0 (“kernel”) and PL3 (“user”)

How to get from Kernel→User

• What does the kernel do to create a new user process?
  – Allocate and initialize address-space control block
  – Read program off disk and store in memory
  – Allocate and initialize translation table
    » Point at code in memory so program can execute
    » Possibly point at statically initialized data
  – Run Program:
    » Set machine registers
    » Set hardware pointer to translation table
    » Set processor status word for user mode
    » Jump to start of program
• How does kernel switch between processes?
  – Same saving/restoring of registers as before
  – Save/restore PSL (hardware pointer to translation table)
Recall: User→Kernel (System Call)

- Can’t let inmate (user) get out of padded cell on own
  - Would defeat purpose of protection!
  - So, how does the user program get back into kernel?

- System call: Voluntary procedure call into kernel
  - Hardware for controlled User→Kernel transition
  - Can any kernel routine be called?
    » No! Only specific ones.
  - System call ID encoded into system call instruction
    » Index forces well-defined interface with kernel

Recall: System Call Continued (1/2)

- What are some system calls?
  - I/O: open, close, read, write, lseek
  - Files: delete, mkdir, rmdir, truncate, chown, chgrp, ...
  - Process: fork, exit, wait (like join)
  - Network: socket create, set options

- Are system calls constant across operating systems?
  - Not entirely, but there are lots of commonalities
  - Also some standardization attempts (POSIX)

Recall: System Call Continued (2/2)

- What happens at beginning of system call?
  » On entry to kernel, sets system to kernel mode
  » Handler address fetched from table/Handler started

- System call argument passing:
  - In registers (not very much can be passed)
  - Write into user memory, kernel copies into kernel mem
    » User addresses must be translated!
    » Kernel has different view of memory than user
  - Every argument must be explicitly checked!

Recall: User→Kernel (Exceptions: Traps & Interrupts)

- A system call instruction causes a synchronous exception
  (or “trap”)
  » In fact, often called a software “trap” instruction

- Other sources of Synchronous Exceptions (“Trap”):
  - Divide by zero, Illegal instruction, Bus error (bad address, e.g. unaligned access)
  - Segmentation Fault (address out of range)
  - Page Fault (for illusion of infinite-sized memory)

- Interrupts are Asynchronous Exceptions
  - Examples: timer, disk ready, network, etc….  
  - Interrupts can be disabled, traps cannot!
Recall: User→Kernel (Exceptions: Traps & Interrupts)

- On system call, exception, or interrupt:
  - Hardware enters kernel mode with interrupts disabled
  - Saves PC, then jumps to appropriate handler in kernel
  - For some processors (x86), processor also saves registers, changes stack, etc.

- Actual handler typically saves registers, other CPU state, and switches to kernel stack

Closing thought: Protection without Hardware (1/2)

- Does protection require hardware support for translation and dual-mode behavior?
  - No: Normally use hardware, but anything you can do in hardware can also do in software (possibly expensive)

- Protection via Strong Typing
  - Restrict programming language so that you can’t express program that would trash another program
  - Loader needs to make sure that program produced by valid compiler or all bets are off
  - Example languages: LISP, Ada, Modula-3 and Java

Closing thought: Protection without Hardware (2/2)

- Protection via software fault isolation:
  - Language independent approach: have compiler generate object code that provably can’t step out of bounds
    » Compiler puts in checks for every “dangerous” operation (loads, stores, etc). Again, need special loader.
    » Alternative, compiler generates “proof” that code cannot do certain things (Proof Carrying Code)
  - Or: use virtual machine to guarantee safe behavior (loads and stores recompiled on fly to check bounds)

Administrivia

- jrk out next week (no office hours)
- Anthony (hopefully!) returning
- Likely guest lecturer(s)
Caching Concept

- Cache: a repository for copies that can be accessed more quickly than the original
  - Make frequent case fast and infrequent case less dominant
- Caching underlies many techniques used today to make computers fast
  - Can cache: memory locations, address translations, pages, file blocks, file names, network routes, etc...
- Only good if:
  - Frequent case frequent enough and
  - Infrequent case not too expensive
- Important measure: Average Access time = (Hit Rate x Hit Time) + (Miss Rate x Miss Time)

Why Bother with Caching?

Processor-DRAM Memory Gap (latency)

“Moore’s Law”
(real Joy’s Law)

“Less’ Law?”

Processor-Memory Performance Gap:
grows 50% / year

CPU

µProc
60%/yr.
(2X/1.5yr)

DRAM
9%/yr.
(2X/10 yrs)

Another Major Reason to Deal with Caching

- Cannot afford to translate on every access
  - At least three DRAM accesses per actual DRAM access
  - Or: perhaps I/O if page table partially on disk!
- Even worse: What if we are using caching to make memory access faster than DRAM access?
- Solution? Cache translations!
  - Translation Cache: TLB (“Translation Lookaside Buffer”)
Why Does Caching Help? Locality!

• Temporal Locality (Locality in Time):
  – Keep recently accessed data items closer to processor
• Spatial Locality (Locality in Space):
  – Move contiguous blocks to the upper levels

Memory Hierarchy of a Modern Computer System

• Take advantage of the principle of locality to:
  – Present as much memory as in the cheapest technology
  – Provide access at speed offered by the fastest technology

A Summary on Sources of Cache Misses

• Compulsory (cold start or process migration, first reference): first access to a block
  – “Cold” fact of life: not a whole lot you can do about it
  – Note: If you are going to run “billions” of instruction, Compulsory Misses are insignificant
• Capacity:
  – Cache cannot contain all blocks access by the program
  – Solution: increase cache size
• Conflict (collision):
  – Multiple memory locations mapped to the same cache location
  – Solution 1: increase cache size
  – Solution 2: increase associativity
• Coherence (Invalidation): other process (e.g., I/O) updates memory

How is a Block found in a Cache?

• Index Used to Lookup Candidates in Cache
  – Index identifies the set
• Tag used to identify actual copy
  – If no candidates match, then declare cache miss
• Block is minimum quantum of caching
  – Data select field used to select data within block
  – Many caching applications don’t have data select field
Review: Direct Mapped Cache

- **Direct Mapped** $2^N$ byte cache:
  - The uppermost (32 - N) bits are always the Cache Tag
  - The lowest M bits are the Byte Select (Block Size = $2^M$
- **Example:** 1 KB Direct Mapped Cache with 32 B Blocks
  - Index chooses potential block
  - Tag checked to verify block
  - Byte select chooses byte within block

```
<table>
<thead>
<tr>
<th>Cache Index</th>
<th>Byte Select</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
```

Review: Set Associative Cache

- **N-way** set associative: N entries per Cache Index
  - N direct mapped caches operates in parallel
- **Example:** Two-way set associative cache
  - Cache Index selects a "set" from the cache
  - Two tags in the set are compared to input in parallel
  - Data is selected based on the tag result

```
<table>
<thead>
<tr>
<th>Cache Index</th>
<th>Byte Select</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
```

Review: Fully Associative Cache

- **Fully Associative:** Every block can hold any line
  - Address does not include a cache index
  - Compare Cache Tags of all Cache Entries in Parallel
- **Example:** Block Size=32B blocks
  - We need N 27-bit comparators
  - Still have byte select to choose from within block

```
<table>
<thead>
<tr>
<th>Cache Tag (27 bits long)</th>
<th>Byte Select</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x50</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
```

Where does a Block Get Placed in a Cache?

- **Example:** Block 12 placed in 8 block cache
  - Block Address Space: 32-Block
    - **Direct mapped:** block 12 can go only into block 4 (12 mod 8)
    - **Set associative:** block 12 can go anywhere in set 0 (12 mod 4)
    - **Fully associative:** block 12 can go anywhere
Review: Which block should be replaced on a miss?

- Easy for Direct Mapped: Only one possibility
- Set Associative or Fully Associative:
  - Random
  - LRU (Least Recently Used)

Miss rates for a workload:

<table>
<thead>
<tr>
<th>Size</th>
<th>2-way</th>
<th>4-way</th>
<th>8-way</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LRU Random</td>
<td>LRU Random</td>
<td>LRU Random</td>
</tr>
<tr>
<td>16 KB</td>
<td>5.2%</td>
<td>5.7%</td>
<td>4.7%</td>
</tr>
<tr>
<td>64 KB</td>
<td>1.9%</td>
<td>2.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>256 KB</td>
<td>1.15%</td>
<td>1.17%</td>
<td>1.13%</td>
</tr>
</tbody>
</table>

Review: What happens on a write?

- Write through: The information is written to both the block in the cache and to the block in the lower-level memory
- Write back: The information is written only to the block in the cache
  - Modified cache block is written to main memory only when it is replaced
  - Question is block clean or dirty?
- Pros and Cons of each?
  - WT:
    - PRO: read misses cannot result in writes
    - CON: Processor held up on writes unless writes buffered
  - WB:
    - PRO: repeated writes not sent to DRAM processor not held up on writes
    - CON: More complex
      - Read miss may require writeback of dirty data

Caching Applied to Address Translation

- Question is one of page locality: does it exist?
  - Instruction accesses spend a lot of time on the same page (since accesses sequential)
  - Stack accesses have definite locality of reference
  - Data accesses have less page locality, but still some…
- Can we have a TLB hierarchy?
  - Sure: multiple levels at different sizes/speeds

What Actually Happens on a TLB Miss? (1/2)

- Hardware traversed page tables:
  - On TLB miss, hardware in MMU looks at current page table to fill TLB (may walk multiple levels)
    - If PTE valid, hardware fills TLB and processor never knows
    - If PTE marked as invalid, causes Page Fault, after which kernel decides what to do afterwards
- Software traversed Page tables (like MIPS):
  - On TLB miss, processor receives TLB fault
    - Kernel traverses page table to find PTE
      - If PTE valid, fills TLB and returns from fault
      - If PTE marked as invalid, internally calls Page Fault handler
What Actually Happens on a TLB Miss? (2/2)

• Most chip sets provide hardware traversal
  – Modern operating systems tend to have more TLB faults since they use translation for many things
  – Examples:
    » shared segments
    » user-level portions of an operating system

What happens on a Context Switch?

• Need to do something, since TLBs map virtual addresses to physical addresses
  – Address Space just changed, so TLB entries no longer valid!
• Options?
  – Invalidate TLB: simple but might be expensive
    » What if switching frequently between processes?
  – Include ProcessID in TLB
    » This is an architectural solution: needs hardware
• What if translation tables change?
  – For example, to move page from memory to disk or vice versa…
  – Must invalidate TLB entry!
    » Otherwise, might think that page is still in memory!

Summary

• The Principle of Locality:
  – Program likely to access a relatively small portion of the address space at any instant of time.
    » Temporal Locality: Locality in Time
    » Spatial Locality: Locality in Space

• Three (+1) Major Categories of Cache Misses:
  – Compulsory Misses: sad facts of life. Example: cold start misses.
  – Conflict Misses: increase cache size and/or associativity
  – Capacity Misses: increase cache size
  – Coherence Misses: Caused by external processors or I/O devices

• Cache Organizations:
  – Direct Mapped: single block per set
  – Set associative: more than one block per set
  – Fully associative: all entries equivalent