15-410
“...We are Computer Scientists!...”

Virtual Memory #1
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Synchronization

Who has read some test code?
- How about the “thread group” library?
- If you haven't read a lot of mutex/cvar code before, you have some in hand!

Code drop is possible soon
- Remember to “make update” when prompted
Outline

Text
  - Reminder: reading list on class “Schedule” page
  - “213 review material”
    - Linking, fragmentation

The Problem: logical vs. physical

Contiguous memory mapping

Fragmentation

Paging
  - Type theory
  - A sparse map
Logical vs. Physical

“It's all about address spaces”

- Generally a complex issue
  - IPv4 $\Rightarrow$ IPv6 is mainly about address space exhaustion

213 review (?)

- Combining .o's changes addresses
- But what about two programs?
Every .o uses the same address space
Linker combines .o's, changes addresses
What About Two Programs?

- Stack: FFFFFFF000
- BSS: 00010300
- Data: 00010200
- Code: 00010000

- Stack: FFFFE000
- BSS: 00010300
- Data: 00010100
- Code: 00010000
Logical vs. Physical Addresses

**Logical address**
- Each program has its own *address space* ...
  - *fetch:* address $\Rightarrow$ data
  - *store:* address, data $\Rightarrow$ unit
- ...as envisioned by programmer, compiler, linker

**Physical address**
- Where your program ends up in memory
- They can't *all* be loaded at 0x10000!
Reconciling Logical, Physical

Programs could take turns in memory
- Requires swapping programs out to disk
- Very slow

Could run programs at addresses other than linked
- Requires using linker to “relocate one last time” at launch
- Done by some old mainframe OSs
- Slow, complex, or both

We are computer scientists!
Reconciling Logical, Physical

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We are computer scientists!
- Insert a level of indirection
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We are computer scientists!
- Insert a level of indirection
  - Well, get the ECE folks to do it for us
“Type Theory”

**Physical memory behavior**
- fetch: address ⇒ data
- store: address, data ⇒ unit

**Process thinks of memory as...**
- fetch: address ⇒ data
- store: address, data ⇒ unit
“Type Theory”

Physical memory behavior
- fetch: address $\Rightarrow$ data
- store: address, data $\Rightarrow$ unit

Process thinks of memory as...
- fetch: address $\Rightarrow$ data
- store: address, data $\Rightarrow$ unit

Goal: each process has “its own memory”
- process-id $\Rightarrow$ fetch: (address $\Rightarrow$ data)
- process-id $\Rightarrow$ store: (address, data $\Rightarrow$ unit)
“Type Theory”

Physical memory behavior

- fetch: address ⇒ data
- store: address, data ⇒ unit

Process thinks of memory as...

- fetch: address ⇒ data
- store: address, data ⇒ unit

Goal: each process has “its own memory”

- process-id ⇒ fetch: (address ⇒ data)
- process-id ⇒ store: (address, data ⇒ unit)

What really happens

- process-id ⇒ map: (virtual-address ⇒ physical-address)
- Machine does “fetch o map” and “store o map”
Simple Mapping Functions

**P1**
If $V > 8191$ ERROR
Else $P = 1000 + V$

**P2**
If $V > 16383$ ERROR
Else $P = 9192 + V$

**Address space**
- Base address
- Limit
Contiguous Memory Mapping

Processor contains two control registers
- Memory base
- Memory limit

Each memory access checks
If \( V < \text{limit} \)
\[
P = \text{base} + V;
\]
Else
\[
\text{ERROR} /* \text{what do we call this error? */}
\]

During context switch...
- Save/load user-visible registers
- Also load process's base, limit registers
Problems with Contiguous Allocation

1. How do we grow a process?
   - Must increase “limit” value
   - Cannot expand into another process's memory!
   - Must move entire address spaces around
     - Very expensive

2. Fragmentation
   - New processes may not fit into unused memory “holes”

3. Partial memory residence
   - Must entire program be in memory at same time?
Can We Run Process 4?

Process exit creates “holes”

New processes may be too large

May require moving entire address spaces
Term: “External Fragmentation”

Free memory is small chunks
Doesn't fit large objects
Can “disable” lots of memory
Can fix

- Costly “compaction”
  - aka “Stop & copy”
Term: “Internal Fragmentation”

Allocators often round up
- 8K boundary (some power of 2!)

Some memory is wasted inside each segment

Can't fix via compaction

Effects typically non-fatal

![Memory Allocation Diagram]
Swapping

Multiple user processes

- Sum of memory demands \(> \) system memory
- Goal: Allow each process 100\% of system memory
Swapping

**Multiple user processes**
- Sum of memory demands > system memory
- Goal: Allow *each process* 100% of system memory

**Take turns**
- Temporarily evict process(es) to disk
  - Not runnable
  - Blocked on *implicit I/O request* (e.g., “swapread”)
- “Swap daemon” shuffles process in & out
- Can take *seconds* per process
  - Modern analogue: laptop suspend-to-disk
- Maybe we need a better plan?
Contiguous Allocation ⇒ Paging

Solves multiple problems
- Process growth problem
- Fragmentation compaction problem
- Long delay to swap a whole process

Approach: divide memory more finely
- \textit{Page} = small region of \textit{virtual} memory (\(\frac{1}{2}K, 4K, 8K, \ldots\))
- \textit{Frame} = small region of \textit{physical} memory
- [I will get this wrong, feel free to correct me]

Key idea!!!
- Any page can map to (occupy) any frame
Per-process Page Mapping
Problems Solved by Paging

Process growth problem?
- Any process can use any free frame for any purpose

Fragmentation compaction problem?
- Process doesn't need to be contiguous, so don't compact

Long delay to swap a whole process?
- Swap \textit{part} of the process instead!
Partial Residence

Diagram showing the allocation of memory blocks for P0 and P1 processes, including stacks and data segments.
Must Evolve Data Structure Too

Contiguous allocation
- Each process was described by (base, limit)

Paging
- Each page described by (base, limit)?
  - Pages typically one size for whole system
- Ok, each page described by (base address)
- Arbitrary page ⇒ frame mapping requires some work
  - Abstract data structure: “map”
  - Implemented as...
Data Structure Evolution

Contiguous allocation
- Each process previously described by (base, limit)

Paging
- Each *page* described by (base, limit)?
  - Pages typically one size for whole system
- Ok, each *page* described by (base address)
- Arbitrary page $\Rightarrow$ frame mapping requires some work
  - Abstract data structure: “map”
  - Implemented as...
    - Linked list?
    - Array?
    - Hash table?
    - Skip list?
    - Splay tree??????
“Page Table” Options

**Linked list**
- O(n), so V ⇒ P time gets longer for large addresses!

**Array**
- Constant time access
- Requires (large) contiguous memory for table

**Hash table**
- Vaguely-constant-time access
- Not really bounded though

**Splay tree**
- Excellent amortized expected time
- *Lots* of memory reads & writes possible for one mapping
- Not yet demonstrated in hardware
“Page Table”: Array Approach

Page table array: Page 3, Page 2, Page 1, Page 0

Page array: Page 3, Page 2, Page 1, Page 0

Frame array: f29, f34, ....
Paging – Address Mapping

1. 4K page size ⇒ 12 bits
2. 32 - 12 ⇒ 20 bits of page #
Paging – Address Mapping
Paging – Address Mapping

Page Offset → Copy → Frame Offset

Logical Address

Page table

....
f29
f34
....
Paging – Address Mapping

Logical Address

Page Offset

Frame Offset

Page table

Physical Address

.... f29 f34 ....
Paging – Address Mapping

User view
- Memory is a linear array

OS view
- Each process requires N frames, located anywhere

Fragmentation?
- Zero external fragmentation
- Internal fragmentation: average ½ page per region
Bookkeeping

One “page table” for each process

One global “frame table”
- Manages free frames
- (Typically) remembers who owns each frame

Context switch
- Must “activate” switched-to process's page table
Hardware Techniques

Small number of pages?
- Page “table” can be a few registers
- PDP-11: 64k address space
  - 8 “pages” of 8k each – 8 registers

Typical case
- Large page tables, live in memory
  - Processor has “Page Table Base Register” (names vary)
  - Set during context switch
Double trouble?

Program requests memory access
- MOVL (%ESI), %EAX

Processor makes \textit{two} memory accesses!
- Splits address in %esi into page number, intra-page offset
- Adds page number to page table base register
- \textit{Fetches page table entry (PTE) from memory}
- Concatenates frame address with intra-page offset
- \textit{Fetches program's data from memory into %eax}

Solution: “TLB”
- Not covered today
Page Table Entry Mechanics

**PTE conceptual job**
- Specify a frame number
Page Table Entry Mechanics

**PTE conceptual job**
- Specify a frame number

**PTE flags**
- **Valid bit**
  - Not-set means access should generate an exception
- **Protection**
  - Read/Write/Execute bits
- **Reference bit, “dirty” bit**
  - Set if page was read/written “recently”
  - Used when paging to disk (later lecture)
- **Specified by OS for each page/frame**
  - Inspected/updated by hardware
Page Table Structure

**Problem**

- Assume 4 KByte pages, 4-Byte PTEs
- Ratio: 1024:1
  - 4 GByte virtual address (32 bits) ⇒ ________ page table
Page Table Structure

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**One Approach: Page Table Length Register (PTLR)**

- (names vary)
- Many programs don't use entire virtual space
- Restrict a process to use entries 0...N of page table
- On-chip register detects out-of-bounds reference (>N)
- Allows small PTs for small processes
  - (as long as stack isn't far from data)
Page Table Structure

**Key observation**

- Each process page table is a *sparse mapping*
- Many pages are not backed by frames
  - Address space is sparsely used
    - Enormous “hole” between bottom of stack, top of heap
    - Often occupies 99% of address space!
  - Some pages are on disk instead of in memory
Page Table Structure

Key observation
- Each process page table is a *sparse mapping*
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Refining our observation
- Page tables are not randomly sparse
  - Occupied by *sequential memory regions*
  - Text, rodata, data+bss, stack
- “Sparse list of dense lists”
Page Table Structure

How to map “sparse list of dense lists”? 
We are computer scientists!
  - ...?
Page Table Structure

How to map “sparse list of dense lists”? 

We are computer scientists!
- Insert a level of indirection
  - Well, get the ECE folks to do it for us

Multi-level page table
- “Page directory” maps large chunks of address space to...
- ...Page tables, which map pages to frames
- Conceptually the same mapping as last time
  - But the implementation is a two-level tree, not a single step
Multi-level page table

Page Directory

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Page Tables

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>f08</td>
<td>f07</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>f29</td>
</tr>
<tr>
<td>f34</td>
</tr>
<tr>
<td>f25</td>
</tr>
</tbody>
</table>
Multi-level page table
Multi-level page table

Page Directory

P1 P2 Offset

.... f08 ⇒ f07 ⇒ ....

.... f29 f34 f25

.... f99 f87 ....

Page Tables
Multi-level page table

Page Directory

P1 P2 Offset

.... f08 => f07 => ....

Page Tables

.... f99 f87 ....

.... f29 f34 f25
Multi-level page table

P1 P2 Offset

Page Tables

.... f99 f87 ....

.... f29 f34 f25
Multi-level page table
Multi-level page table

P1 P2 Offset

.... f99 f87 ....

f29 f34 f25

Page Tables

f34 Offset
Sparse Mapping?

Assume 4 KByte pages, 4-byte PTEs
- Ratio: 1024:1
  - 4 GByte virtual address (32 bits) ⇒ 4 MByte page table

Now assume page directory with 4-byte PDEs
- 4-megabyte page table becomes 1024 4K page tables
- Plus one 1024-entry page directory to point to them
- Result: ______________
Sparse Mapping?

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Sparse address space...
- ...means most page tables contribute nothing to mapping...
- ...most page tables would contain only “no frame” entries...
- ...replace those PT's with “null pointer” in page directory.
- Result: empty 4GB address space specified by 4KB directory
Sparse Address Space?

**Address space mostly “blank”**
- Reads & writes should fail

**“Compress” out “the middle”**
- Sparse address space should use a small mapping structure
- Fully-occupied address space can justify a larger mapping structure
Sparse Mapping!

“Sparse” page directory
- Pointers to non-empty PT's
- “Null” instead of empty PT

Common case
- Need 2 or 3 page tables
  - One or two map code & data
  - One maps stack
- Page directory has 1024 slots
  - 2-3 point to PT's
  - Remainder are “not present”

Result
- 2-3 PT's, 1 PD
- Map entire address space with 12-16Kbyte, not 4Mbyte
Segmentation

Physical memory is (mostly) linear

Is virtual memory linear?
- Typically a set of “regions”
  - “Module” = code region + data region
  - Region per stack
  - Heap region

Why do regions matter?
- Natural protection boundary
- Natural *sharing* boundary
Segmentation: Mapping

%CS:%EIP

Seg # | Offset

Limit  | Base

Linear Address
Segmentation + Paging

80386 (does it all!)

- Processor address directed to one of six segments
  - CS: Code Segment, DS: Data Segment
  - 32-bit offset within a segment -- CS:EIP
- Descriptor table maps selector to segment descriptor
- Offset fed to segment descriptor, generates linear address
- Linear address fed through page directory, page table
- See textbook!
x86 Type Theory

Instruction $\Rightarrow$ segment selector
- [PUSHL implicitly specifies selector in %SS]

Process $\Rightarrow$ (selector $\Rightarrow$ (base, limit))
- [Global, Local Descriptor Tables]

Segment, within-segment address $\Rightarrow$ “linear address”
- CS:EIP means “EIP + base of code segment”

Process $\Rightarrow$ (linear address high $\Rightarrow$ page table)
- [Page Directory Base Register, page directory indexing]

Page Table: linear address middle $\Rightarrow$ frame address

Memory: frame address + offset $\Rightarrow$ ...
Summary

Processes emit virtual addresses
- segment-based or linear

A magic process maps virtual to physical

No, it's not magic
- Address validity verified
- Permissions checked
- Mapping may fail (trap handler)

Data structures determined by access patterns
- Most address spaces are sparsely allocated
Any problem in Computer Science can be solved by an extra level of indirection.
–Roger Needham