15-410

"...We are Computer Scientists!..."

Virtual Memory #1
Oct. 2, 2017

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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

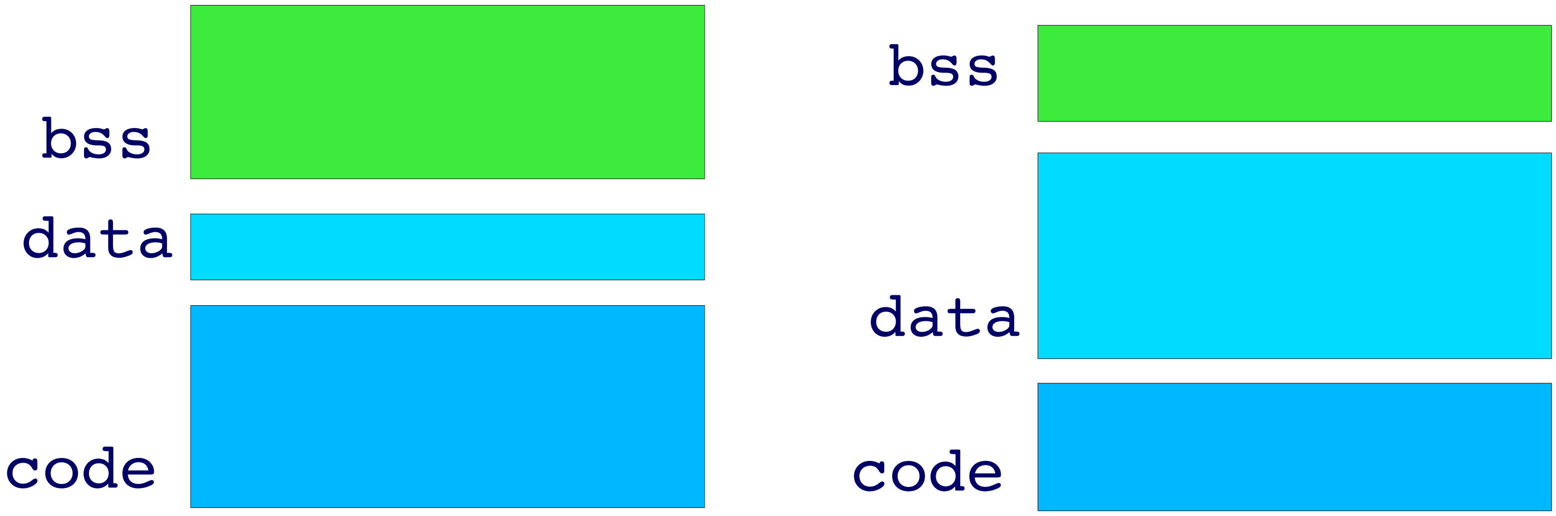
"It's all about address spaces"

- Generally a complex issue
  - IPv4 ⇒ IPv6 is mainly about address space exhaustion

213 review (?)

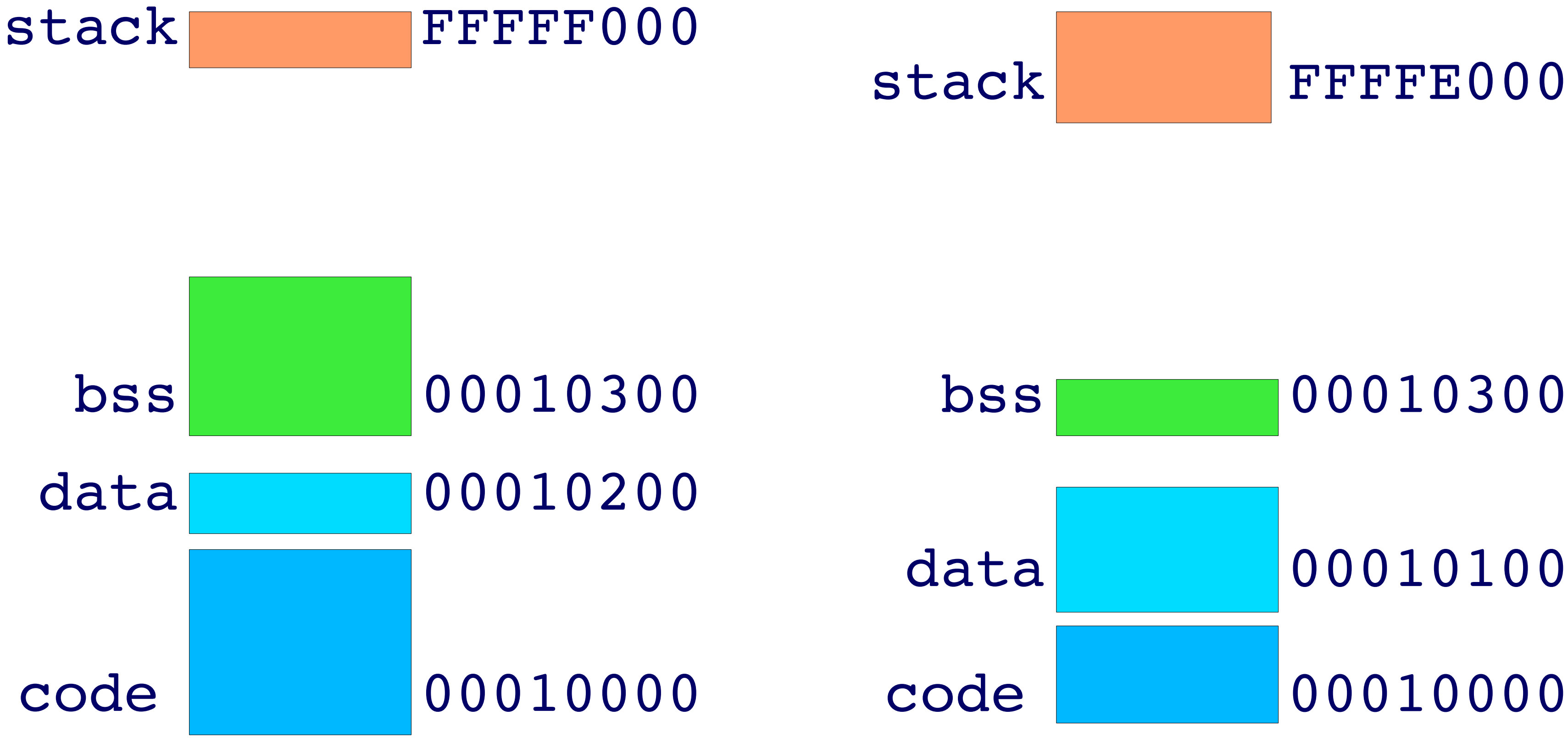
- Combining .o's changes addresses
- But what about *two* programs?

Every .o uses the same address space



Linker combines .o's, changes addresses

What About *Two* Programs?



Logical vs. Physical Addresses

Logical address

- Each program has its own *address space* ...
  - fetch: address ⇒ data
  - store: address, data ⇒ 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!

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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 ⇒ data
- store: address, data ⇒ unit

Process thinks of memory as...

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

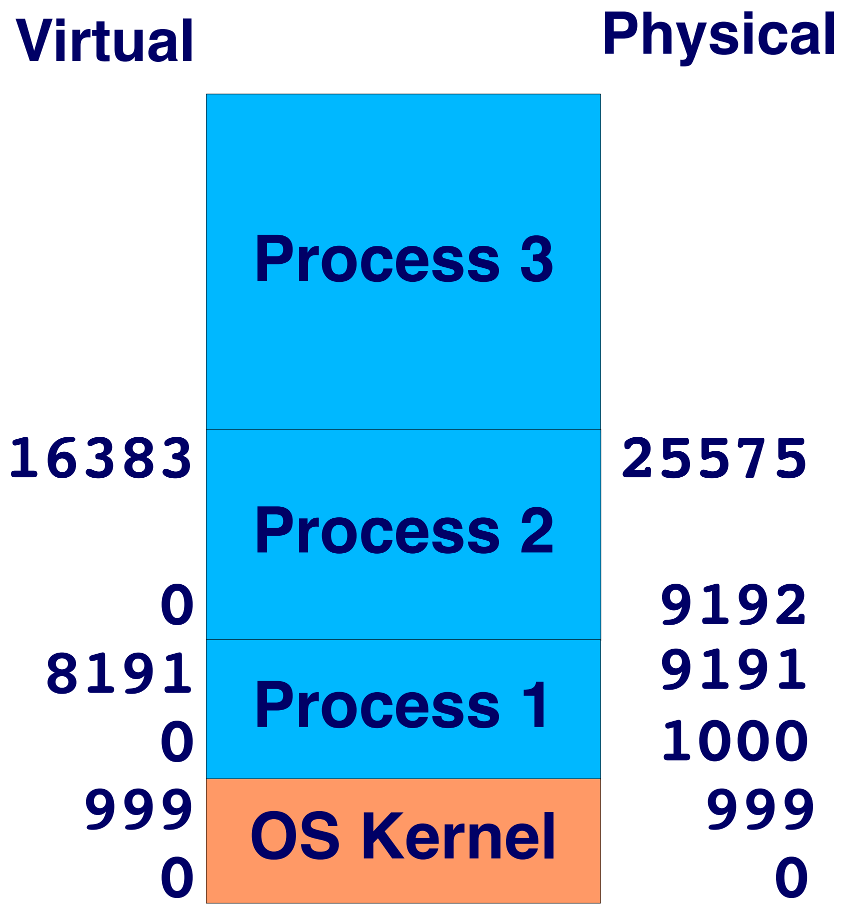
Goal: each process has "its own memory"

- 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 < limit
  P = base + V;
Else
  ERROR /* 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

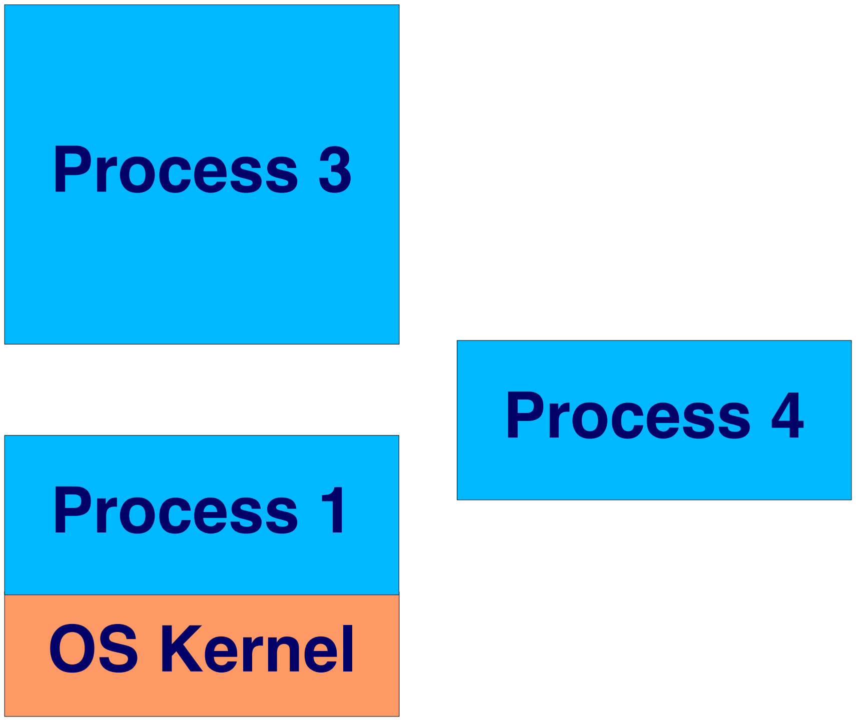
- New processes may not fit into unused memory “holes”

3. Partial memory residence

- Must *entire* program be in memory at same time?

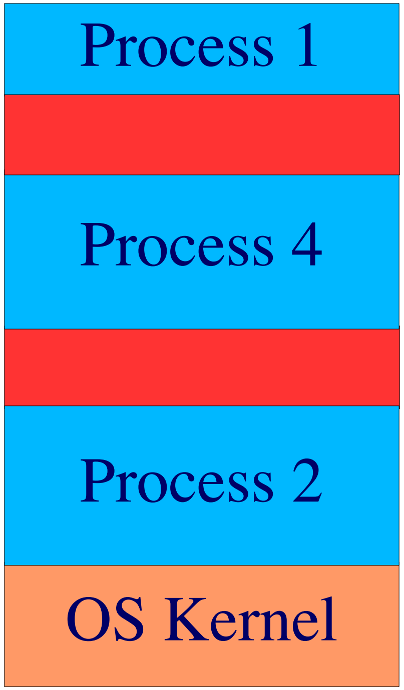
Can We Run Process 4?

- Process exit creates "holes"
- New processes may be too large
- May require moving entire address spaces



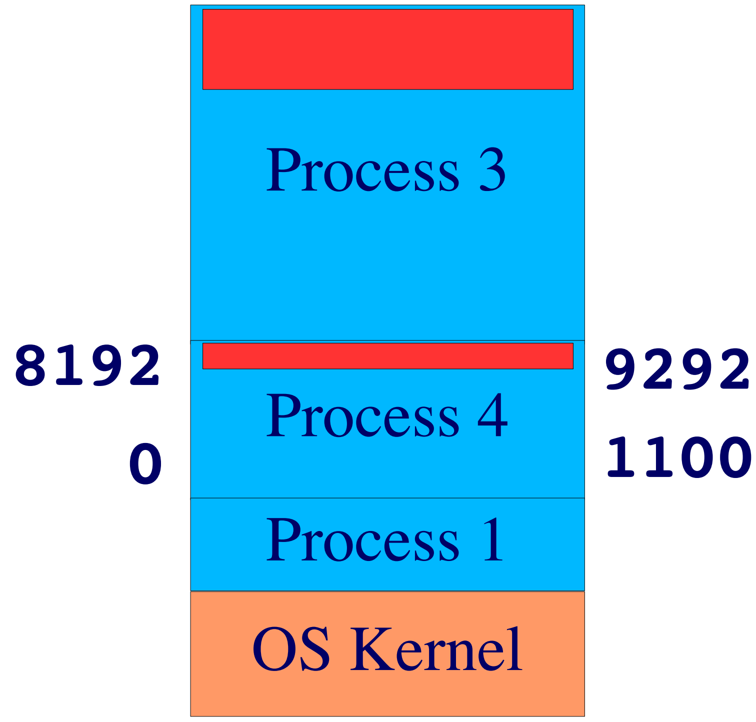
Term: “External Fragmentation”

- 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 often non-fatal**



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

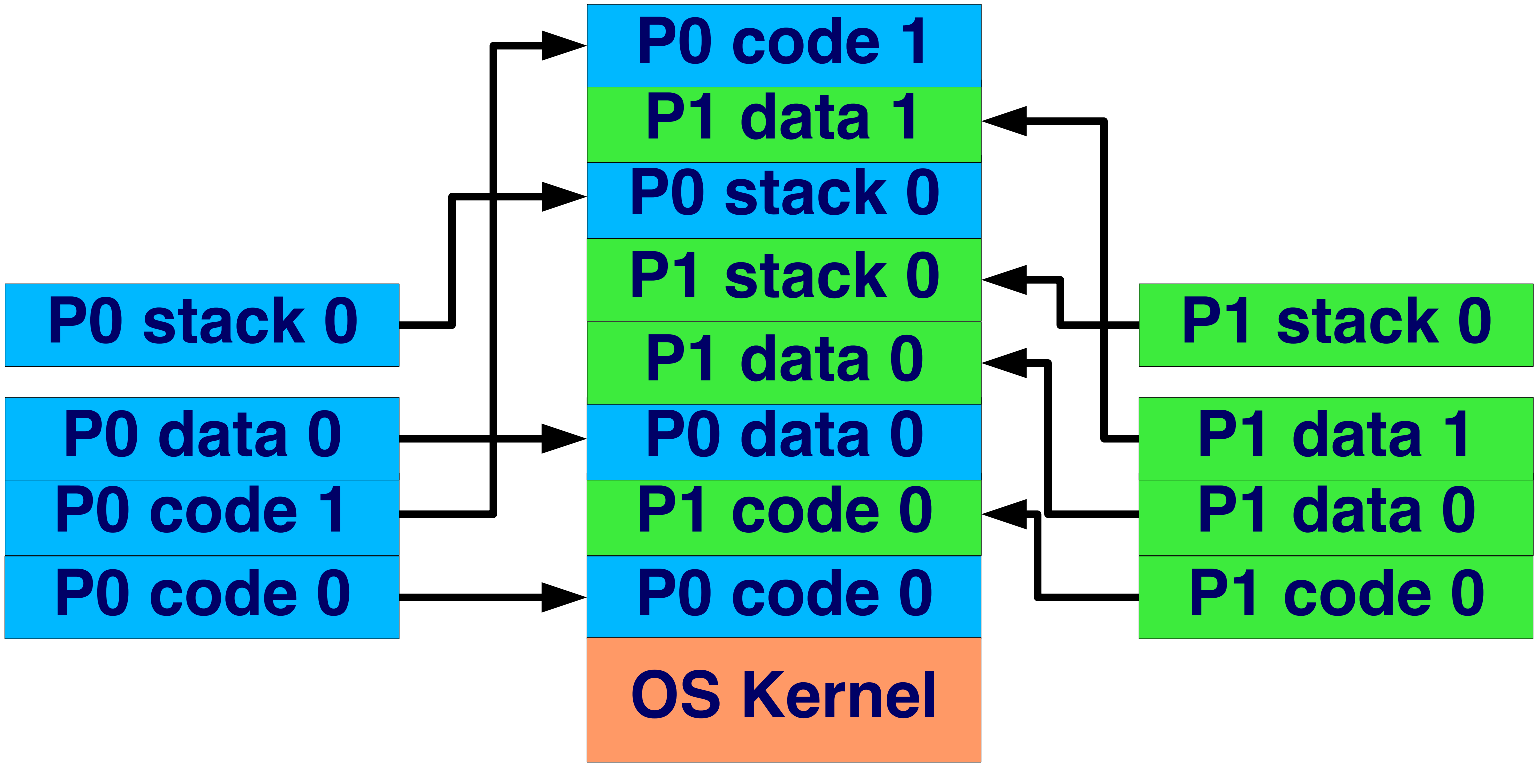
Approach: divide memory more finely

- *Page* = small region of *virtual* memory (½K, 4K, 8K, ...)
- *Frame* = small region of *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

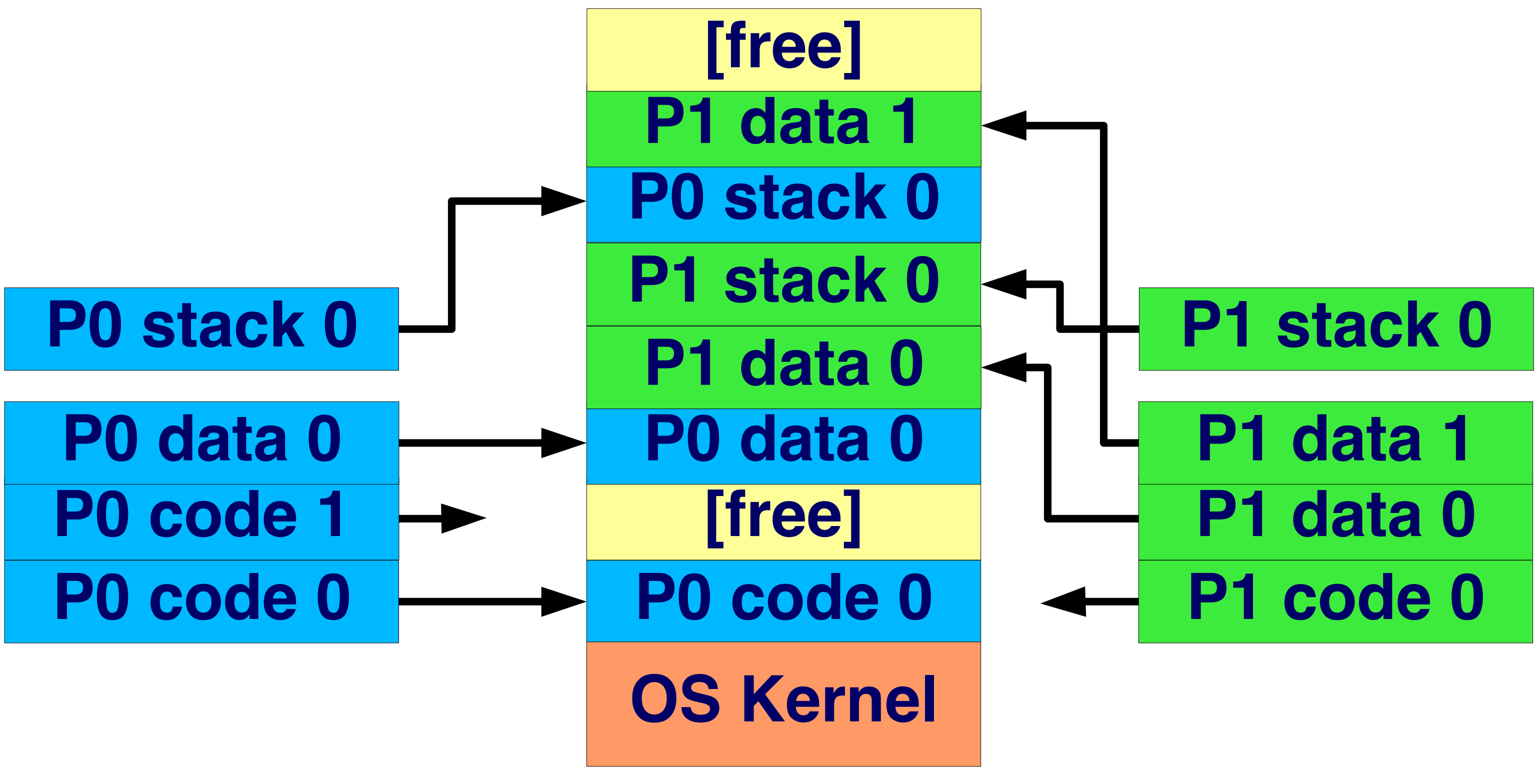
Fragmentation compaction problem?

- Process doesn't need to be contiguous, so don't compact

Long delay to swap a whole process?

- Swap *part* of the process instead!

Partial Residence



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 ⇒ 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

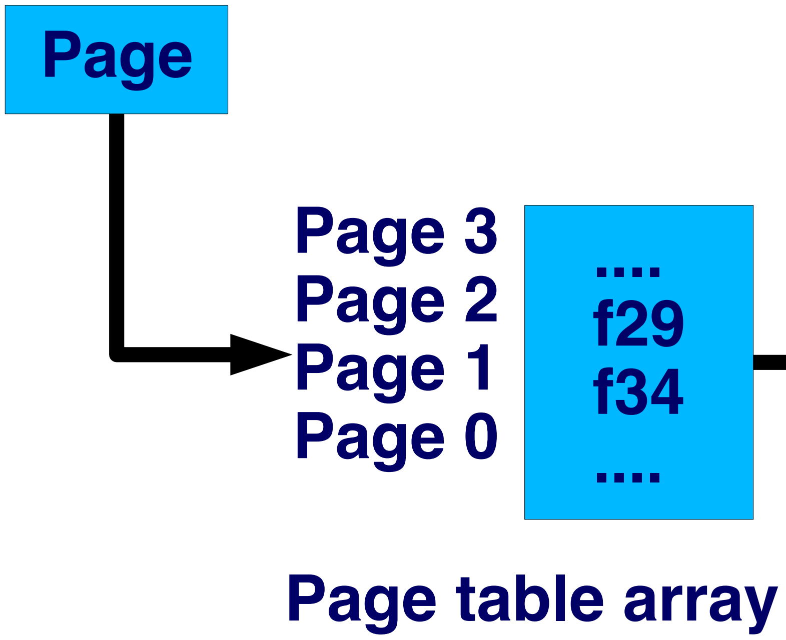
Hash table

- Vaguely-constant-time access
- Not really bounded though

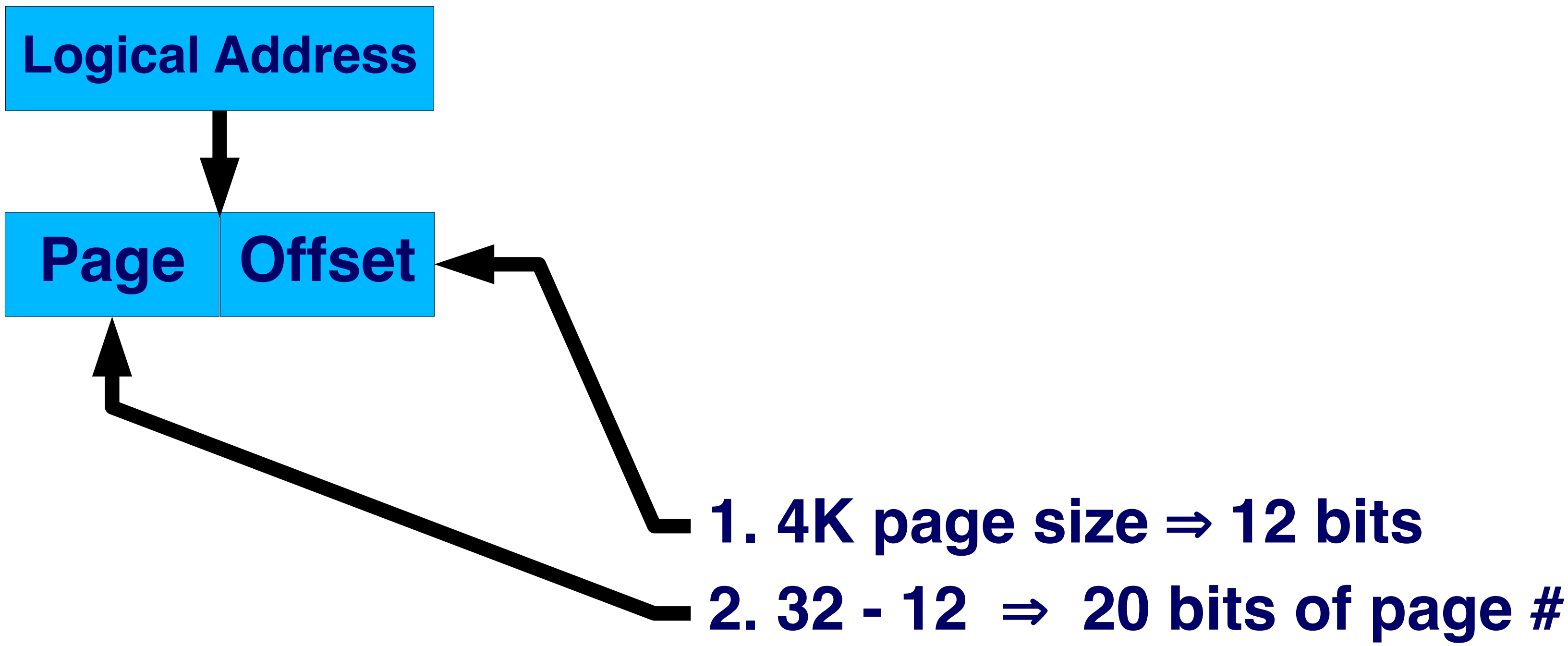
Splay tree

- Excellent amortized expected time
- *Lots* of memory reads & writes possible for one mapping
- Not yet demonstrated in hardware

“Page Table”: Array Approach



Paging – Address Mapping



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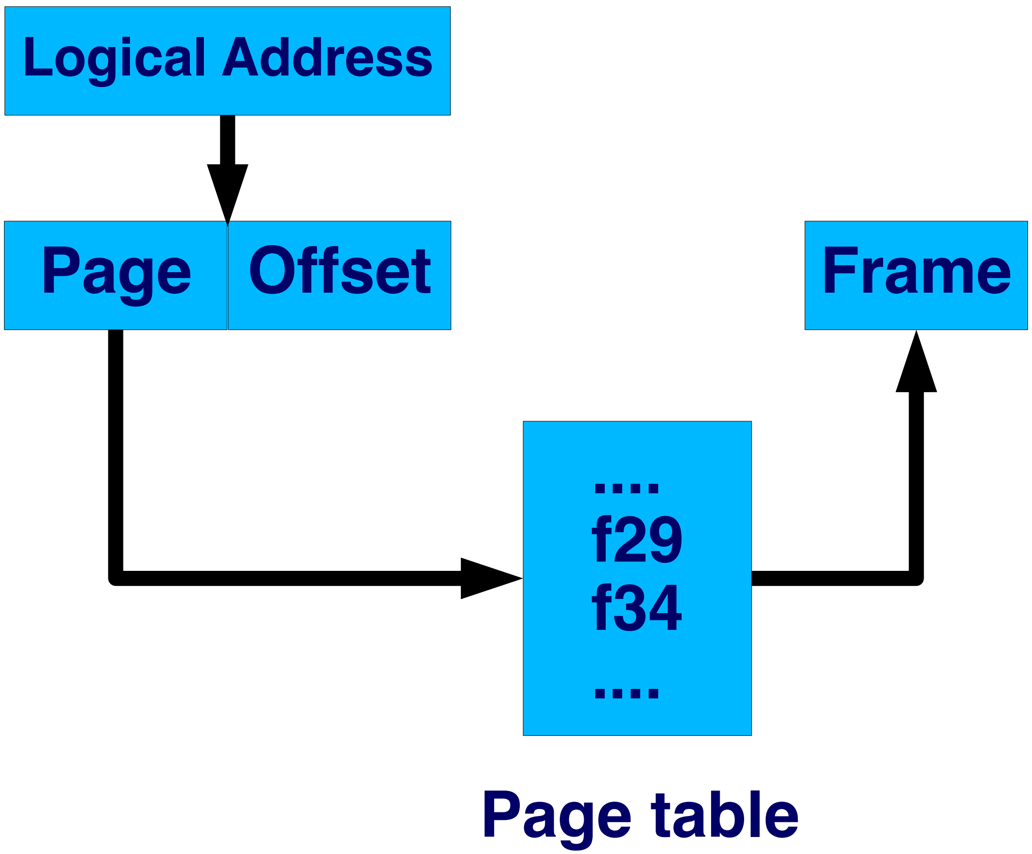

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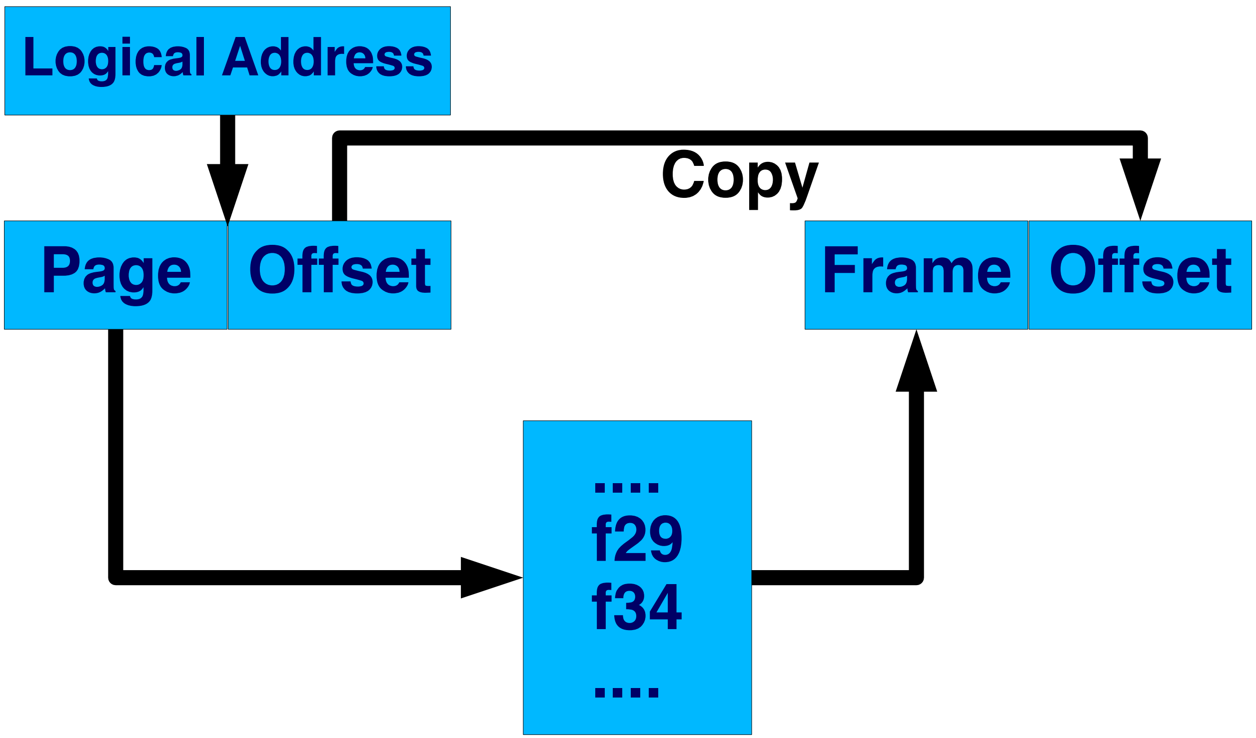
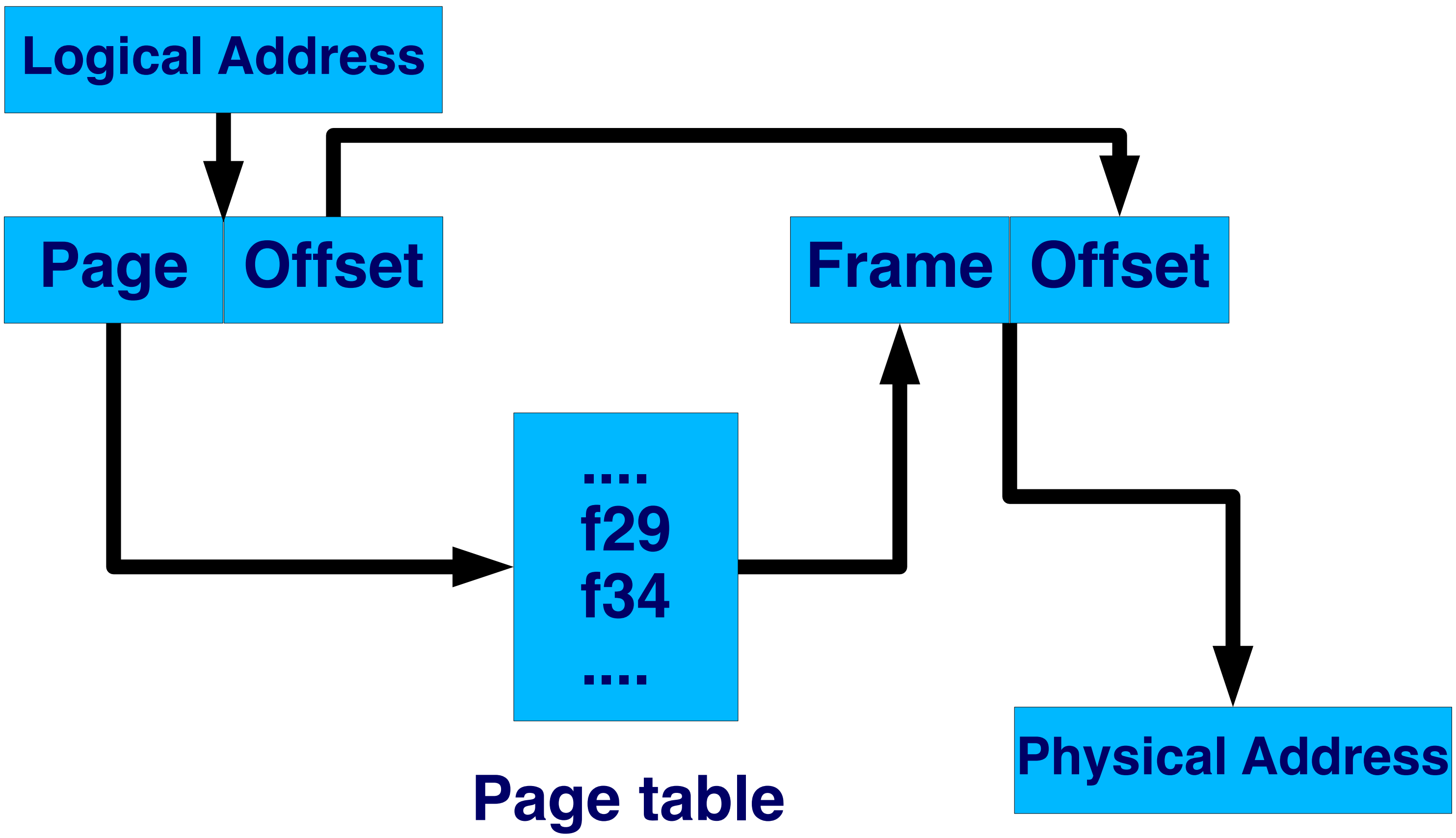


Page table

Paging – Address Mapping



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 *two* memory accesses!

- Splits address in %esi into page number, intra-page offset
- Adds page number to page table base register
- *Fetches page table entry (PTE) from memory*
- Concatenates frame address with intra-page offset
- *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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Page Table Structure

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- **Assume 4 KByte pages, 4-Byte PTEs**
- **Ratio: 1024:1**
  - **4 GByte virtual address (32 bits) ⇒ 4 MByte page table**
  - ***For each process!***

Page Table Structure

Problem

- Assume 4 KByte pages, 4-Byte PTEs
- Ratio: 1024:1
  - 4 GByte virtual address (32 bits) ⇒ 4 MByte page table
  - *For each process!*

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

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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"?

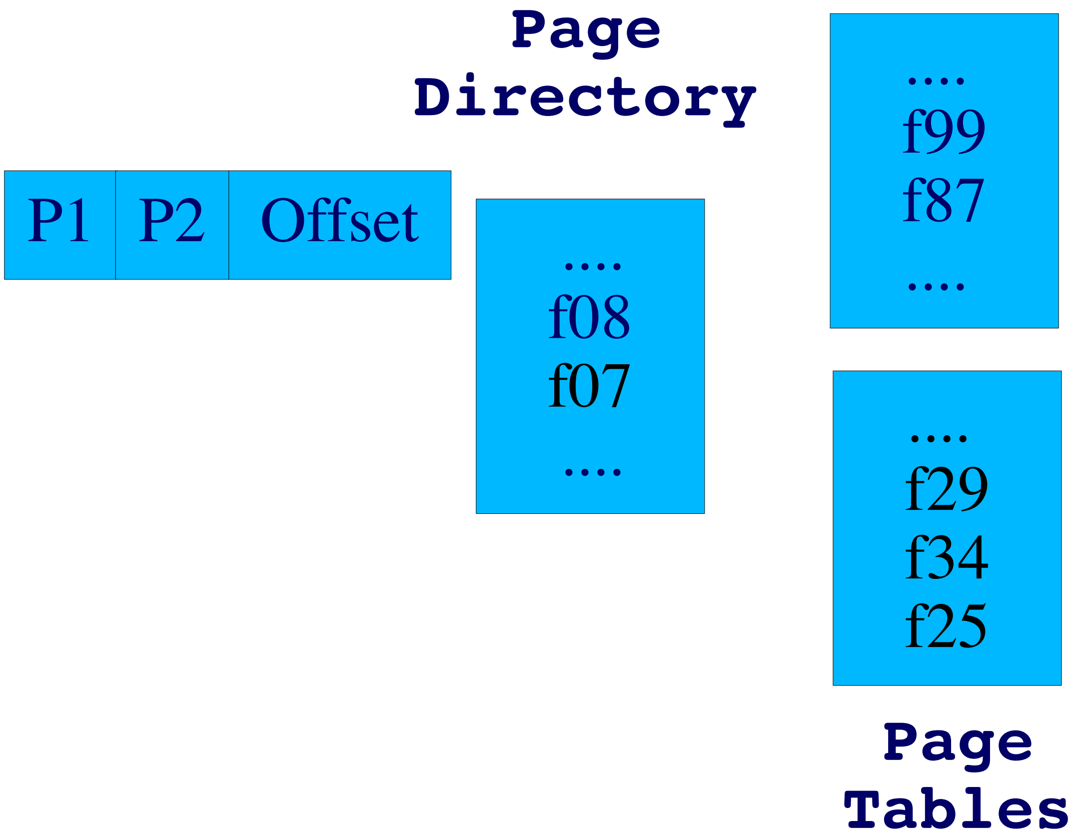
We are computer scientists!

- 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



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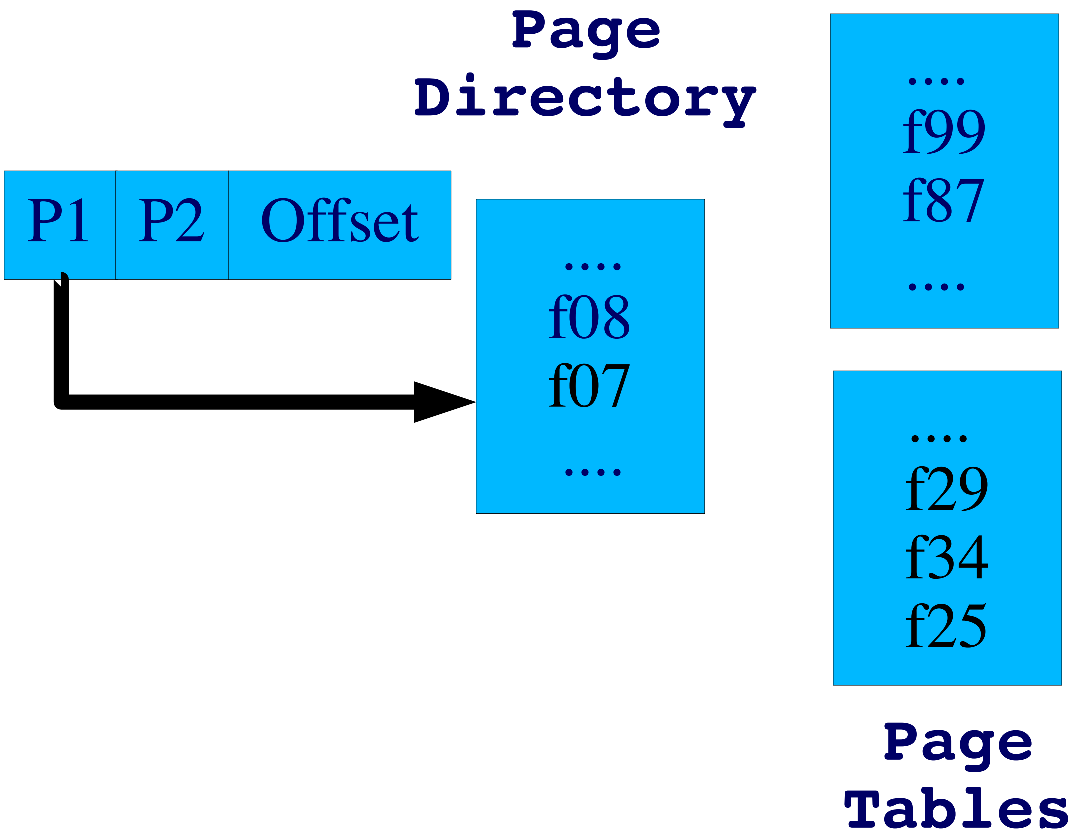

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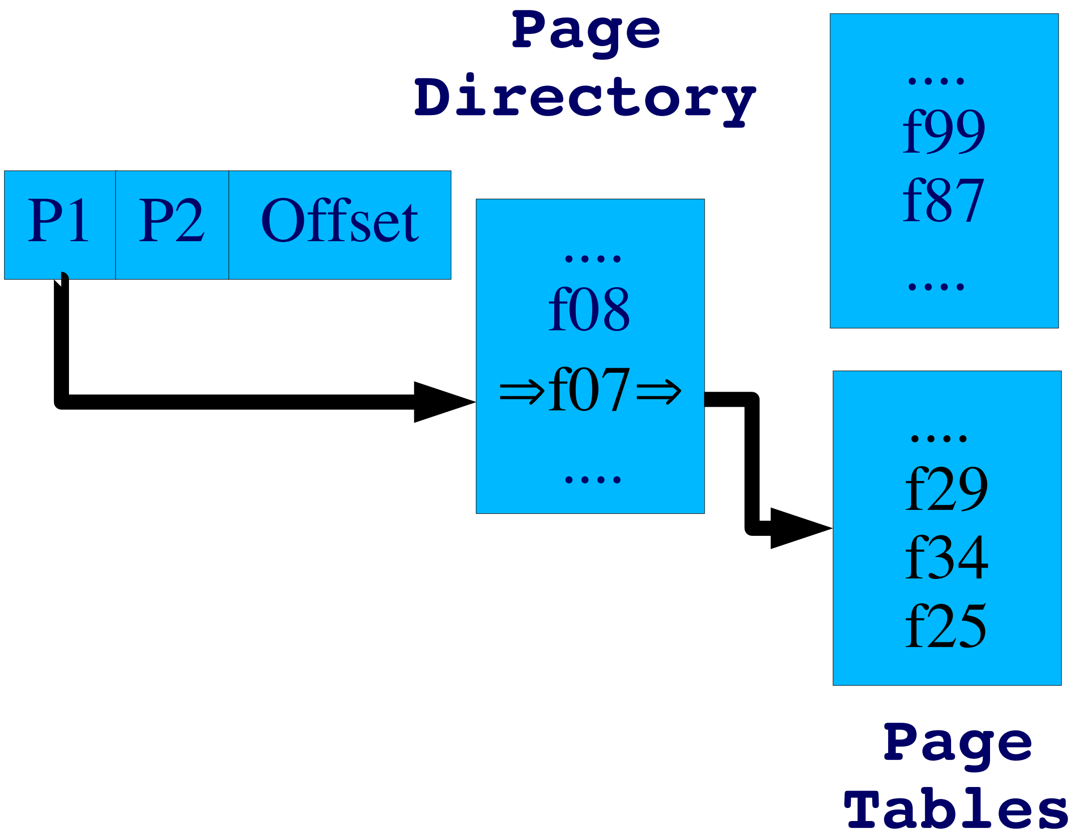

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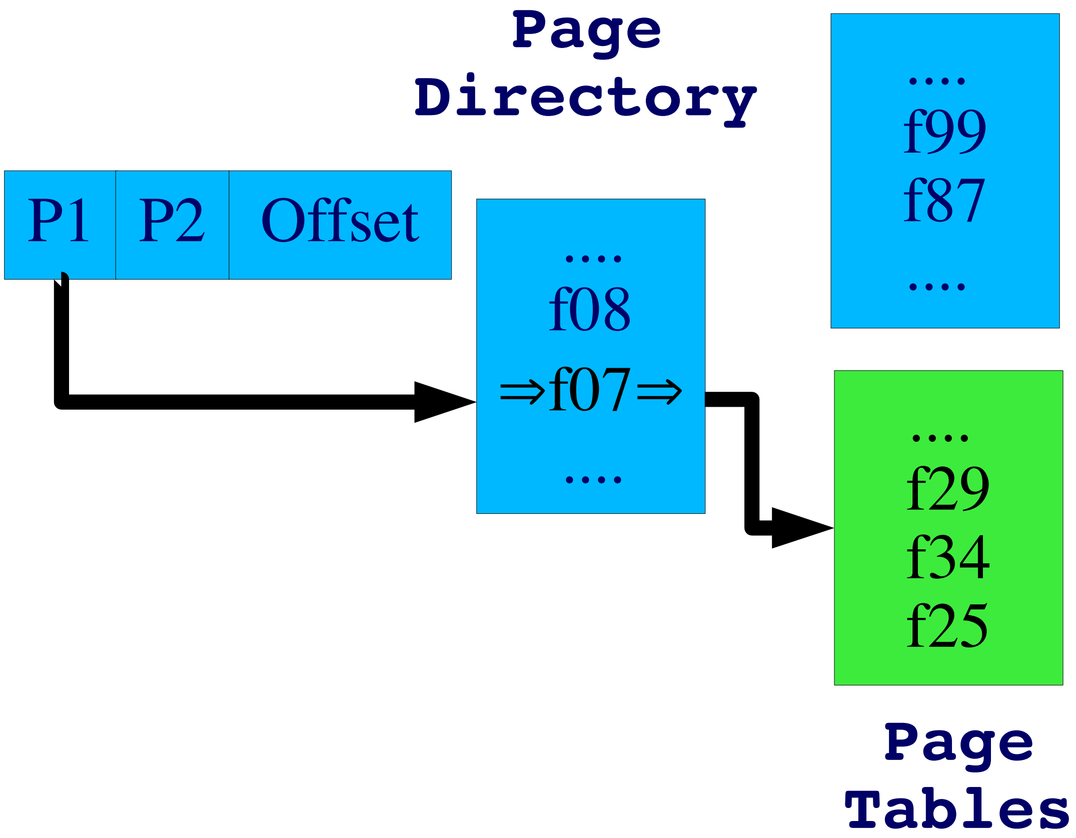

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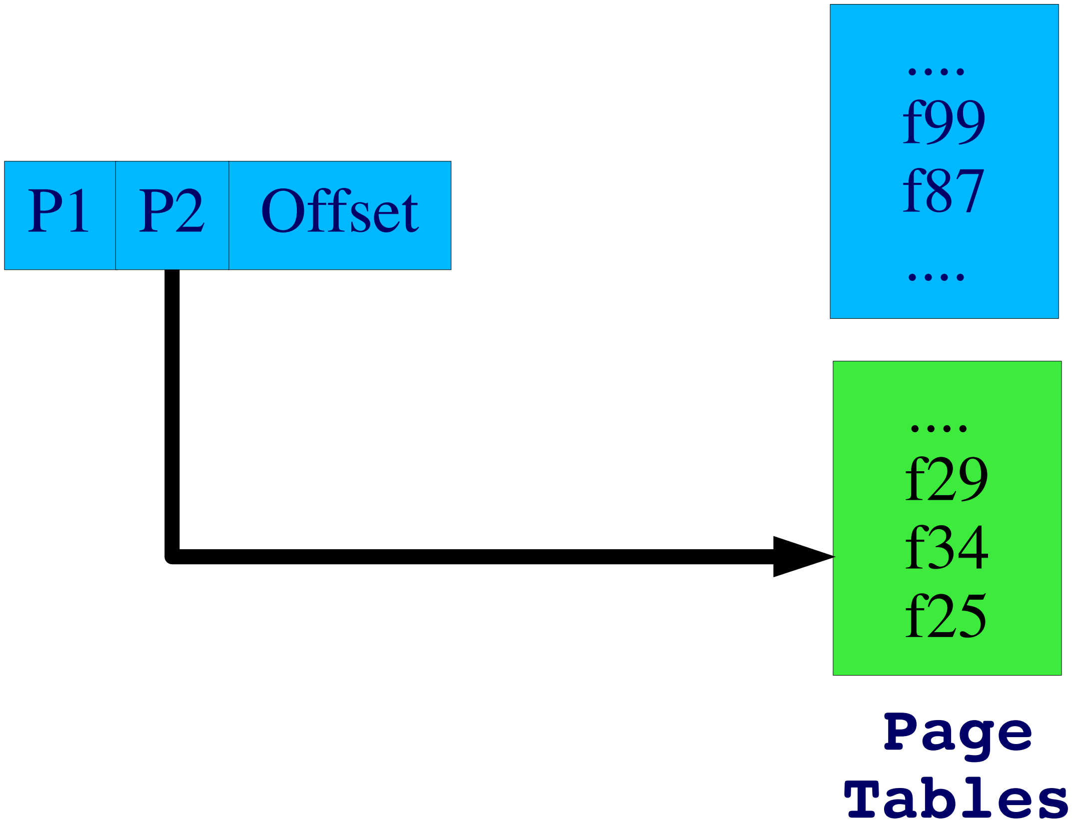

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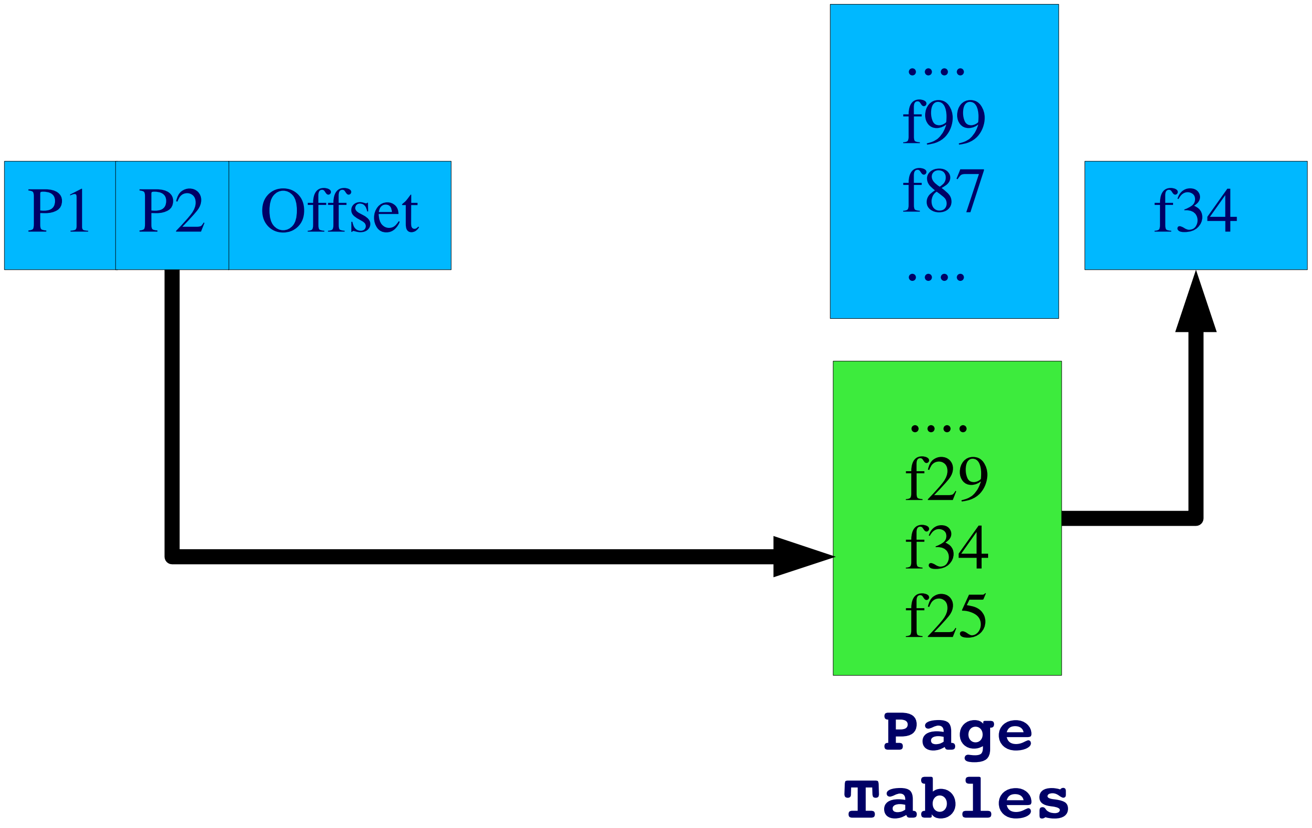

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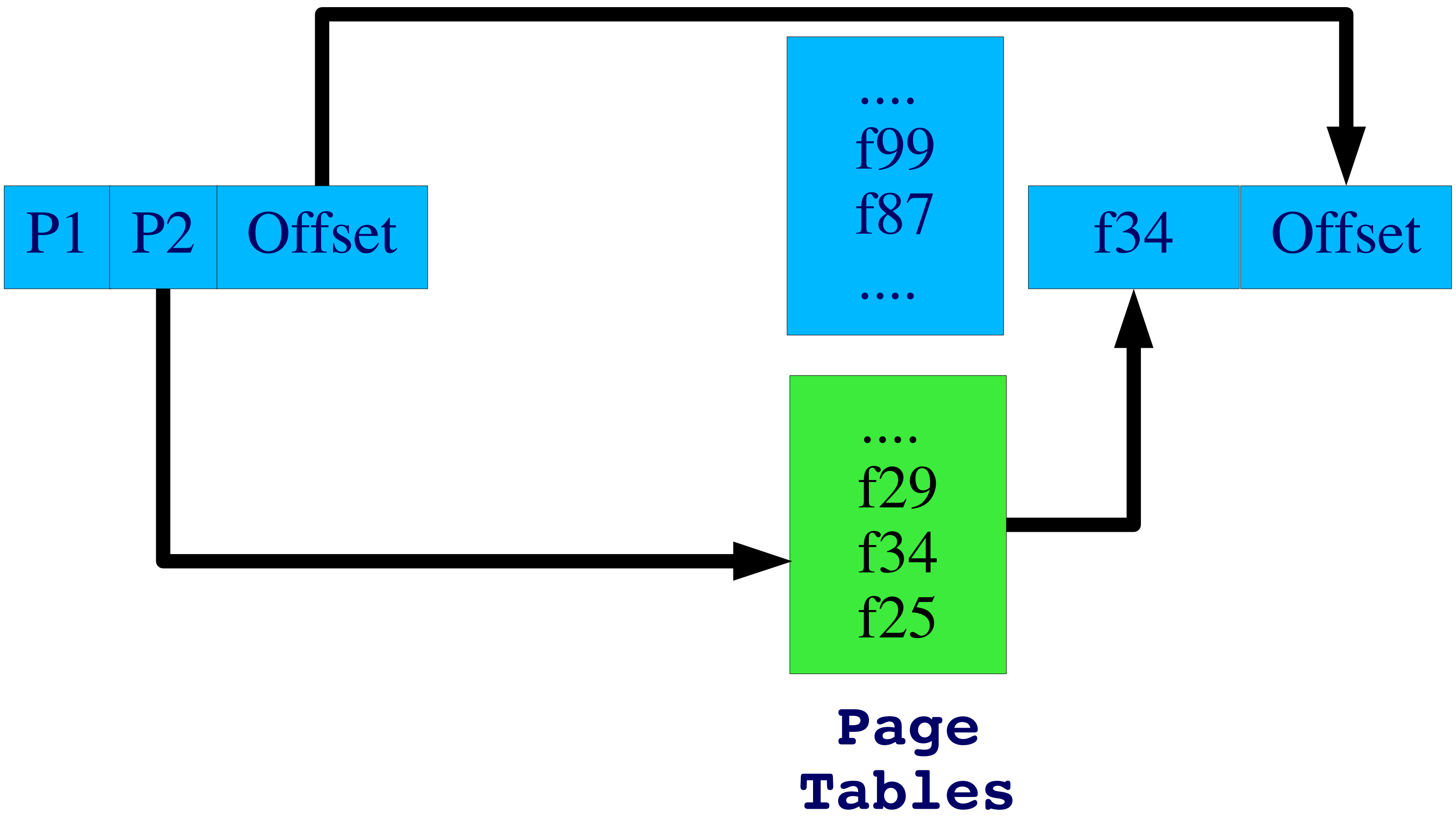

Sparse Mapping?

Assume 4 KByte pages, 4-byte PTEs

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Now assume page *directory* with 4-byte P*D*Es

- 4-megabyte page table becomes 1024 4K page tables
- Plus one 1024-entry page directory to point to them
- Result: ________________

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- Plus one 1024-entry page directory to point to them
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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

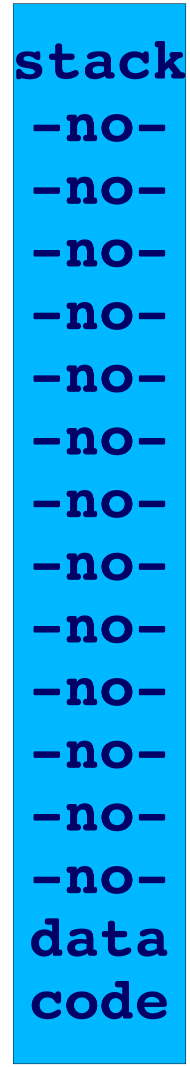
Sparse Address Space?

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

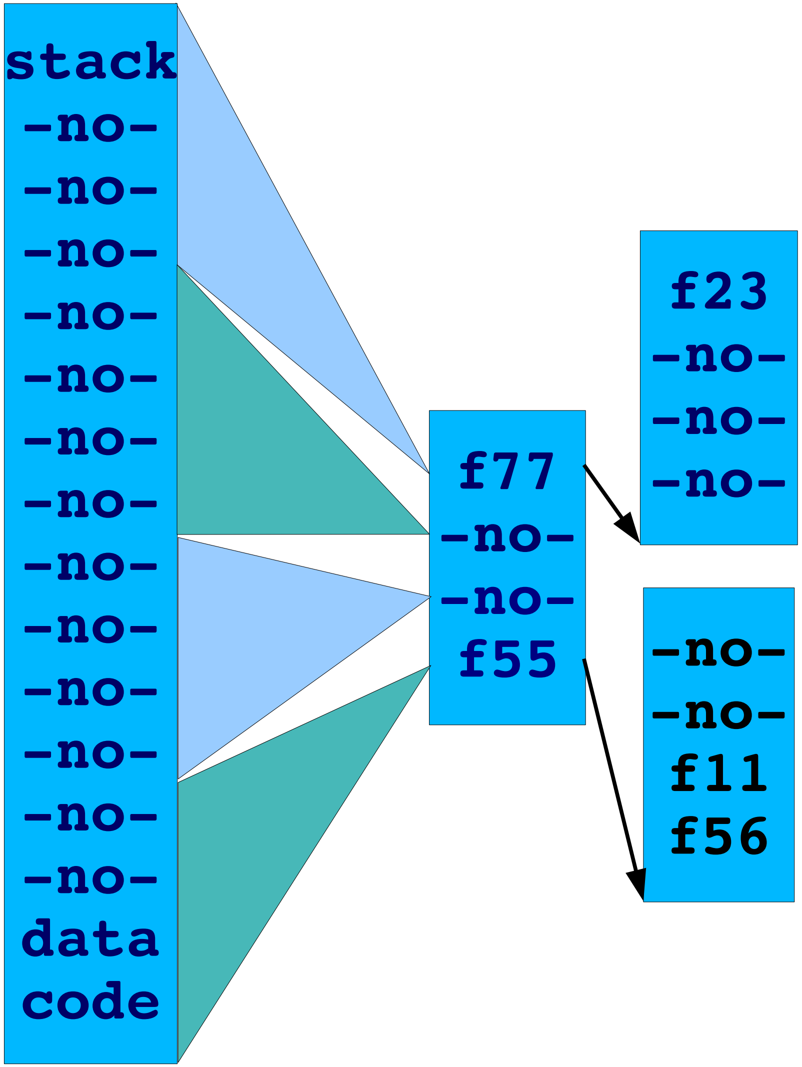
- Pointers to non-empty PT's
- "Null" instead of empty PT

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?

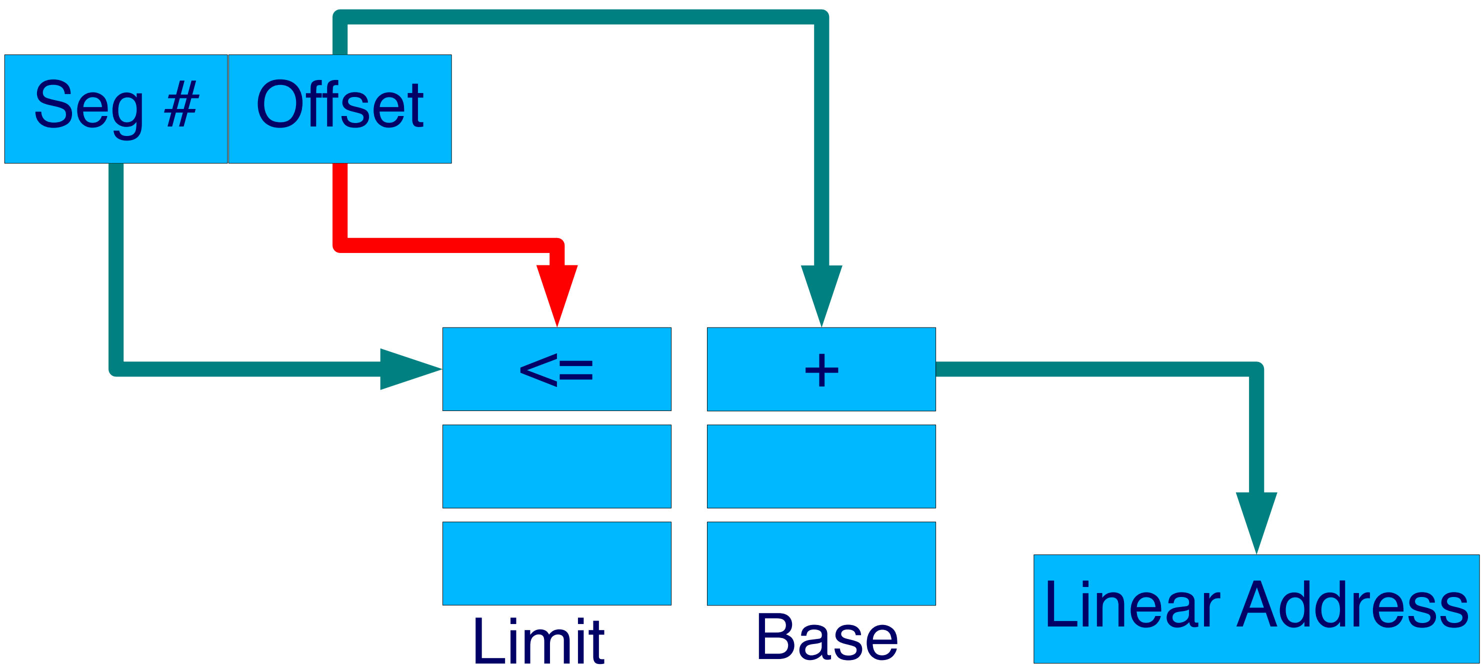
- Typically a set of “regions”
  - “Module” = code region + data region
  - Region per stack
  - Heap region

Why do regions matter?

- Natural protection boundary
- Natural *sharing* boundary

Segmentation: Mapping

%CS:%EIP



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 ⇒ segment selector

- [PUSHL implicitly specifies selector in %SS]

Process ⇒ (selector ⇒ (base,limit))

- [Global,Local Descriptor Tables]

Segment, within-segment address ⇒ "linear address"

- CS:EIP means "EIP + base of code segment"

Process ⇒ (linear address high ⇒ page table)

- [Page Directory Base Register, page directory indexing]

Page Table: linear address middle ⇒ frame address

Memory: frame address + offset ⇒ ...

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*

Quote

Any problem in Computer Science can be solved by an extra level of indirection.

–Roger Needham