Department of Physics,
Computer Science & Engineering

CPSC 410 – Operating Systems I

Virtualizing Memory: Smaller Page Tables

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Adapted from “CS 537 Introduction to Operating Systems”
Arpaci-Dusseau

Questions answered in this lecture:

- Review: What are problems with paging?
- Review: How large can page tables be?
- How can large page tables be avoided with different techniques?
  - segmentation + paging, multilevel page tables
- What happens on a TLB miss?

Disadvantages of Paging

1. Additional memory reference to look up in page table
   - Very inefficient
   - Page table must be stored in memory
   - MMU stores only base address of page table (processor tells it which page table to use)
   - **Avoid extra memory reference for lookup with TLBs (previous lecture)**
2. Storage for page tables may be substantial
   - Simple page table: Requires PTE for all pages in address space
     - Entry needed even if page not allocated
   - Problematic with dynamic stack and heap within address space (today)

QUIZ: How big are page Tables?

1. PTE's are **2 bytes**, and **32** possible virtual page numbers

   32 * 2 bytes = 64 bytes
2. PTE's are **2 bytes**, virtual addrs are **24 bits**, pages are **16 bytes**

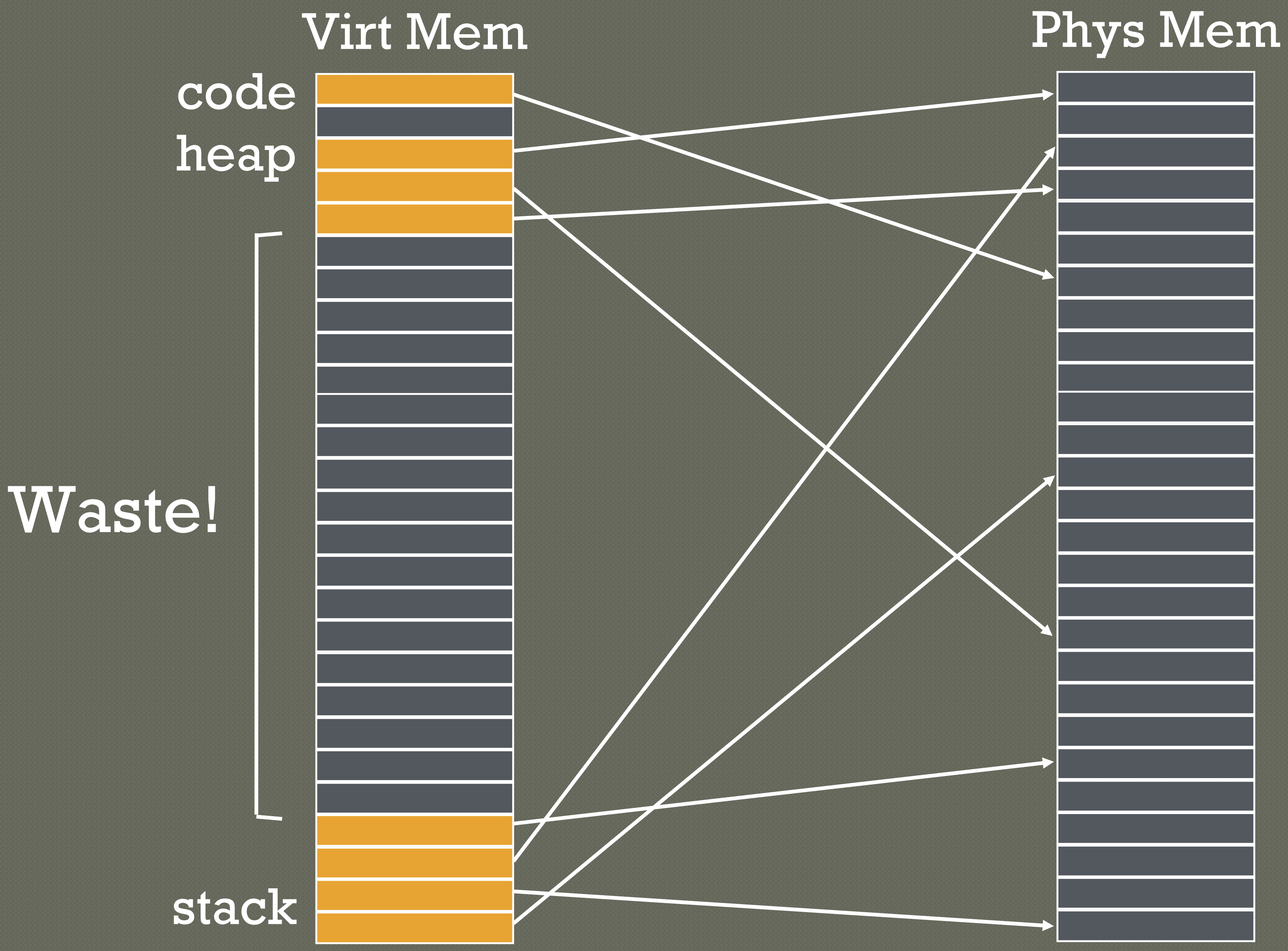
   2 bytes * 2^(24 – lg 16) = **2*(s^21) bytes** (2 MB)
3. PTE's are **4 bytes**, virtual addrs are **32 bits**, and pages are **4 KB**

   4 bytes * 2^(32 – lg 4K) = **4*2^20 bytes** (4 MB)
4. PTE's are **8 bytes**, virtual addrs are **64 bits**, and pages are **4 KB**

   8 bytes * 2^(64 – lg 4K) = 2^3*2^(64-12)=**2^55 byt**

How big is each page table?

Why ARE Page Tables so Large?



Need 1 entry per physical frame

But you are using very few of the entries

Many invalid PT entries

Format of linear page tables:

PFN	valid	protection
10	1	r-x
-	0	-
23	1	rw-
-	0	-
-	0	-
-	0	-
-	0	-
…many more invalid…		
-	0	-
-	0	-
-	0	-
-	0	-
28	1	rw-
4	1	rw-

how to avoid storing these?

BTW where is the code?

Invalid pages are not used but still are in page table

Avoid simple linear Page Tables

Use more complex page tables, instead of just big array

Any data structure is possible with software-managed TLB

- Hardware looks for vpn in TLB on every memory access
- If TLB does not contain vpn, TLB miss
  - Trap into OS and let OS find vpn->ppn translation
  - OS notifies TLB of vpn->ppn for future accesses

Approaches

1. Segmented Pagetables
2. Multi-level Pagetables
   - Page the page tables
   - Page the page tables of page tables...

valid PTEs are Contiguous

PFN	valid	prot
10	1	r-x
-	0	-
23	1	rw-
-	0	-
-	0	-
-	0	-
-	0	-
…many more invalid…		
-	0	-
-	0	-
-	0	-
-	0	-
28	1	rw-
4	1	rw-

how to avoid storing these?

Note "hole" in addr space: valids vs. invalids are clustered

How did OS avoid allocating holes in phys memory?

Segmentation

Combine Paging and Segmentation

Divide address space into segments (code, heap, stack)

- Segments can be variable length

Divide each segment into fixed-sized pages

Logical address divided into three portions

seg # (4 bits)	page number (8 bits)	page offset (12 bits)

Implementation

- Each segment has a page table
- Each segment tracks base (physical address) and bounds of **page table** for that segment

Quiz: Paging and Segmentation

seg # (4 bits)	page number (8 bits)	page offset (12 bits)

seg	base	bounds	R W
0	0x002000	0xff	1 0
1	0x000000	0x00	0 0
2	0x001000	0x0f	1 1

```
0x002070 read:
0x202016 read:
0x104c84 read:
0x210014 write:

0x203568 read:
```

. . .	
0x01f	0x001000
0x011	
0x003	
0x02a	
0x013	
. . .	
0x00c	0x002000
0x007	
0x004	
0x00b	
0x006	
. . .	

Quiz: Paging and Segmentation

seg # (4 bits)	page number (8 bits)	page offset (12 bits)

seg	base	bounds	R W
0	0x002000	0xff	1 0
1	0x000000	0x00	0 0
2	0x001000	0x0f	1 1

```
0x002070 read:
0x202016 read:
0x104c84 read:
0x210014 write:

0x203568 read:
```

Go to seg 0 get base
0x002000
02<=0xff ?
Yes go to entry here
And build address
0x004070

...	
0x01f	0x001000
0x011	
0x003	
0x02a	
0x013	
...	
0x00c	0x002000
0x007	
0x004	
0x00b	
0x006	
...	

Quiz: Paging and Segmentation

seg # (4 bits)	page number (8 bits)	page offset (12 bits)

seg	base	bounds	R W
0	0x002000	0xff	1 0
1	0x000000	0x00	0 0
2	0x001000	0x0f	1 1

. . .	
0x01f	0x001000
0x011	
0x003	
0x02a	
0x013	
. . .	
0x00c	0x002000
0x007	
0x004	
0x00b	
0x006	
. . .	

```
0x002070 read:   0x004070
0x202016 read:   0x003016
0x104c84 read:   err bound=0
0x210014 write:  err 0x10>0x0f
                 (exceeded bounds)

0x203568 read:   0x02a568
```

Advantages of Paging and Segmentation

Advantages of Segments

- Supports sparse address spaces
  - Decreases size of page tables
  - If segment not used, not needed for page table

Advantages of Pages

- No external fragmentation
- Segments can grow without any reshuffling
- Can run process when some pages are swapped to disk (next lecture)

Advantages of Both

- Increases flexibility of sharing
  - Share either single page or entire segment
  - How?

Disadvantages of Paging and Segmentation

Potentially large page tables (for each segment)

- Must allocate each page table contiguously
- More problematic with more address bits
- Page table size?
  - Assume 2 bits for segment, 18 bits for page number, 12 bits for offset

    Worst case (bounds register =2^18)
    Each page table is:
      = Number of entries * size of each entry
      = Number of pages * 4 bytes
      = 2^18 * 4 bytes = 2^20 bytes = 1 MB!!!

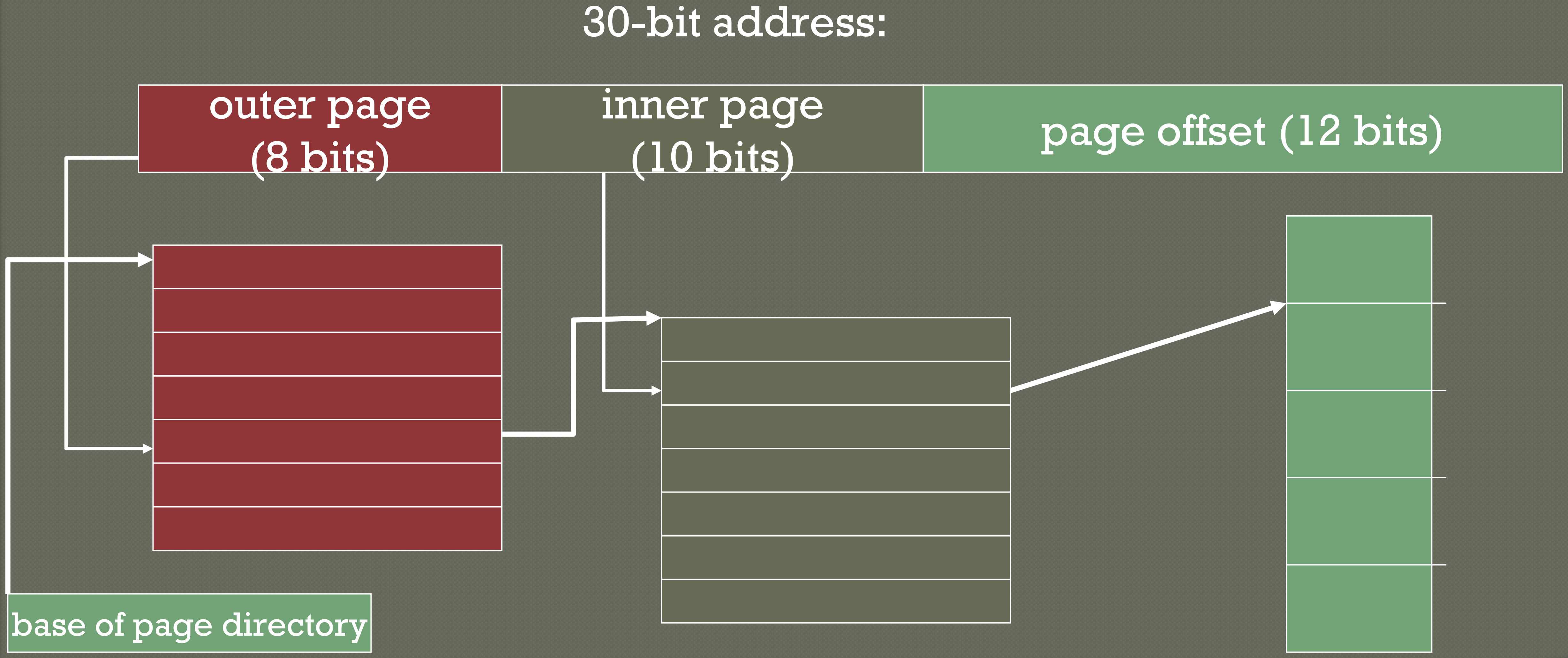
Other Approaches

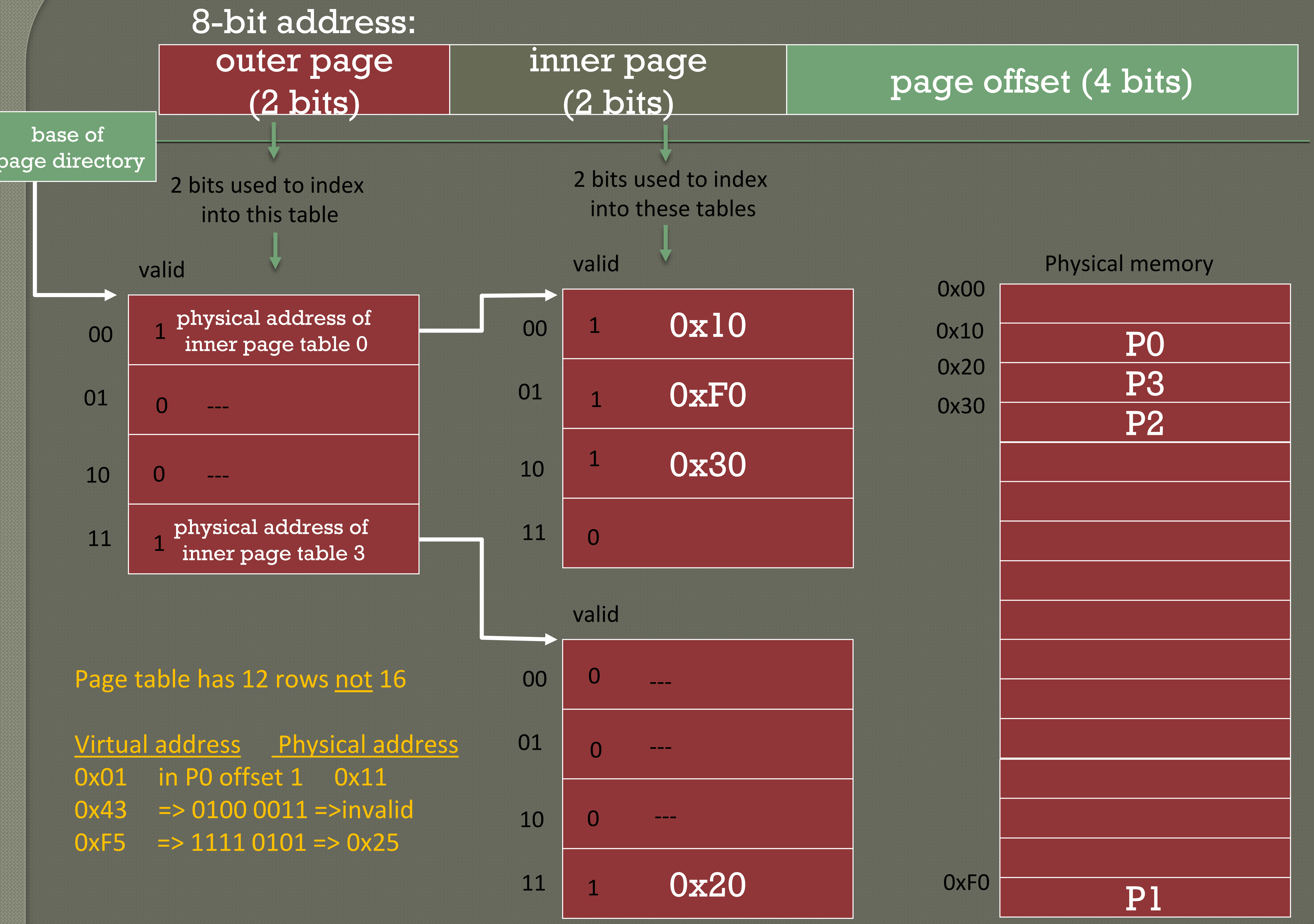
1. Segmented Pagetables
2. Multi-level Pagetables
   - Page the page tables
   - Page the pages of page tables…

3) Multilevel Page Tables

Goal: Allow page tables to be allocated non-contiguously
Idea: Page the page tables

- Creates multiple levels of page tables; outer level "page directory"
- Only allocate page tables for pages in use
- Used in x86 architectures (hardware can walk known structure)





Page table has 12 rows not 16

Virtual address		Physical address
0x01	in P0 offset 1	0x11
0x43	=> 0100 0011 =>invalid	
0xF5	=> 1111 0101 => 0x25	

Quiz: Multilevel

page directory

PPN	valid
0x3	1
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
0x92	1

page of PT (@PPN:0x3)

PPN	valid
0x10	1
0x23	1
-	0
-	0
0x80	1
0x59	1
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0

page of PT (@PPN:0x92)

PPN	valid
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
-	0
0x55	1
0x45	1

translate 0x01ABC

0x23ABC

translate 0x00000

0x10000

translate 0xFEED0

0x55ED0

20-bit address:

outer page (4 bits)	inner page (4 bits)	page offset (12 bits)

QUIZ: Address format for multilevel Paging

30-bit address:

outer page	inner page	page offset (12 bits)

How should logical address be structured?

- How many bits for each paging level?

Goal?

- Each page table fits within a page
- PTE size * number PTE = page size
  - Assume PTE size = 4 bytes
  - Page size = 2^12 bytes = 4KB ← Want entire page table to fit in 4kb
  - 2^2 bytes * number PTE = 2^12 bytes
  - → number PTE = 2^10 ← can have 1024 4byte rows
- → # bits for selecting inner page = 10

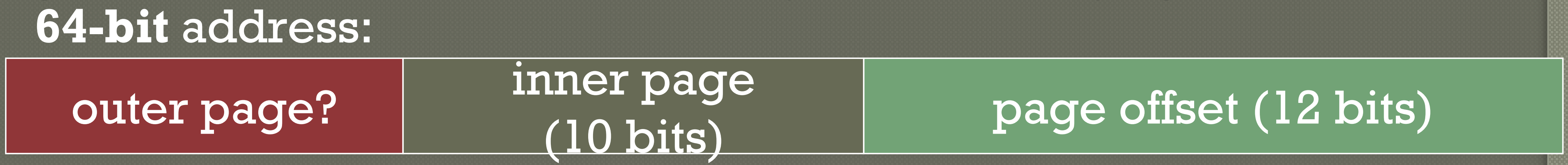
Remaining bits for outer page:

- 30 – 10 – 12 = 8 bits

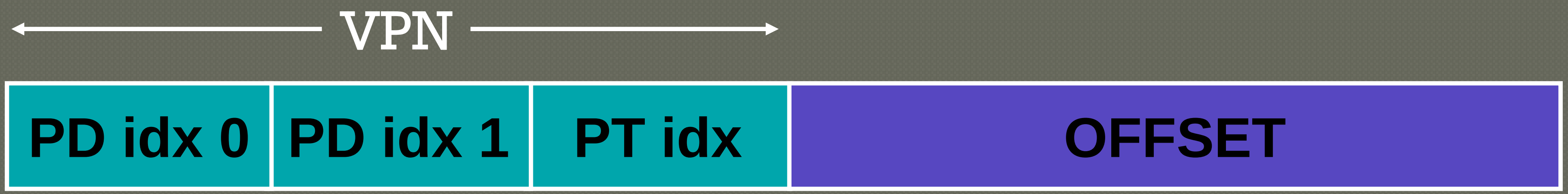
Problem with 2 levels?

Problem: page directories (outer level) may not fit in a page

Solution:



- Split page directories into pieces
- Use another page dir to refer to the page dir pieces.



How large is virtual address space with 4 KB pages, 4 byte PTEs, each page table fits in page given 1, 2, 3 levels? Assume 10 bits/level (1K)

4KB / 4 bytes → 1K entries per level

1 level: 1K * 4K = **2^22** = 4 MB

2 levels: 1K * 1K * 4K = **2^32** ≈ 4 GB

3 levels: 1K * 1K * 1K * 4K = **2^42** ≈ 4 TB

QUIZ: FULL SYSTEM WITH TLBS

On TLB miss: lookups with more levels more expensive

How much does a miss cost?

ASID	VPN	PFN	Valid
211	0xbb	0x91	1
211	0xff	0x23	1
122	0x05	0x91	1
211	0x05	0x12	0

Assume 3-level page table
Assume 256-byte pages (8 bits)
Assume 16-bit addresses (so 8 bits for 3 levels)
Assume ASID of current process is 211

How many physical accesses for each instruction? (Ignore previous ops changing TLB)

(a) 0xAA10: movl 0x1111, %edi
0xaa: (TLB miss -> 3 for addr trans) + 1 instr fetch
0x11: (TLB miss -> 3 for addr trans) + 1 movl

Total: 8

(b) 0xBB13: addl $0x3, %edi
0xbb: (TLB hit -> 0 for addr trans) + 1 instr fetch from 0x9113

Total: 1

(c) 0x0519: movl %edi, 0xFF10
0x05: (TLB miss -> 3 for addr trans) + 1 instr fetch
0xff: (TLB hit -> 0 for addr trans) + 1 movl into 0x2310

Total: 5

Summary:
Better PAGE TABLES

Problem:
Simple linear page tables require too much contiguous memory
If Hardware handles TLB miss, page tables must follow specific format

- Multi-level page tables used in x86 architecture
- Each page table fits within a page

Next Topic:
What if desired address spaces do not fit in physical memory?