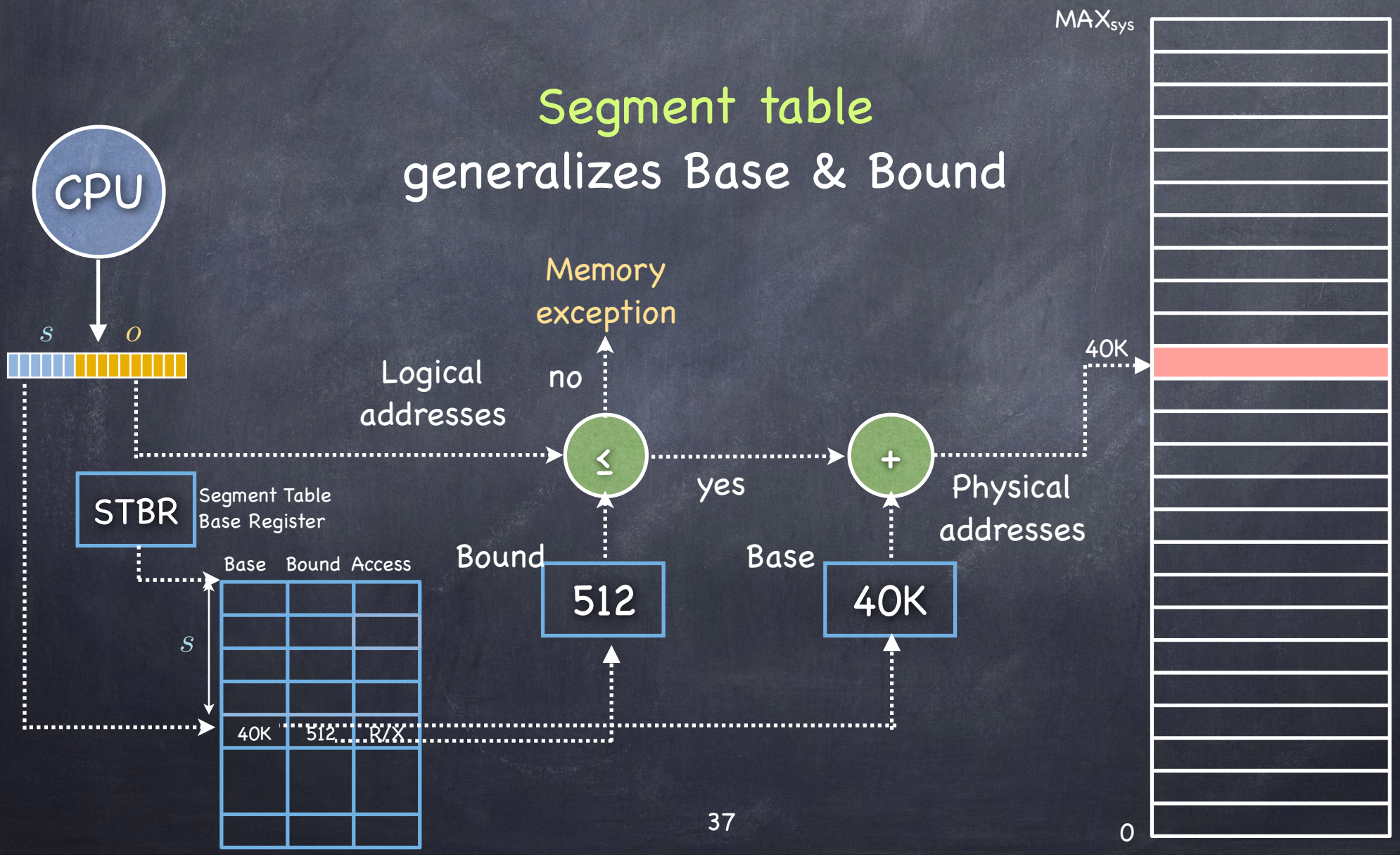
Segment Table

- Use s bits to index to the appropriate row of the segment table

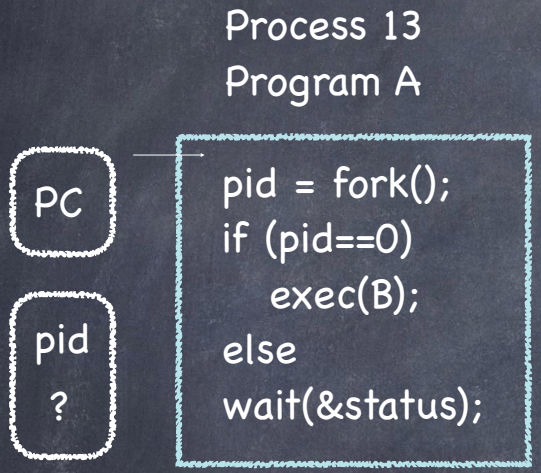
	Base	Bound (Max 4k)	Access
$Code_{00}$	32K	2K	Read/Execute
$Heap_{01}$	34K	3K	Read/Write
$Stack_{10}$	28K	3K	Read/Write

- Segments can be shared by different processes
  - use protection bits to determine if shared Read only (maintaining isolation) or Read/Write (if shared, no isolation)
    - processes can share code segment while keeping data private

Implementing Segmentation



Revisiting fork()



Revisiting fork()

Process 13
Program A

PC

pid
?

```
pid = fork();
if (pid==0)
    exec(B);
else
wait(&status);
```

Process 13
Program A

PC

pid
14

```
pid = fork();
if (pid==0)
    exec(B);
else
wait(&status);
```

Process 14
Program B

PC

pid
0

```
main() {
pid = fork();
if (pid==0)
    ...
    exec(B);
    exit(3);
else
}
wait(&status);
```

Revisiting fork()

Process 13
Program A

PC

pid
?

```
pid = fork();
if (pid==0)
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wait(&status);
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Process 13
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14

```
pid = fork();
if (pid==0)
    exec(B);
else
wait(&status);
```

Status
3

Process 14
Program B

PC

```
main() {
    ...
  exit(3);
}
```

Revisiting fork()

- Copying an entire address space can be costly…
  - especially if you proceed to obliterate it right away with exec()!

Revisiting fork(): Segments to the Rescue

- Instead of copying entire address space, copy just segment table (the VA->PA mapping)

	Base	Bound	Access
Code	32K	2K	RX
Heap	34K	3K	RW
Stack	28K	3K	RW

Parent

	Base	Bound	Access
Code	32K	2K	RX
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Stack	28K	3K	RW

Child

- but change all writeable segments to Read only

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	Base	Bound	Access
Code	32K	2K	RX
Heap	34K	3K	R
Stack	28K	3K	R

Child

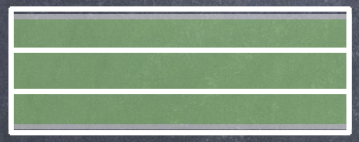
- but change all writeable segments to Read only
- Segments in VA spaces of parent and child point to same locations in physical memory

Copy on Write (COW)

- When trying to modify an address in a COW segment:
  - exception!
    - exception handler copies just the affected segment, and changes both the old and new segment back to writeable
- If exec() is immediately called, only stack segment is copied!
  - it stores the return value of the fork() call, which is different for parent and child

Managing Free space

- Many segments, different processes, different sizes
- OS tracks free memory blocks ("holes")
  - Initially, one big hole
- Many strategies to fit segment into free memory (think "assigning classrooms to courses")
  - First Fit: first big-enough hole
  - Next Fit: Like First Fit, but starting from where you left off
  - Best Fit: smallest big-enough hole
  - Worst Fit: largest big-enough hole



External Fragmentation

- Over time, memory can become full of small holes
  - Hard to fit more segments
  - Hard to expand existing ones
- Compaction
  - Relocate segments to coalesce holes

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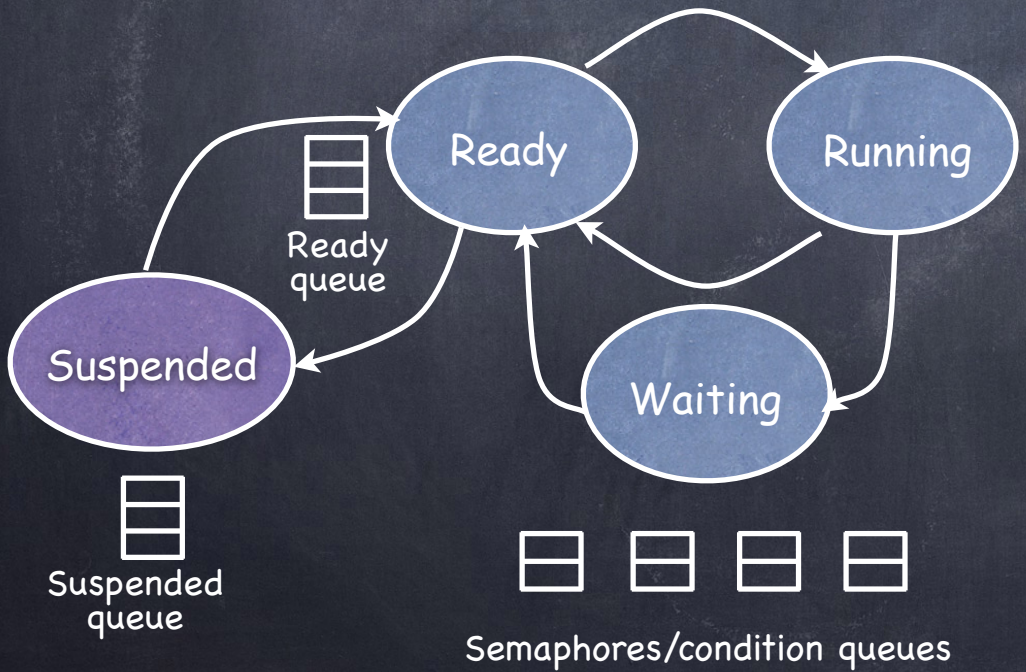
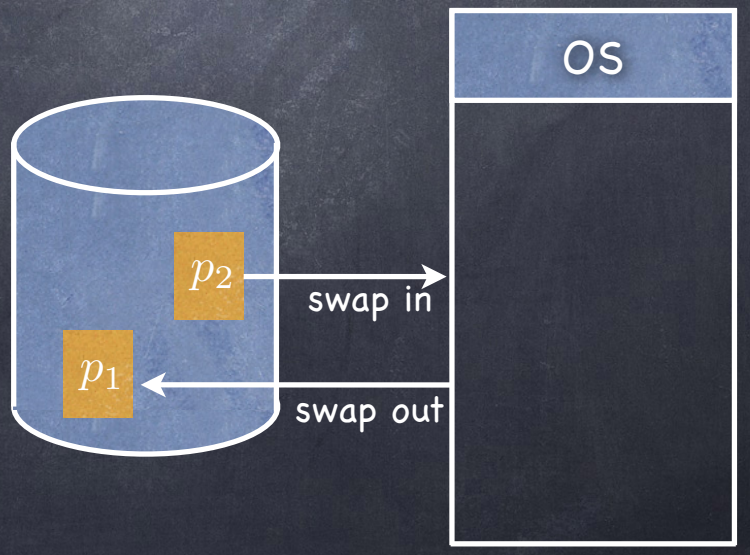
- Over time, memory can become full of small holes
  - Hard to fit more segments
  - Hard to expand existing ones
- Compaction
  - Relocate segments to coalesce holes
    - Copying eats up a lot of CPU time!
      - if 4 bytes in 10ns, 8 GB in 20s!
- But what if a segment wants to grow?

Eliminating External Fragmentation: Swapping

- Preempt processes and reclaim their memory
- Move images of suspended processes to backing store

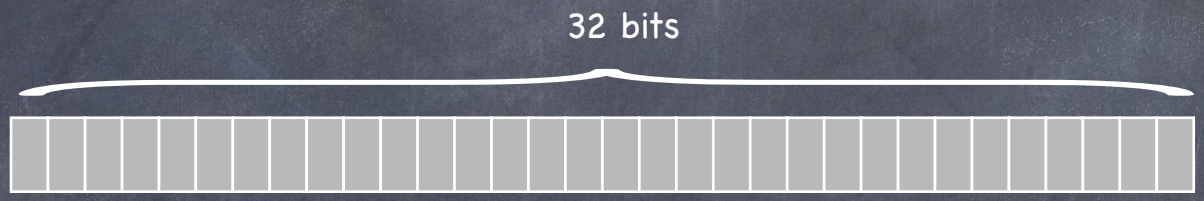




Paging

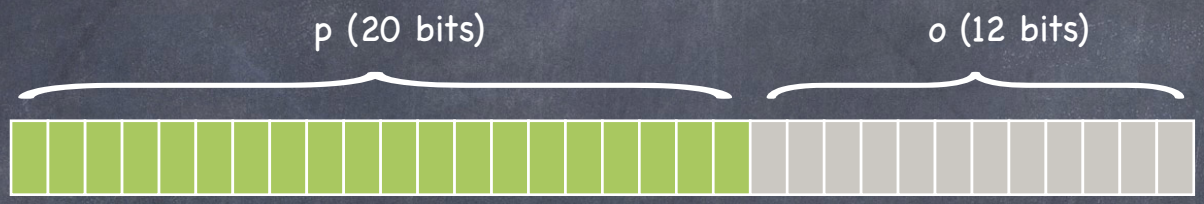
- Allocate VA & PA memory in chunks of the same, fixed size (pages and frames, respectively)
- Adjacent pages in VA (say, within the stack) need not map to contiguous frames in PA!
  - free frames can be tracked using a simple bitmap
    - 00111110011110111110000 one bit/frame
  - no more external fragmentation!
  - but now internal fragmentation (you just can't win...)
    - when memory needs are not a multiple of a page
    - typical size of page/frame: 4KB to 16KB

Virtual address



- Interpret VA as comprised of two components
  - page: which page?
  - offset: which byte within that page?

Virtual address



- Interpret VA as comprised of two components
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    - no. of bits specifies no. of pages are in the VA space
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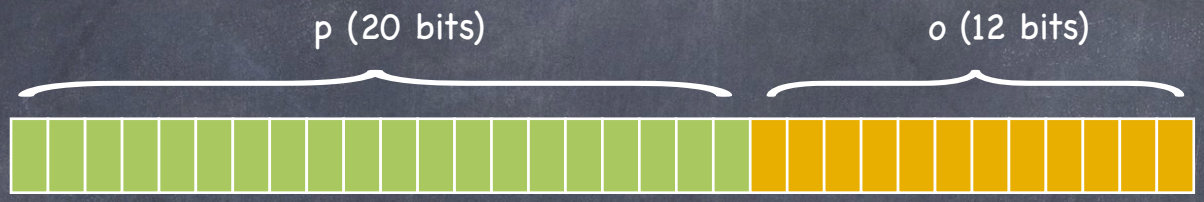
Virtual address



- Interpret VA as comprised of two components
  - page: which page?
    - no. of bits specifies no. of pages are in the VA space
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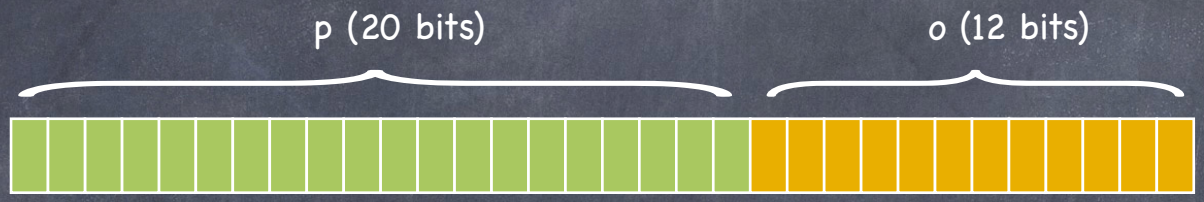
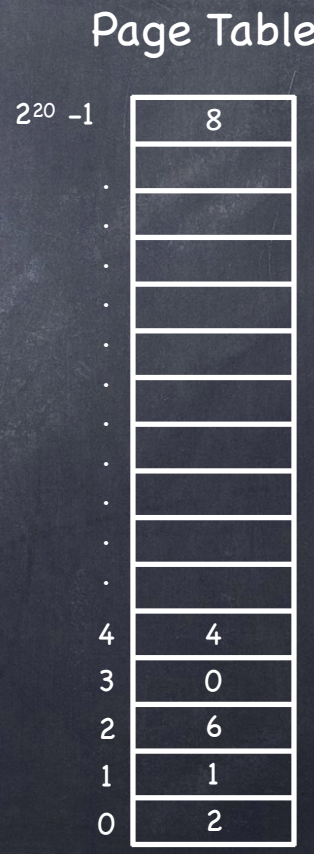
    - no. of bits specifies size of page/frame

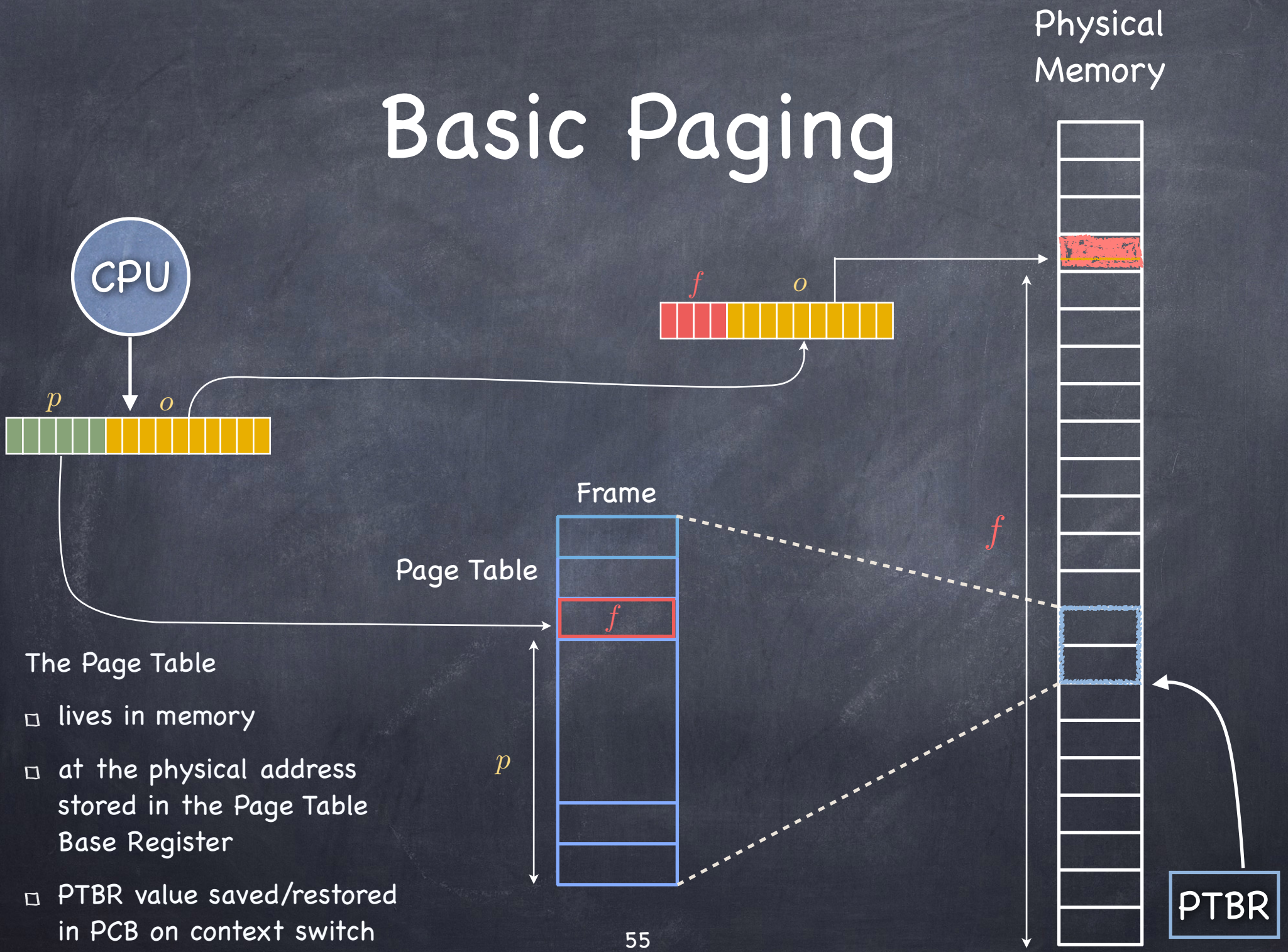
Virtual address



- To access a byte
  - extract page number
  - map that page number into a frame number using a page table
    - Note: not all pages may be mapped to frames
  - extract offset
  - access byte at offset in frame



Basic Paging



The Page Table

- lives in memory
- at the physical address stored in the Page Table Base Register
- PTBR value saved/restored in PCB on context switch

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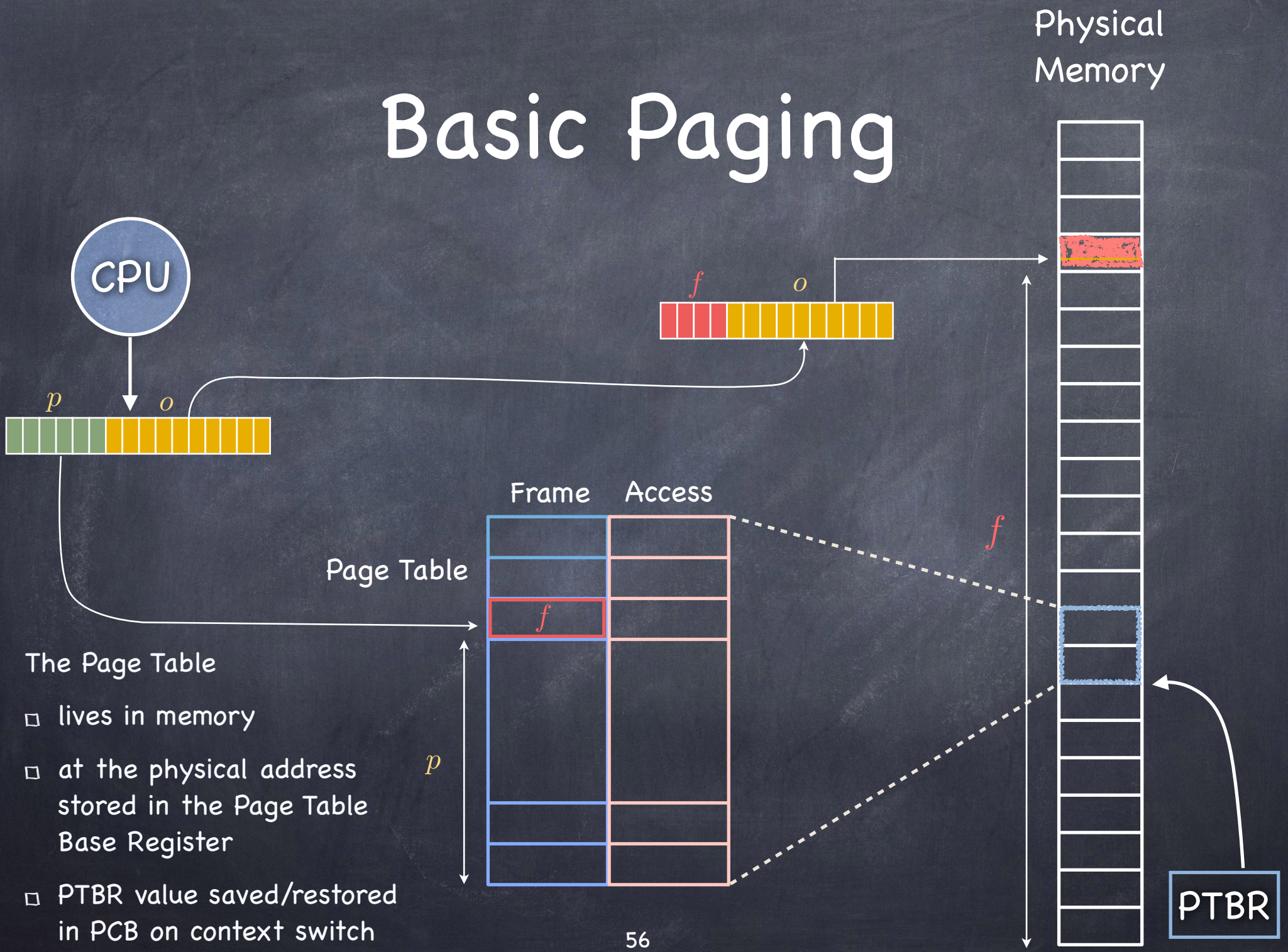

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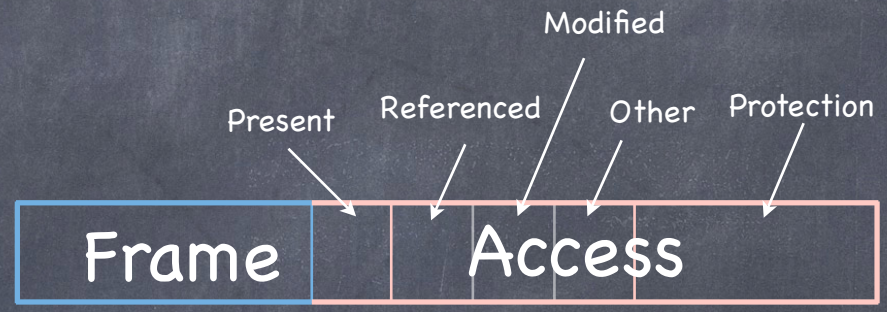
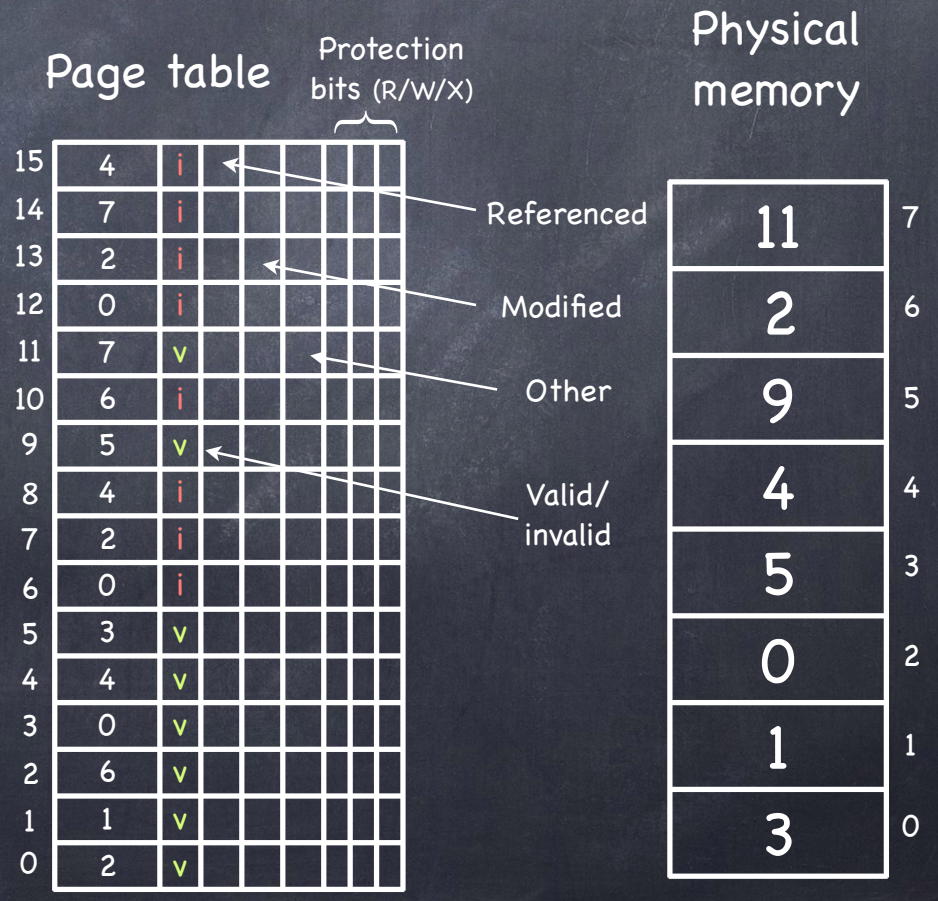
Page Table Entries

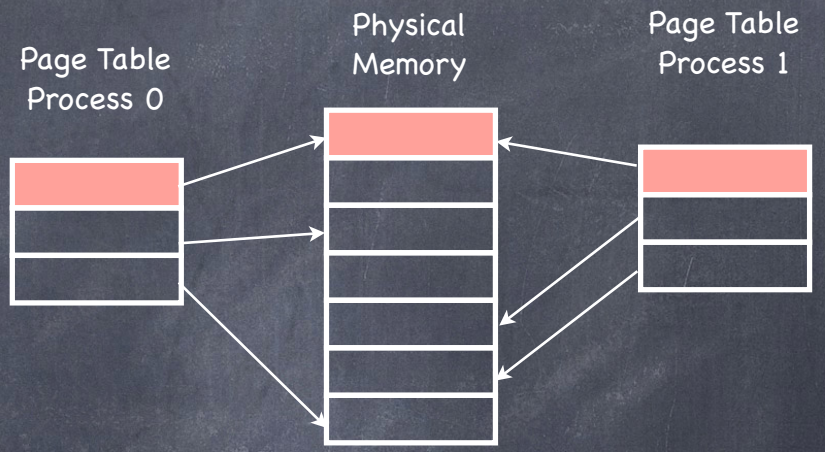
- Frame number
- Valid/Invalid (Present) bit
  - Set if entry stores a valid mapping. If not, and accessed, page fault
- Referenced bit
  - Set if page has been referenced
- Modified bit
  - Set if page has been modified
- Protection bits (R/W/X)





Sharing

- Processes share a page by each mapping a page of their own virtual address space to the same frame
  - Fine tuning using protection bits (RWX)
- We can refine COW to operate at the granularity of pages
  - on fork, mark all pages in page table Read only

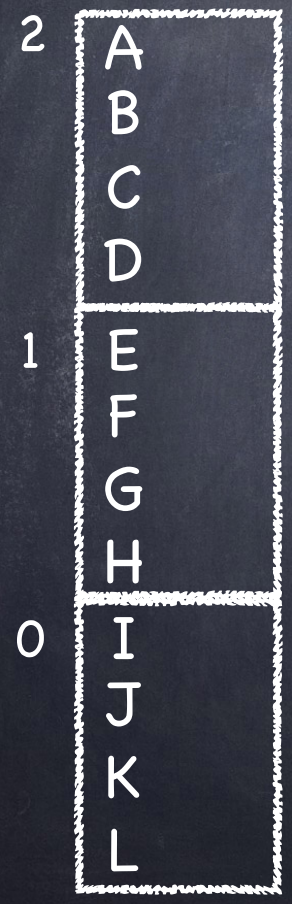


  - on write:
    - page fault
    - allocate new frame
    - copy page
    - mark both pages R/W

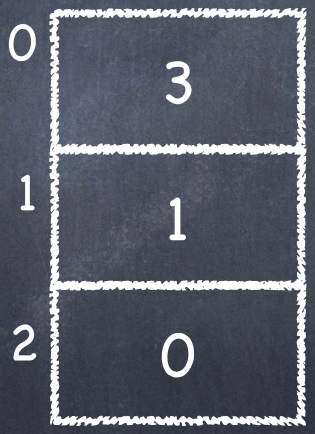
Example

Page size: 4 bytes

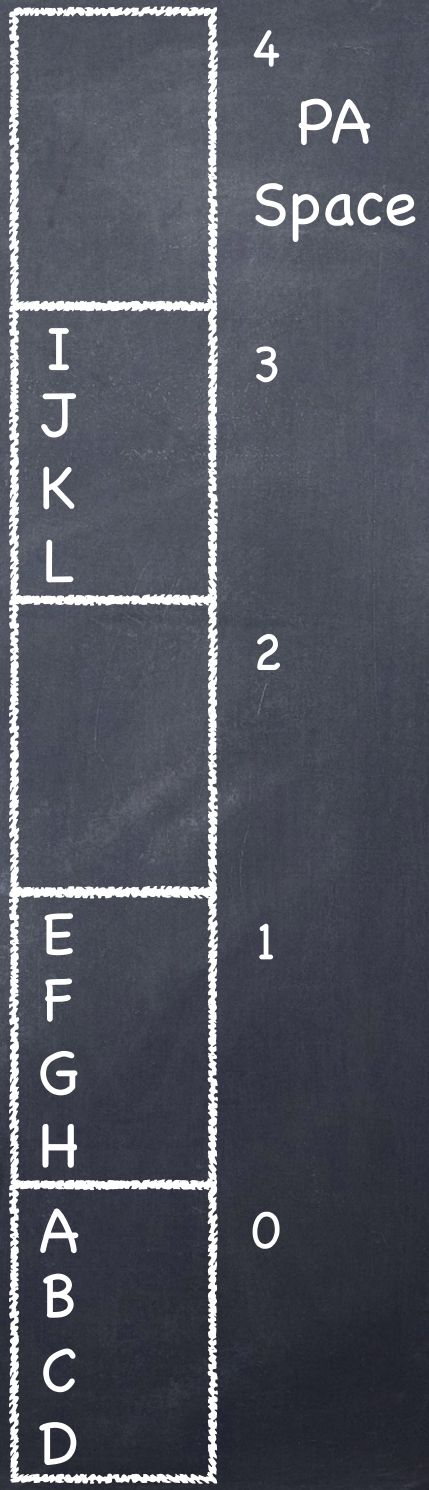
VA Space



Page Table



PA Space



Space overhead

- Two sources, in tension:
  - data structure overhead (the Page Table itself)
  - fragmentation
    - How large should a page be?

Overhead for paging:

(#entries x sizeofEntry) + (#"segments" x pageSize/2) =

= ((VA_Size/pagesize) x sizeofEntry) + (#"segments" x pageSize/2)

  - Size of entry
    - enough bits to identify physical page ($\log_2$ (PA_Size / page size))
    - should include control bits (present, dirty, referenced, etc)
    - usually word or byte aligned

Computing paging overhead

- 1 MB maximum VA, 1 KB page, 3 segments (program, stack, heap)
  - $((2^{20} / 2^{10}) \times \text{sizeofEntry}) + (3 \times 2^9)$
  - If I know PA is 64 KB then sizeofEntry = sizeofFrameNo + #ofAccessBits= 6 (2^6 frames) + #ofAccessBits
    - if 7 access bits, byte aligned size of entry: 16 bits

What's not to love?

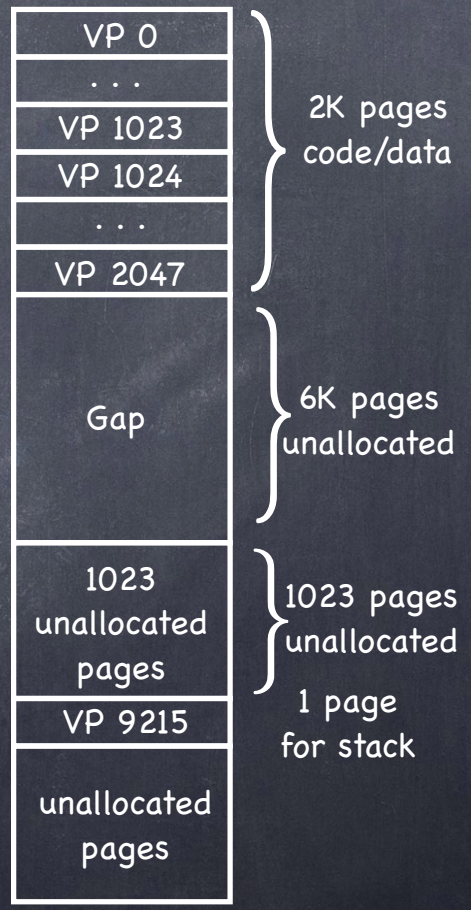
- Space overhead
  - With a 64-bit address space, size of page table can be huge
- Time overhead
  - Accessing data now requires two memory accesses
    - must also access page table, to find mapped frame

Reducing the Storage Overhead of Page Tables

- Size of the page table for a machine with 64-bit addresses and a page size of 4KB?
  - an array of 2^{52} entries!
- Good news
  - most space is unused
- Use a better data structure to express the Page Table
  - a tree!

Example

- 32 bit address space
- 4Kb pages
- 4 bytes PTE



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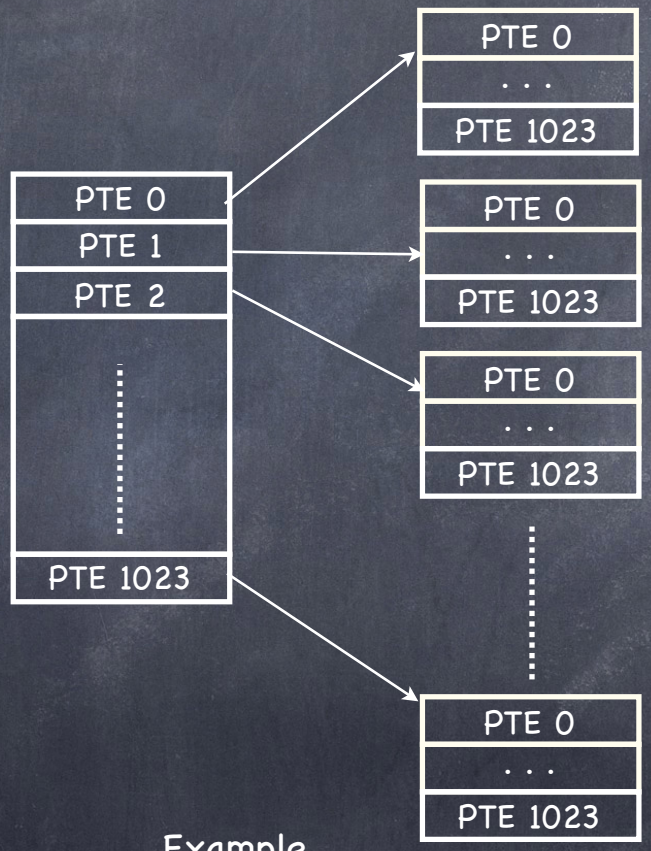

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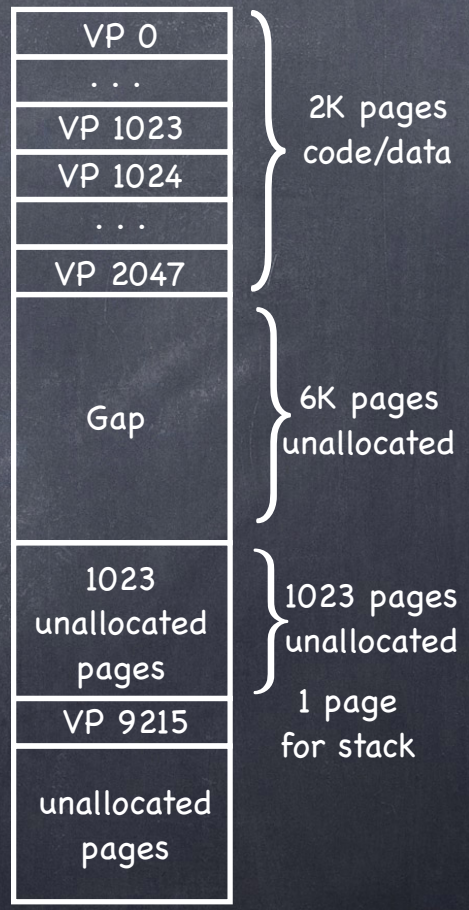

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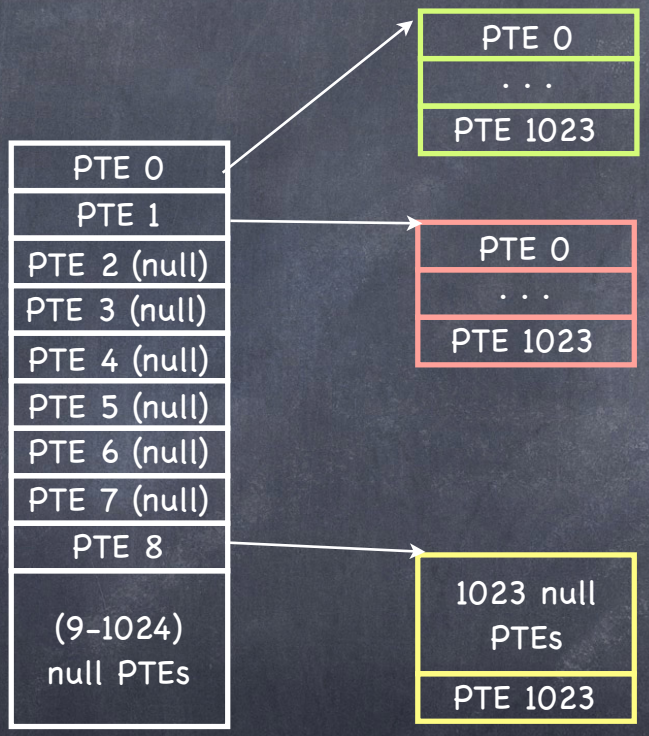

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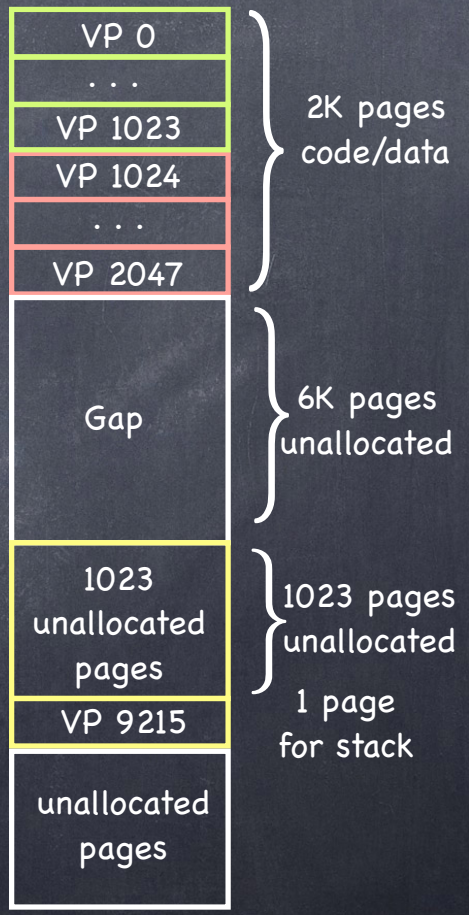
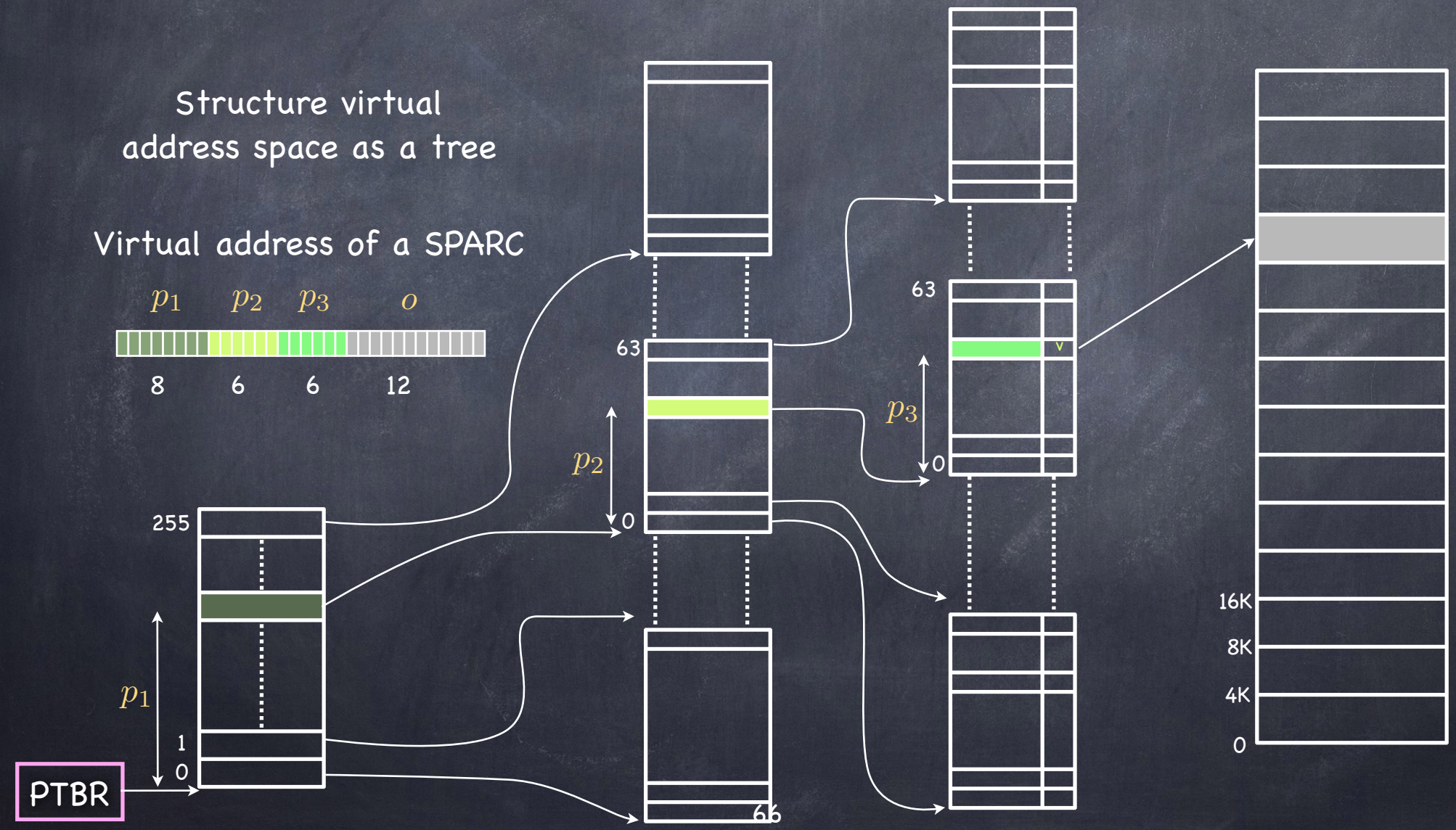
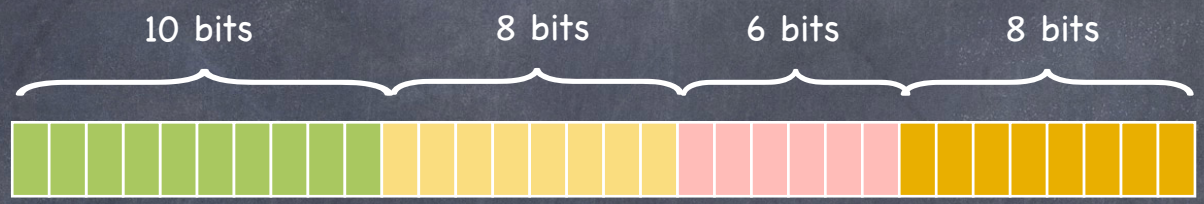


Page Table

Multi-level Paging

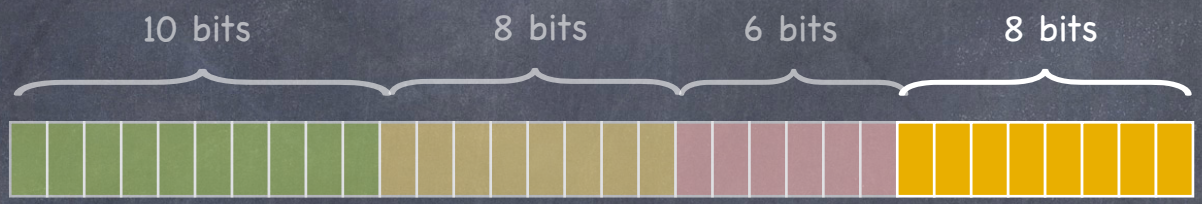


Example



- What is the page size?

Example



- What is the page size? Page size is 256 bytes (2^8)
- What is the Page Table size for a process that uses 256 contiguous KB of its VAS starting at address 0? [Assume each PTE is 2 bytes]
  - if we used a linear representation of the page table:

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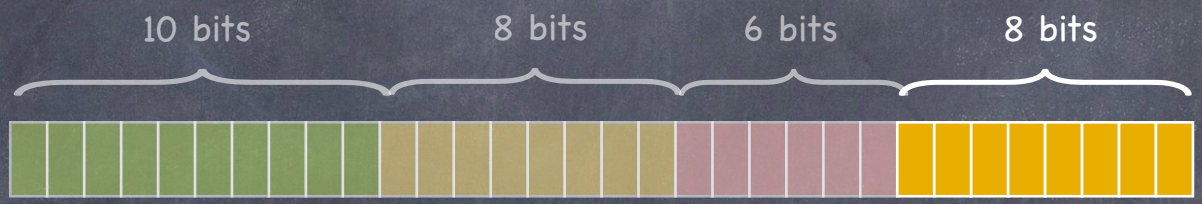

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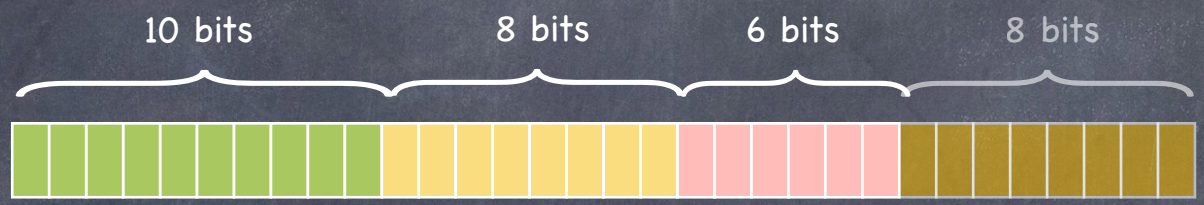

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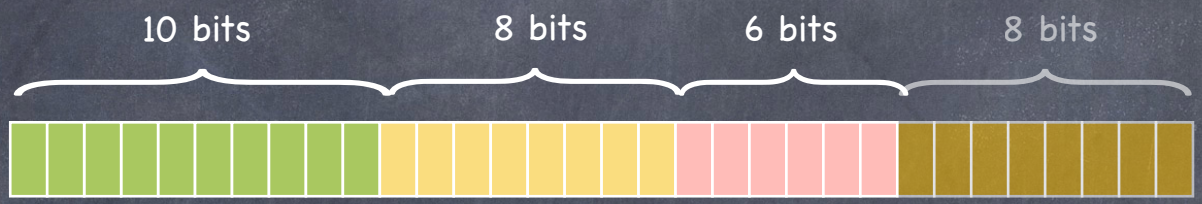
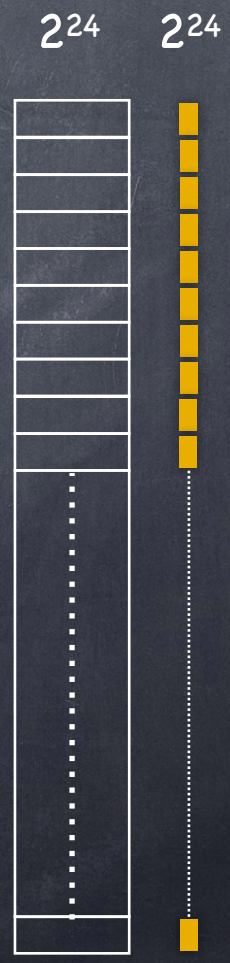
    - Page Table has 2^{24} entries
    - PT Size: 2^{24} x 2 bytes = 2^{25} bytes = 32MB

Example





- What is we use a tree?
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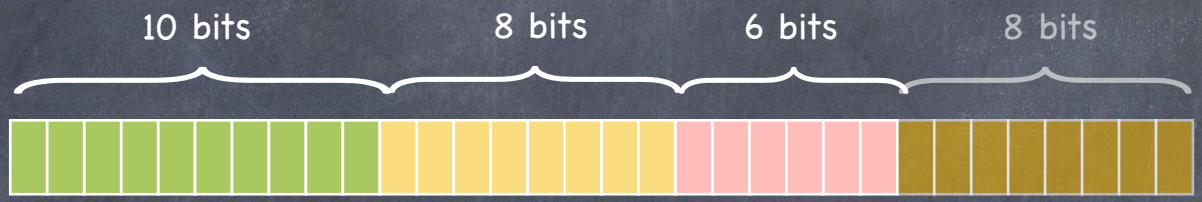

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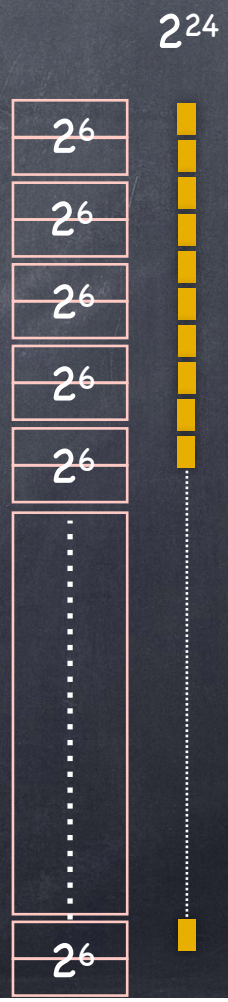

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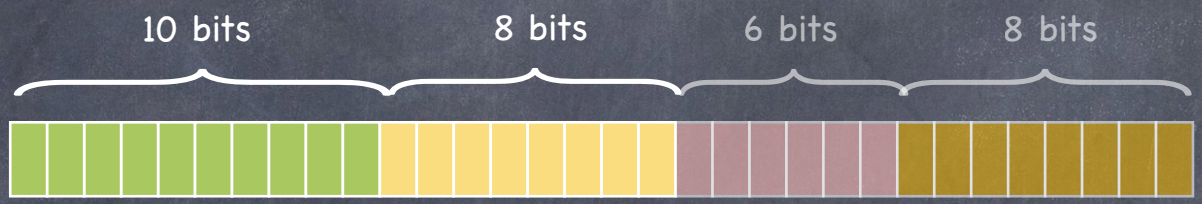

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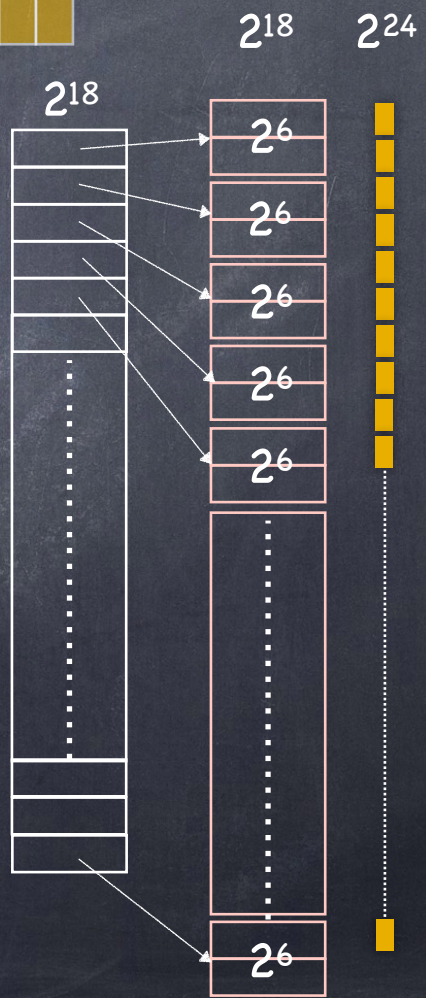

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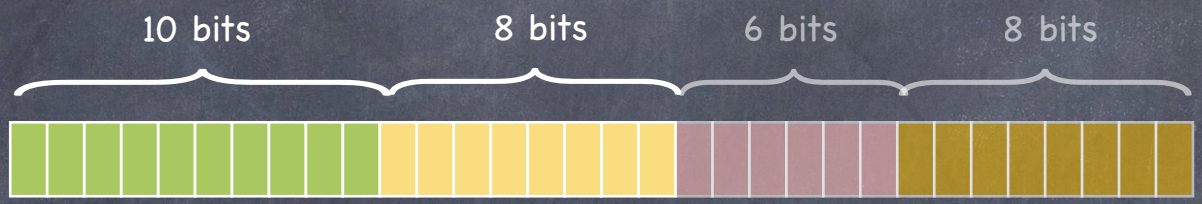

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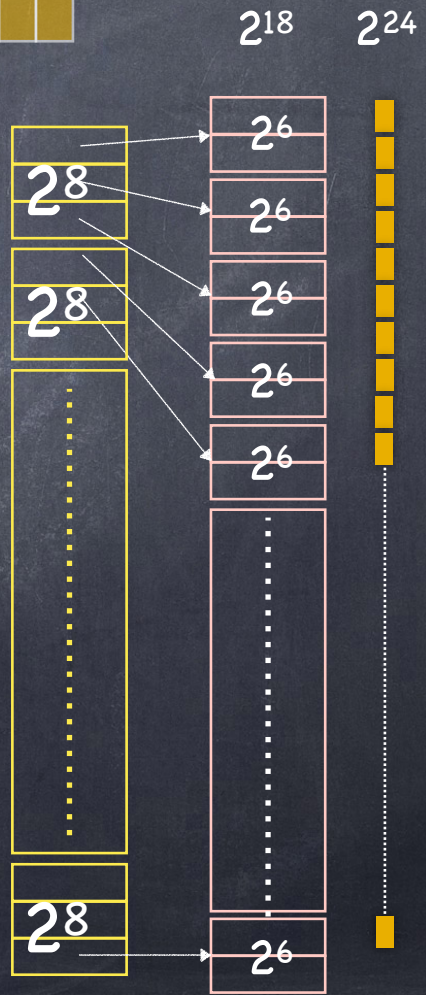

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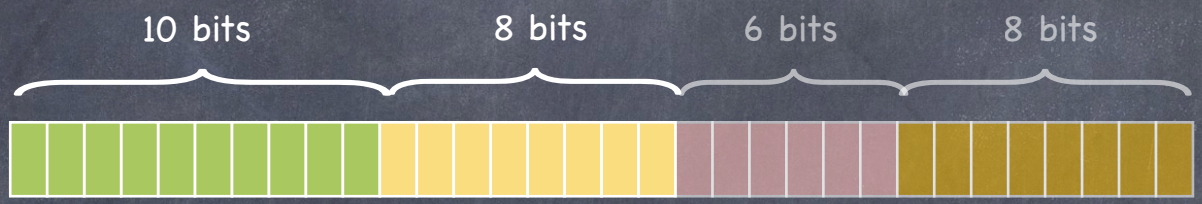

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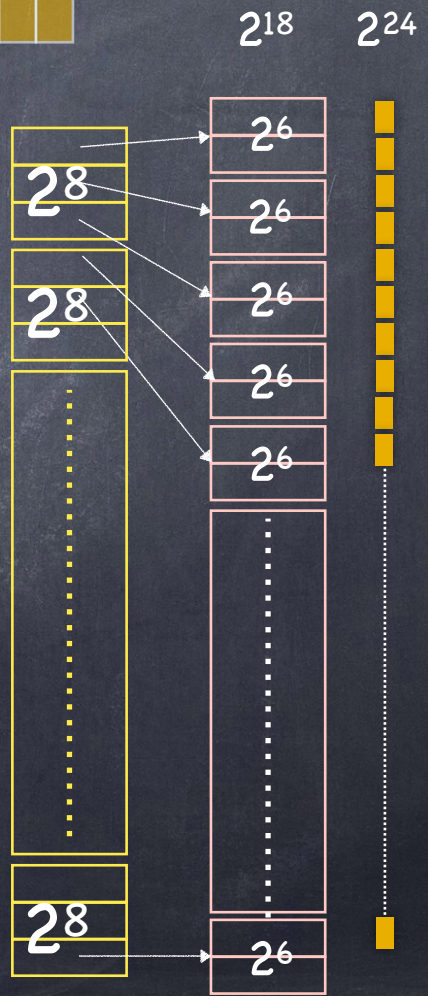
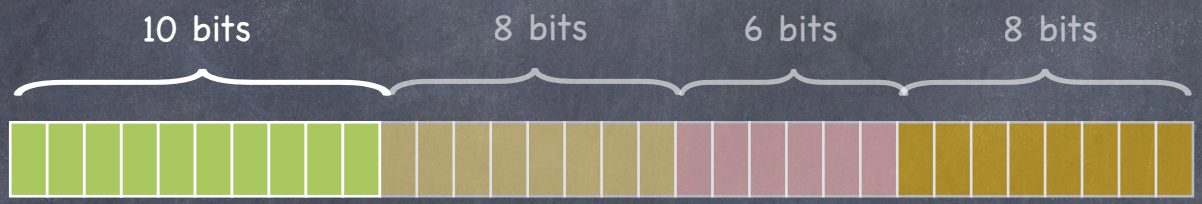
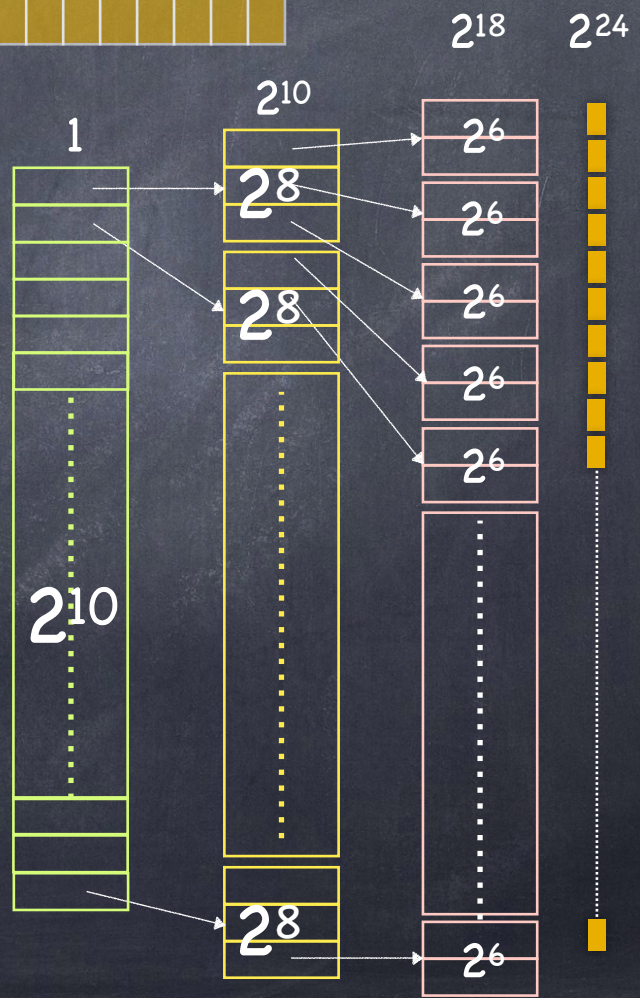


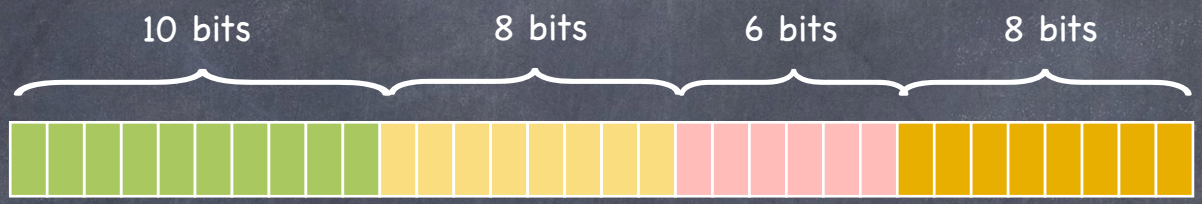
Example



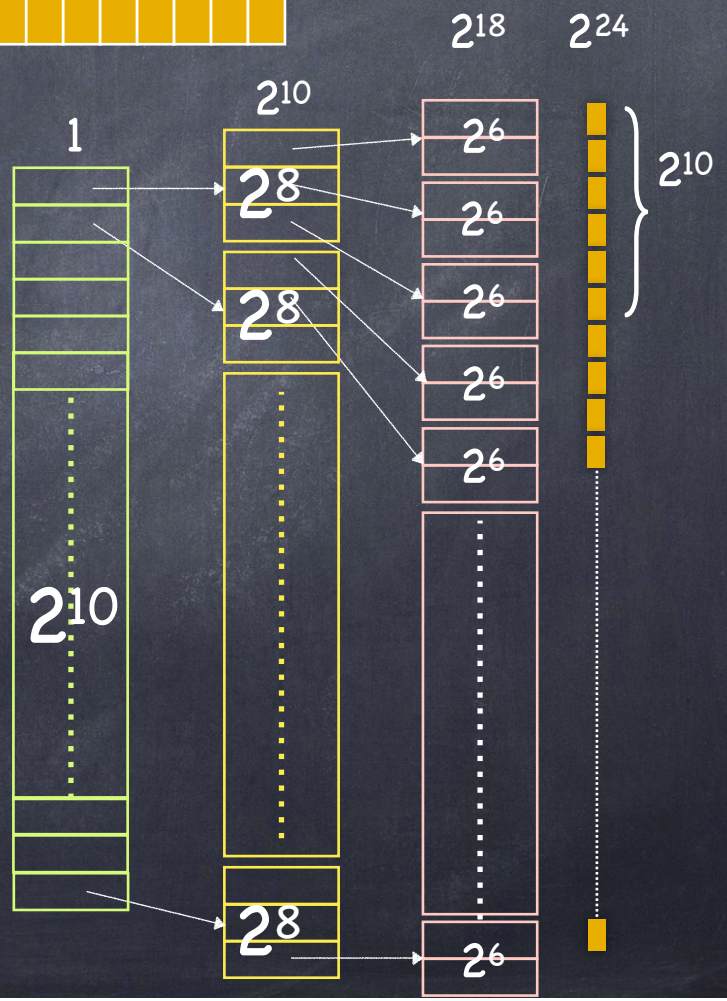
- What is we use a tree?
  - We still need to account for 2^{24} pages...
  - ...but we are going to partition the PT in a sequence of chunks, each with 2^6 entries
  - we'll need an index with 2^{18} entries...
  - ...which we'll partition in chunks of 2^8 entries
  - We'll need an index of 2^{10}



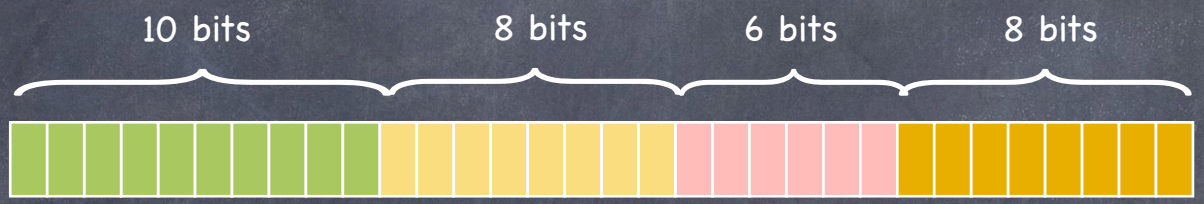
Example



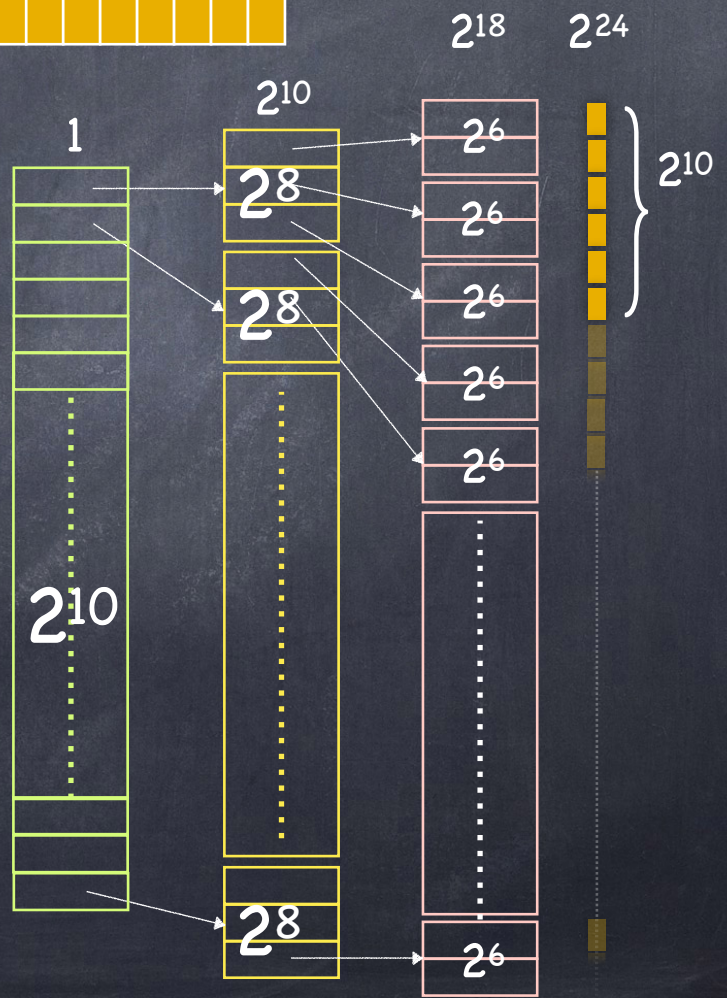
- Are we better off?
  - The number of PT entries now is $(2^6 \times 2^{18}) + (2^{10} \times 2^8) + 2^{10} > 2^{24}$!!
  - But we only need the portion of the tree needed to map the first 1K (2^{10}) pages!



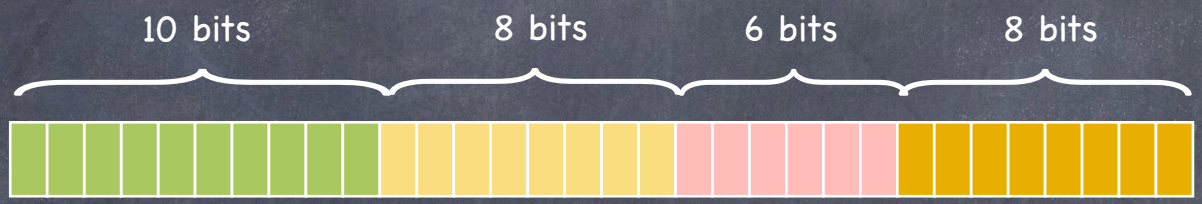
Example



- How many chunks of size 2^6 are needed to hold 2^{10} PTEs of consecutive pages starting at 0?
  - $2^{10}/2^6 = 2^4 = 16$



Example



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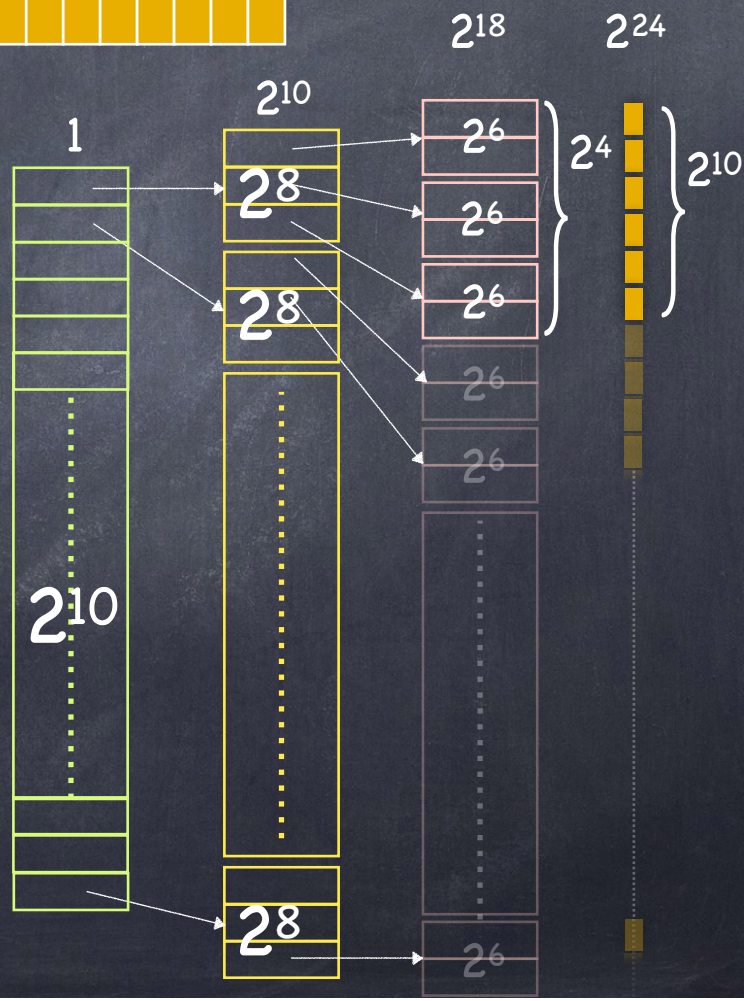
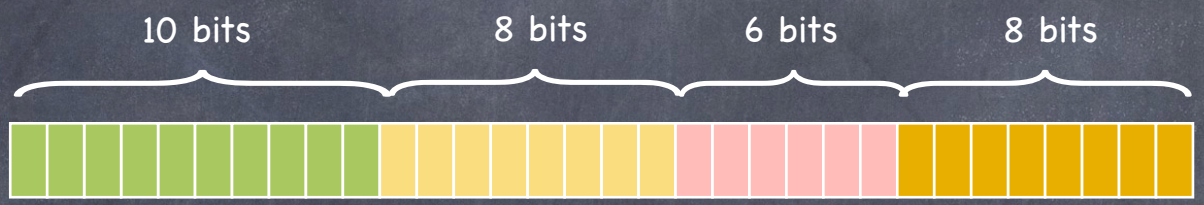
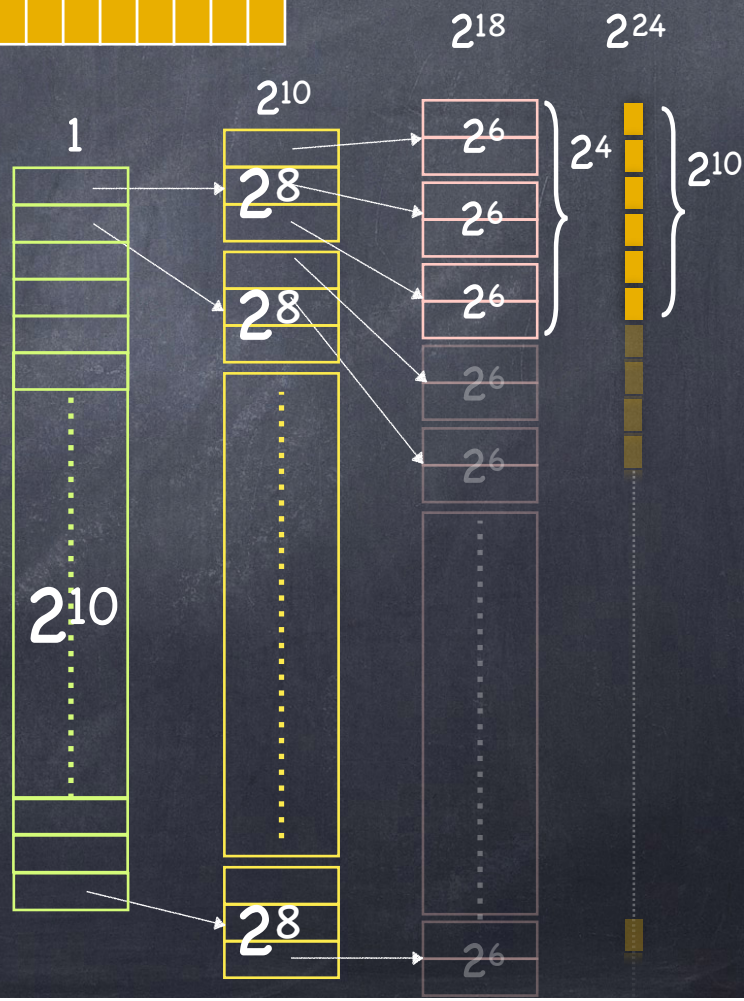


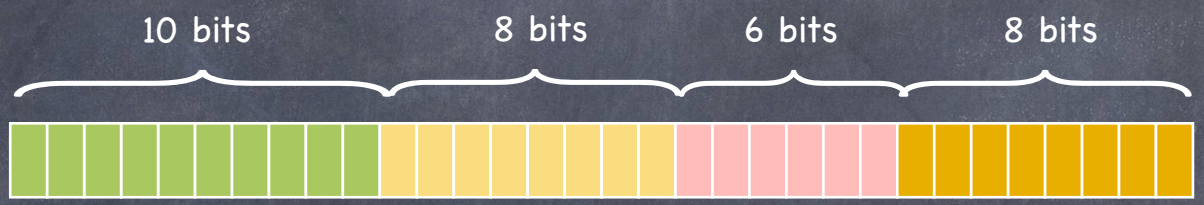
Example



- How many chunks of size 2^6 are needed to hold 2^{10} PTEs of consecutive pages starting at 0?
  - $2^{10}/2^6 = 2^4 = 16$
- How many chunks of size 2^8 are needed to hold pointers to 16 pink chunks?
  - 1



Example



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  - 1
- So, if each PTE is 2 bytes, the PT takes
  - 2 x (1 x 1024 + 1 x 256 + 16 x 64) = 4608 bytes