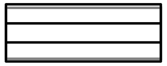
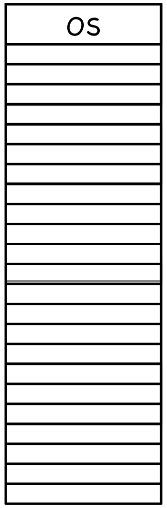
# Managing Free space

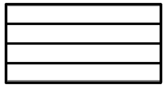
- Many segments, different processes, different sizes
- OS tracks free memory blocks ("holes")
  - Initially, one big hole
- Many strategies to fit segment into free memory (think "assigning classrooms to courses")
  - First Fit: first big-enough hole
  - Next Fit: Like First Fit, but starting from where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

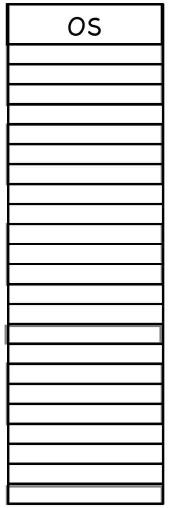




# External Fragmentation

- 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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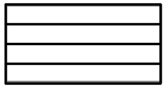
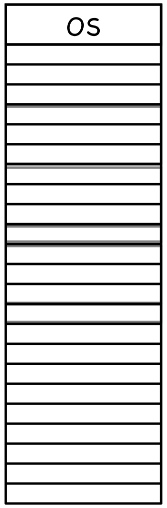
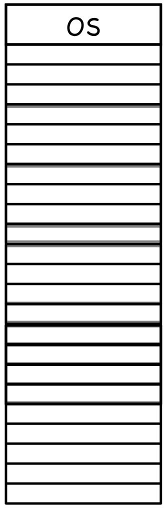




# External Fragmentation

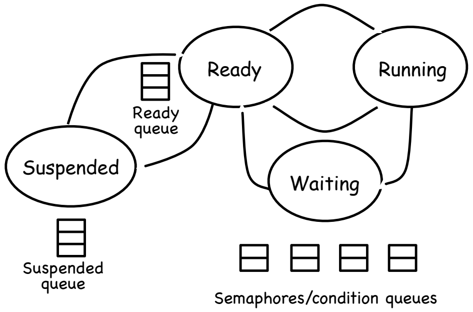
- Over time, memory can become full of small holes
  - Hard to fit more segments
  - Hard to expand existing ones
- Compaction
  - Relocate segments to coalesce holes
    - Copying eats up a lot of CPU time!
      - if 4 bytes in 10ns, 8 GB in 20s!
- But what if a segment wants to grow?

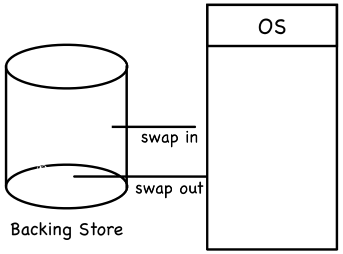


# Eliminating External Fragmentation: Swapping

- Preempt processes and reclaim their memory

- Move images of suspended processes to swap space on backing store

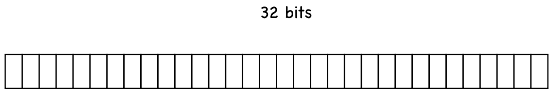




# Paging

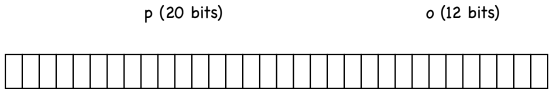
- Allocate VA & PA memory in fixed-sized chunks (pages and frames, respectively)
  - free frames can be tracked using a simple bitmap
    - 0011111001111011110000 one bit/frame
  - no more external fragmentation!
  - but now internal fragmentation (you just can't win…)
    - when memory needs are not a multiple of a page
    - typical size of page/frame: 4KB to 16KB
- Adjacent pages in VA (say, within the stack) need not map to contiguous frames in PA!

# Virtual address



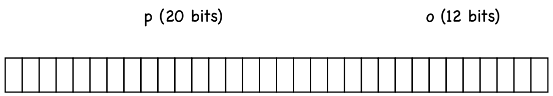
- Interpret VA as comprised of two components
  - page: which page?
  - offset: which byte within that page?

# Virtual address



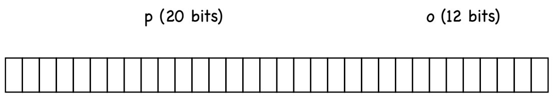
- Interpret VA as comprised of two components
  - page: which page?
    - no. of bits specifies no. of pages in VA space
  - offset: which byte within that page?

# Virtual address



- Interpret VA as comprised of two components
  - page: which page?
    - no. of bits specifies no. of pages in VA space
  - offset: which byte within that page?
    - no. of bits specifies size of page/frame

# Virtual address

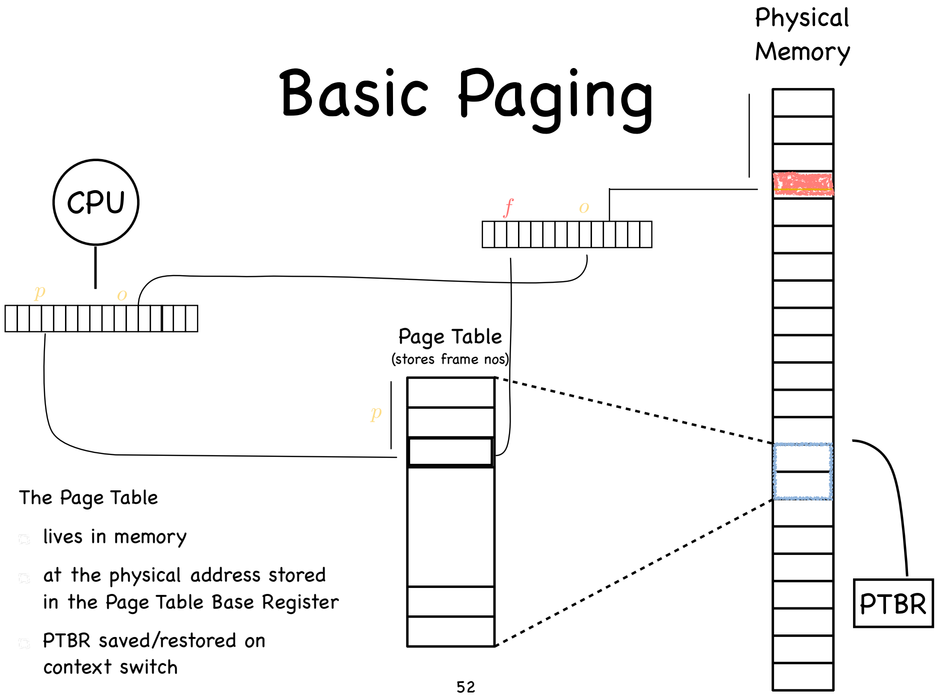


- To access a byte
  - extract page number
  - map that page number into a frame number using a page table
  - extract offset
  - access byte at offset in frame

Page Table

| | |
|---|---|
| 0 | 2 |
| 1 | 1 |
| 2 | 6 |
| 3 | 0 |
| 4 | 4 |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| . | |
| $2^{20} - 1$ | 8 |

# Basic Paging

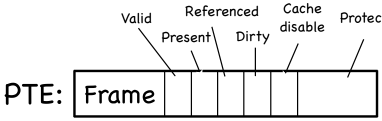


The Page Table

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

# Page Table Entries

- Frame number
- Valid/Invalid bit
  - Set if process can reference that portion of VA space
- Present bit
  - Set if page is mapped to a frame
- Referenced bit
  - Set if page has been referenced
- Dirty bit
  - Set if page has been modified
- Cache disable bit
  - Set if page can't be cached
- Protection bits (R/W/X)



Page table

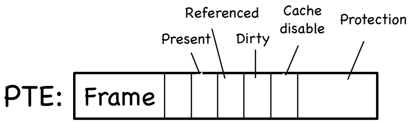
| | Frame # | V | P | R | D | C | Protection bits (R/W/X) | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | 1 | 1 | | | | | | |
| 1 | | 1 | 1 | | | | | | |
| 2 | | 1 | 1 | | | | | | |
| 3 | | 1 | 1 | | | | | | |
| 4 | | 1 | 1 | | | | | | |
| 5 | | 1 | 1 | | | | | | |
| 6 | | 0 | 0 | | | | | | |
| 7 | | 0 | 0 | | | | | | |
| 8 | | 0 | 0 | | | | | | |
| 9 | | 1 | 1 | | | | | | |
| 10 | | 1 | 0 | | | | | | |
| 11 | | 1 | 1 | | | | | | |
| 12 | | 0 | 0 | | | | | | |
| 13 | | 0 | 0 | | | | | | |
| 14 | | 0 | 0 | | | | | | |
| 15 | | 0 | 0 | | | | | | |

Physical memory

| | |
|---|---|
| 3 | 0 |
| 1 | 1 |
| 0 | 2 |
| 5 | 3 |
| 4 | 4 |
| 9 | 5 |
| 2 | 6 |
| 11 | 7 |

# Page Table Entries

- Frame number
- Valid/Invalid bit
  - Set if process can reference that portion of VA space
- Present bit
  - Set if page is mapped to a frame
- Referenced bit
  - Set if page has been referenced
- Dirty bit
  - Set if page has been modified
- Cache disable bit
  - Set if page can't be cached
- Protection bits (R/W/X)



Page table

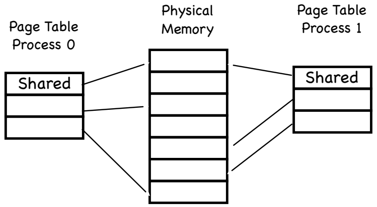
| | Frame # | V | P | R | D | C | Protection bits (R/W/X) | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 2 | 1 | 1 | | | | | | |
| 1 | 1 | 1 | 1 | | | | | | |
| 2 | 6 | 1 | 1 | | | | | | |
| 3 | 0 | 1 | 1 | | | | | | |
| 4 | 4 | 1 | 1 | | | | | | |
| 5 | 3 | 1 | 1 | | | | | | |
| 6 | 0 | 0 | 0 | | | | | | |
| 7 | 0 | 0 | 0 | | | | | | |
| 8 | 0 | 0 | 0 | | | | | | |
| 9 | 5 | 1 | 1 | | | | | | |
| 10 | 5 | 1 | 0 | | | | | | |
| 11 | 7 | 1 | 1 | | | | | | |
| 12 | 0 | 0 | 0 | | | | | | |
| 13 | 0 | 0 | 0 | | | | | | |
| 14 | 0 | 0 | 0 | | | | | | |
| 15 | 0 | 0 | 0 | | | | | | |

On disk

| Physical memory | |
|---|---|
| 3 | 0 |
| 1 | 1 |
| 0 | 2 |
| 5 | 3 |
| 4 | 4 |
| 9 | 5 |
| 2 | 6 |
| 11 | 7 |

# Sharing

- By now, it's old hat:
  - Processes share pages by mapping virtual pages 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 read only
  - on write, copy only the affected page
    - set W bit in both PTEs



# Example

Page size: 4 bytes

| | VA Space |
|---|---|
| 0 | A<br>B<br>C<br>D |
| 1 | E<br>F<br>G<br>H |
| 2 | I<br>J<br>K<br>L |

| | Page Table |
|---|---|
| 0 | 4 |
| 1 | 3 |
| 2 | 1 |

| PA Space | 0 |
|---|---|
| I<br>J<br>K<br>L | 1 |
| | 2 |
| E<br>F<br>G<br>H | 3 |
| A<br>B<br>C<br>D | 4 |

# Space Overhead

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

Overhead for paging:

sequences of contiguous pages

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

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

- What makes up sizeofEntry?
  - bits to identify physical page [$\log_2$ (PA_Size / frame (aka page) size)]
  - control bits (Valid, Present, Dirty, Referenced, etc)
  - usually word or byte aligned (so, however many bits are needed to make it so)

# Computing Paging Overhead

- 1 MB maximum VA, 1 KB page, 3 “segments” (program, stack, heap)
- PA space is 64KB and PTE has 7 control bits

What is the Paging Overhead?

- (($2^{20}$ / $2^{10}$) x sizeofEntry) + (3 x $2^9$) bytes
- sizeofEntry = 6 bits ($2^6$ frames) + 7 control bits
  - byte aligned size of PTE entry: 16 bits

Overhead: $2^{10}$ x 2 + 3 x $2^9$ =
($2^{11}$ + 3 x $2^9$) bytes

# What’s not to love?

- Space overhead
  - With a 64-bit address space, size of page table can be huge
- Time overhead
  - What before used to require one memory access, now needs two
    - one to access the correct PTE and retrieve the correct frame number
    - one to access the actual physical address that contains the data of interest