CSE 120: Principles of Operating Systems
Lecture 8: Memory Management

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Memory Management

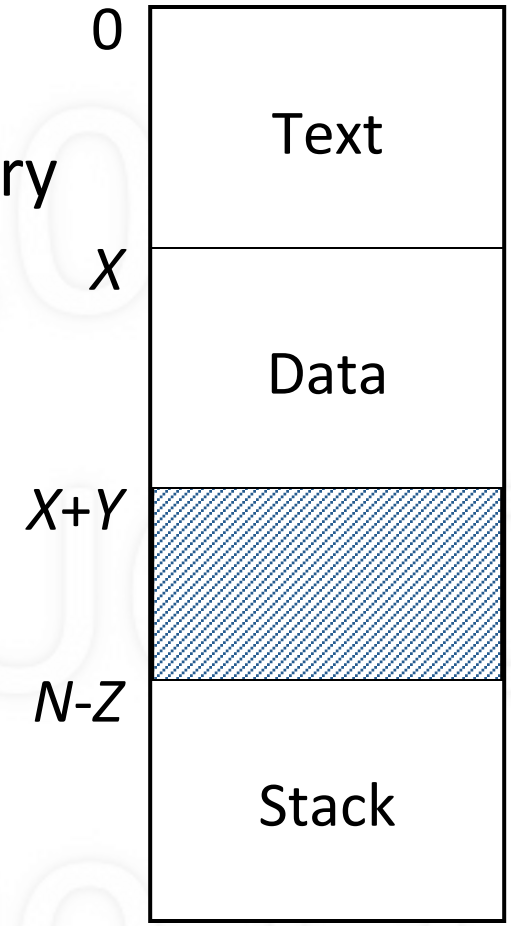
- How to allocate and free portions of memory
- Allocation of memory occurs when
  - new process is created
  - process requests more memory
- Freeing of memory occurs when
  - process exits
  - process no longer needs memory it requested

Process Memory

- Each process requires memory to store
  - Text: code of program
  - Data: static variables, heap
  - Stack: automatic variables, activation records
  - Other: shared memory regions
- Memory characteristics
  - Size, fixed or variable (max size)
  - Permissions: r, w, x

Process's Memory Address Space

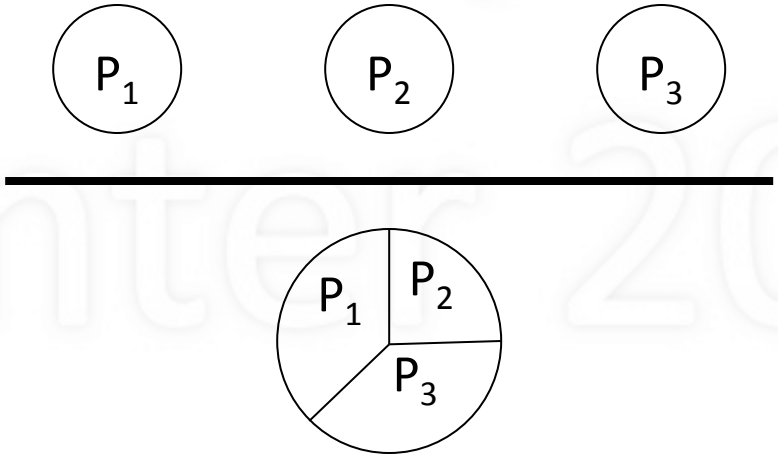
- Address space
  - Set of addresses to access memory
  - Typically, linear and sequential
  - 0 to *N*-1 (for size *N*)
- For process memory of size *N*
  - Text (of size *X*) at 0 to *X*-1
  - Data (of size *Y*) at *X* to *X*+*Y*-1
  - Stack (of size *Z*) at *N*-*Z* to *N*-1



Compiler's Model of Memory

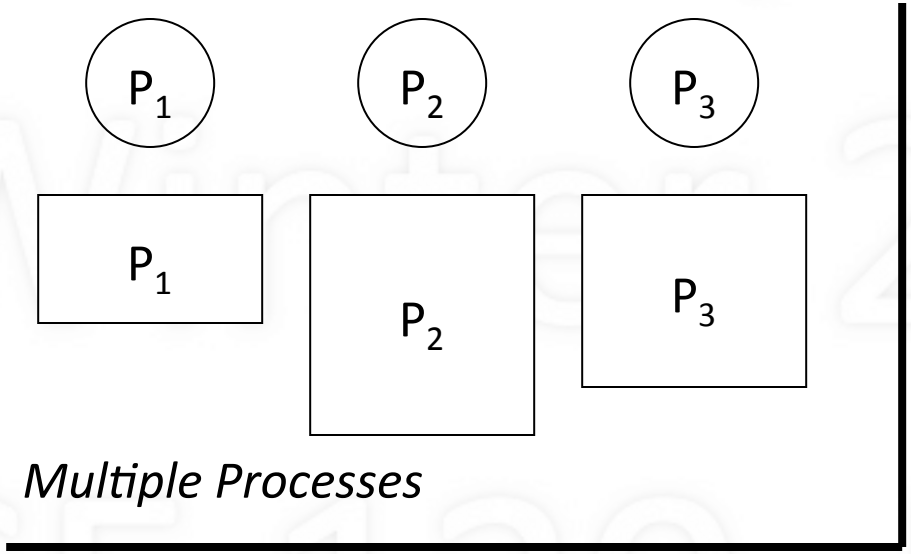
- Compiler generates memory addresses
  - Address ranges for text, data, stack
  - Allow data and stack to grow
- What is not known in compiler
  - Physical memory size (to place stack at high end)
  - Allocated regions of physical memory (to avoid)

Goal: Support Multiple Processes

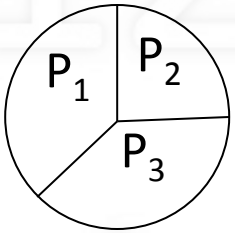


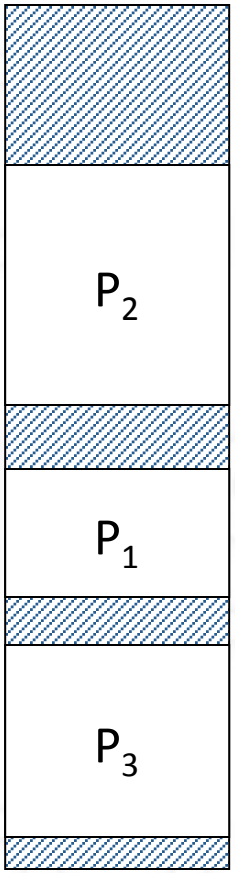
- To support programs running "simultaneously"
  - Implement process abstraction
  - Multiplex CPU time over all runnable processes
- Process requires more than CPU time: memory

Multiple Processes: CPU + Memory



Multiplexed CPU and Memory





Sharing the Physical Memory

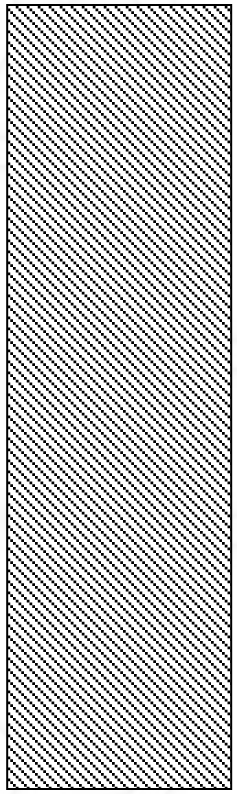
- If process given CPU, must also be in memory
- Problem
  - Context-switching time (CST): 10 µsec
  - Loading from disk: 10 MB/s
  - To load 1 MB process: 100 msec = 10,000 x CST
  - Too much overhead! Breaks illusion of simultaneity
- Solution: keep multiple processes in memory
  - Context switch only between processes in memory

Memory Issues and Topics

- Where should process memories be placed?
  - Topic: Memory management
- How does the compiler model memory?
  - Topics: Logical memory model, segmentation
- How to deal with limited physical memory?
  - Topics: Virtual memory, paging
- Mechanisms and Policies

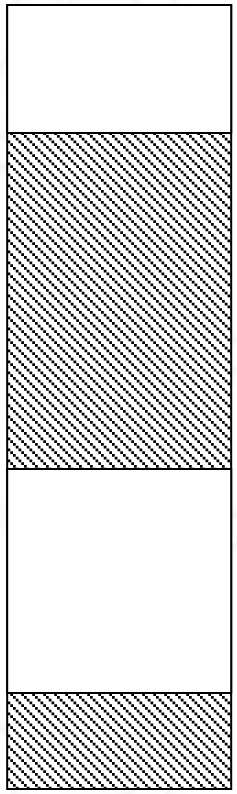
Memory Management Example

- Physical memory starts as one empty “hole”



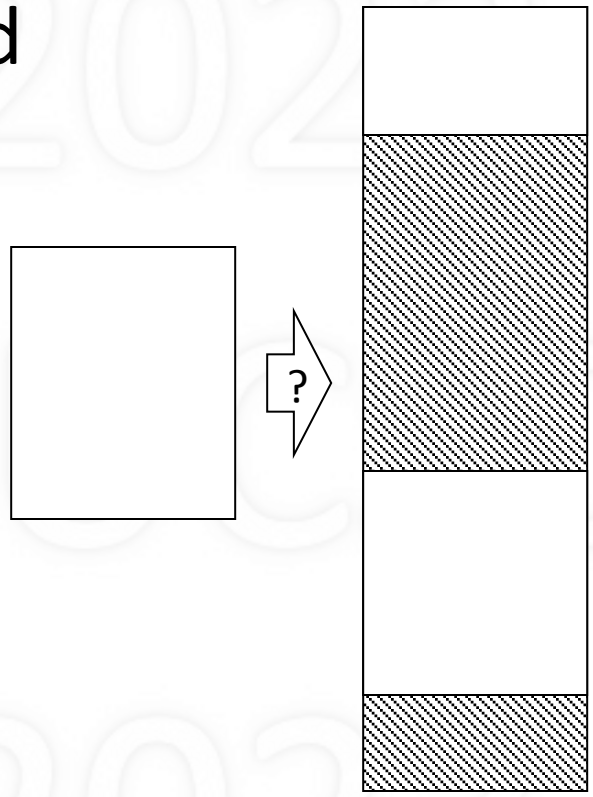
Memory Management Example

- Physical memory starts as one empty “hole”
- Over time, areas get allocated



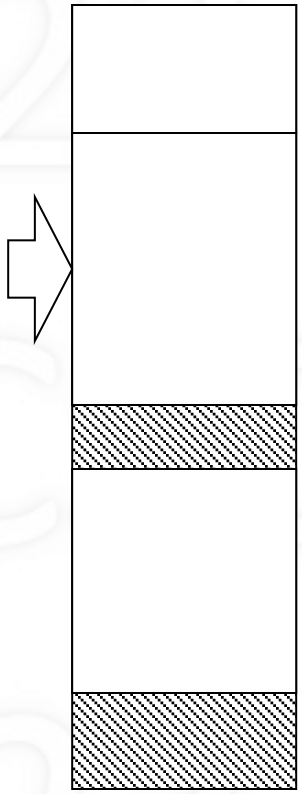
Memory Management Example

- Physical memory starts as one empty “hole”
- Over time, areas get allocated
- To allocate memory
  - Find large enough hole



Memory Management Example

- Physical memory starts as one empty “hole”
- Over time, areas get allocated
- To allocate memory
  - Find large enough hole
  - Allocate region within hole
  - Typically, leaves (smaller) hole



Memory Management Example

- Physical memory starts as one empty “hole”
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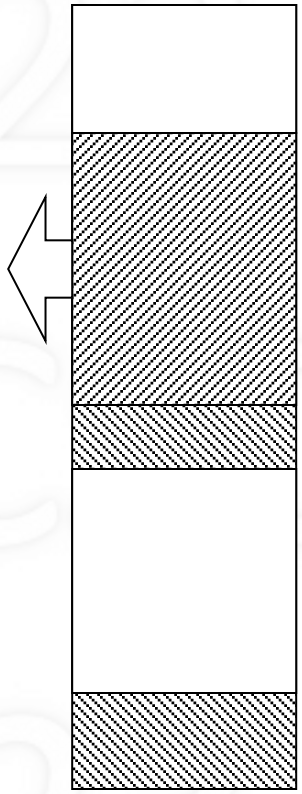
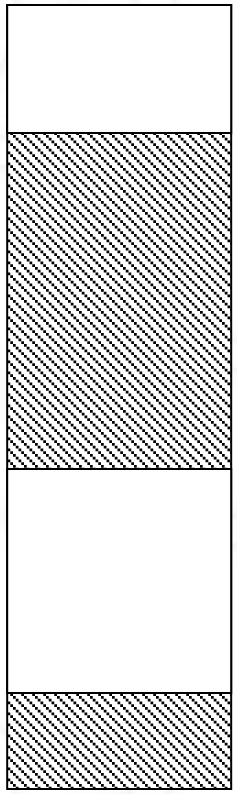
- When no longer needed, release



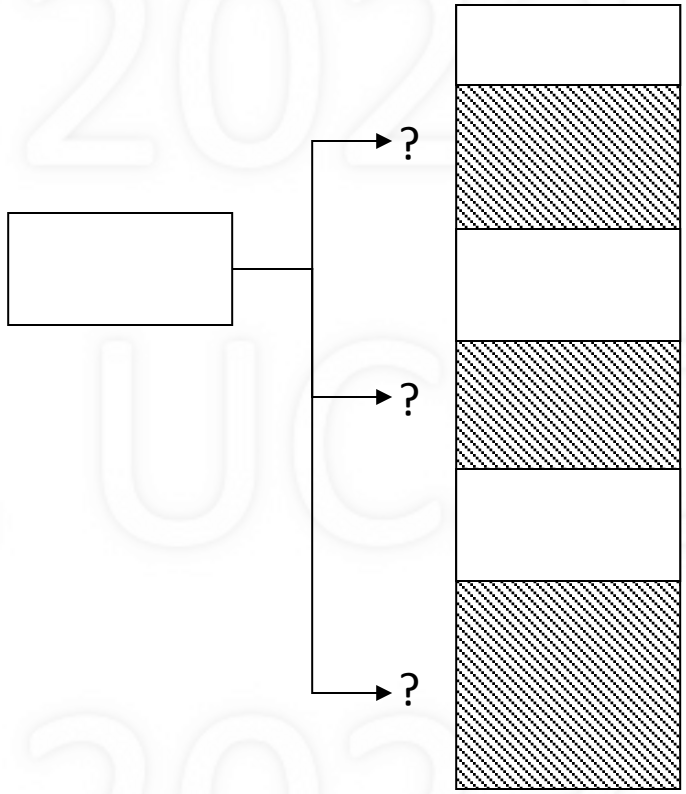
Memory Management Example

- Physical memory starts as one empty “hole”
- Over time, areas get allocated: “blocks”
- To allocate memory
  - Find large enough hole
  - Allocate block within hole
  - Typically, leaves (smaller) hole
- When no longer needed, release
  - Creates a hole, coalesce with adjacent



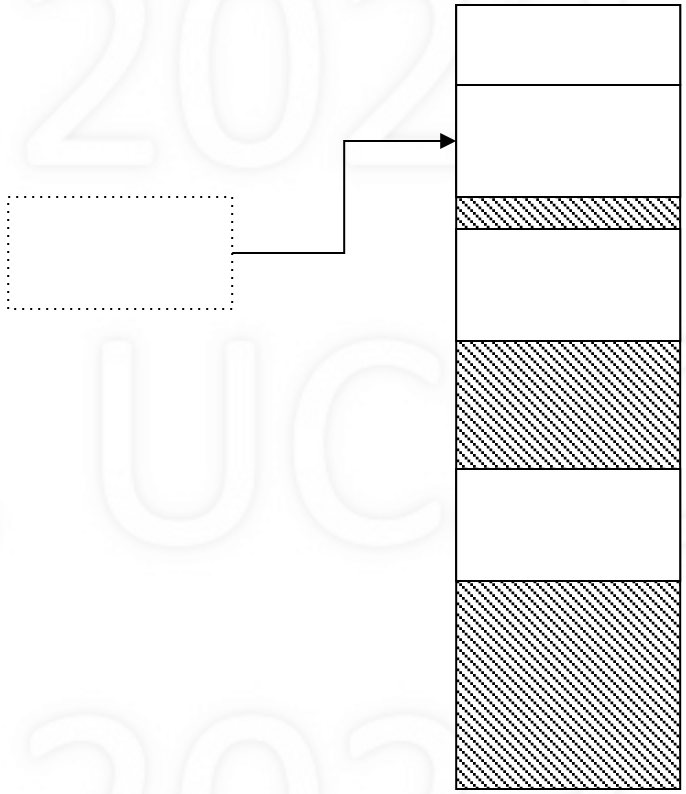
Selecting the Best Hole

- If there are multiple holes, which to select?



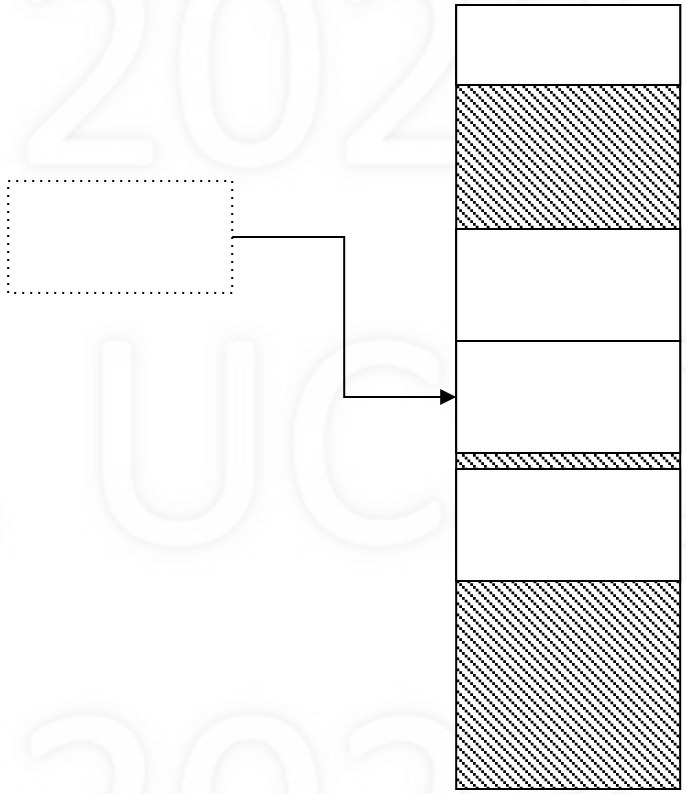
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - *First (or next) fit:*
    - *Simple*
    - *Fast*



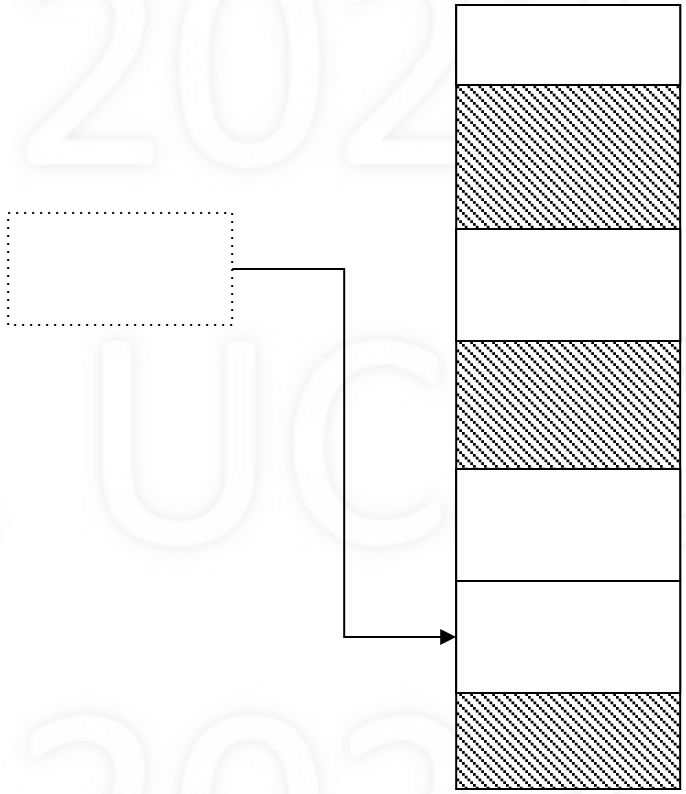
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - First (or next) fit
  - *Best fit*
    - *Optimal?*
    - *Must check every hole*
    - *Leaves very small fragments*



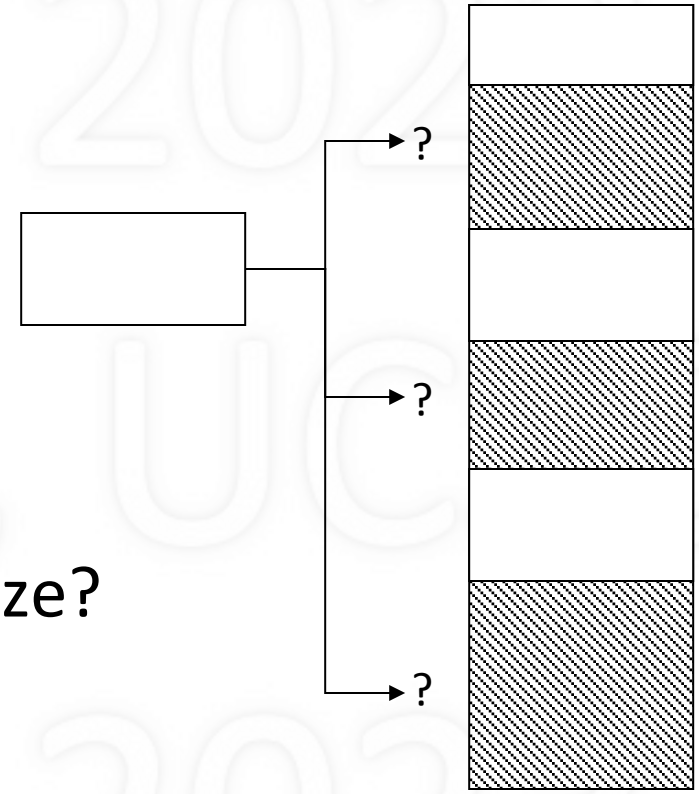
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - First (or next) fit
  - Best fit
  - *Worst fit*
    - *Optimal?*
    - *Leaves large fragments*
    - *Must check every hole*



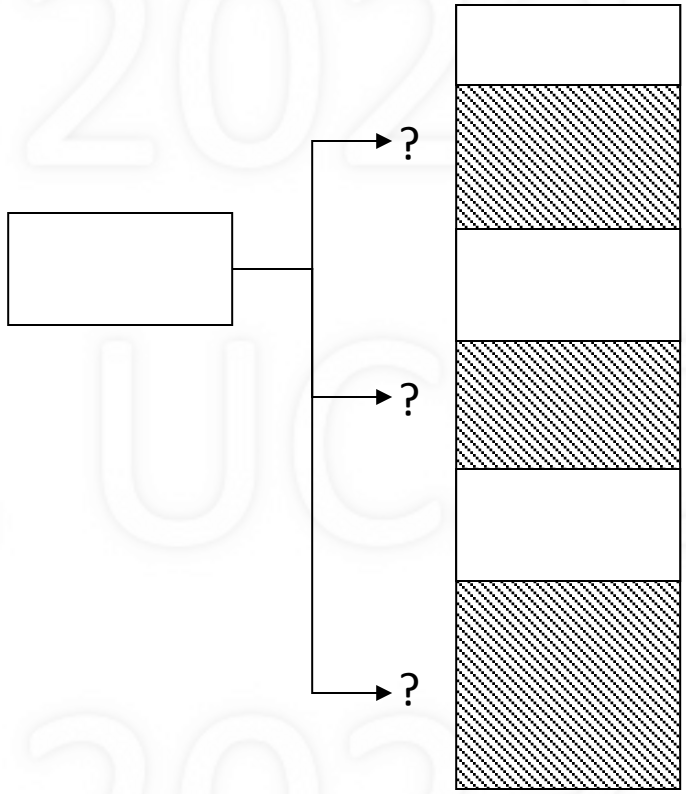
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - First (or next) fit
  - Best fit
  - Worst fit
- Complication
  - Is region fixed or variable size?



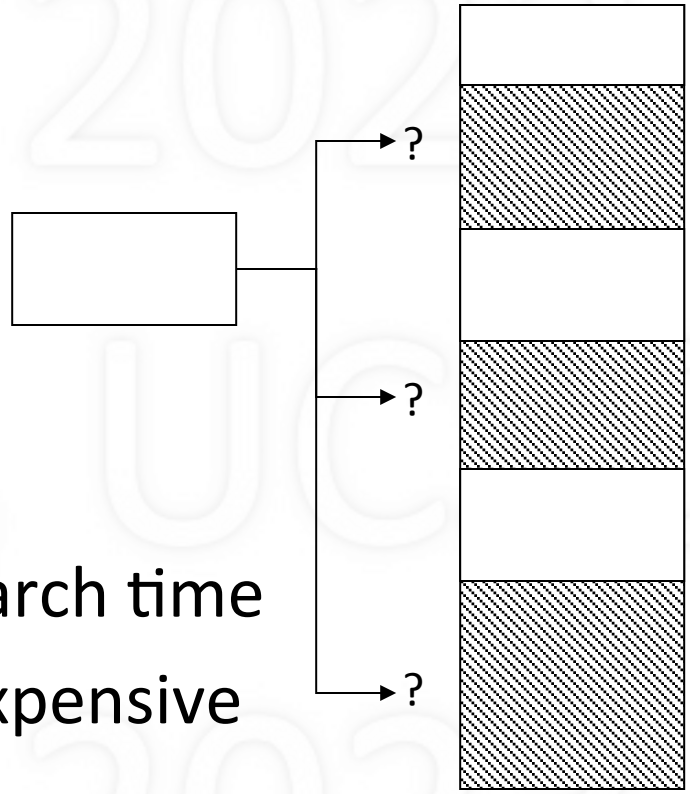
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - First (or next) fit
  - Best fit
  - Worst fit
- So which is best?



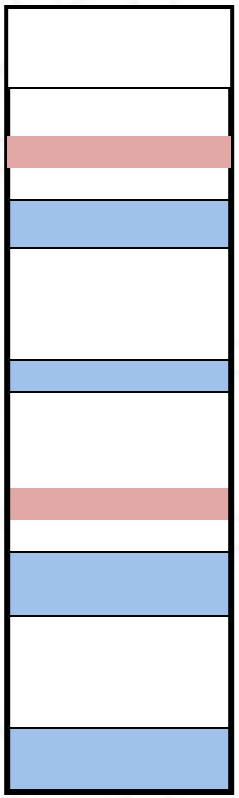
Selecting the Best Hole

- If there are multiple holes, which to select?
- Algorithms
  - First (or next) fit
  - Best fit
  - Worst fit
- So which is best?
  - Consider tradeoff: fit vs. search time
  - Memory is cheap, time is expensive



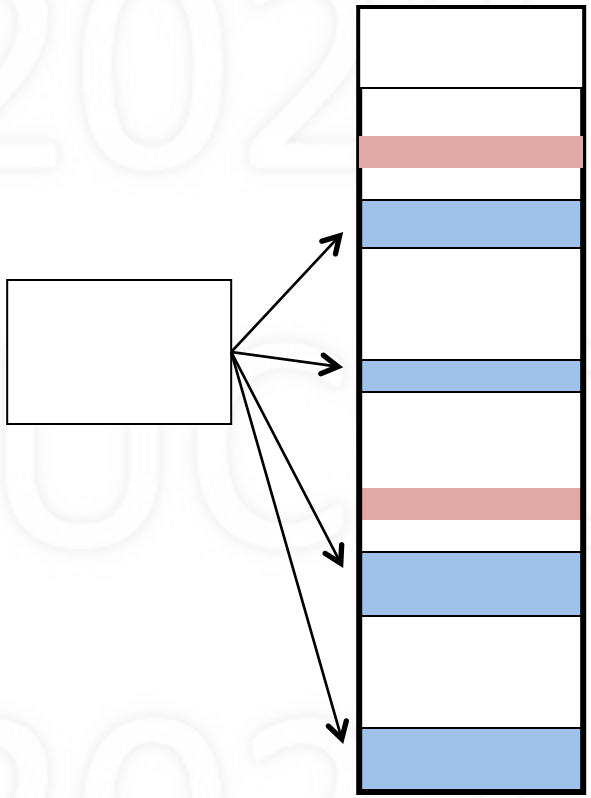
Fragmentation

- Eventually, memory becomes fragmented
- Internal fragmentation
  - Unused space *within* (allocated) block
  - Cannot be allocated to others
  - Can come in handy for growth
- External fragmentation
  - Unused space *outside* any blocks (holes)
  - Can be allocated (too small/not useful?)



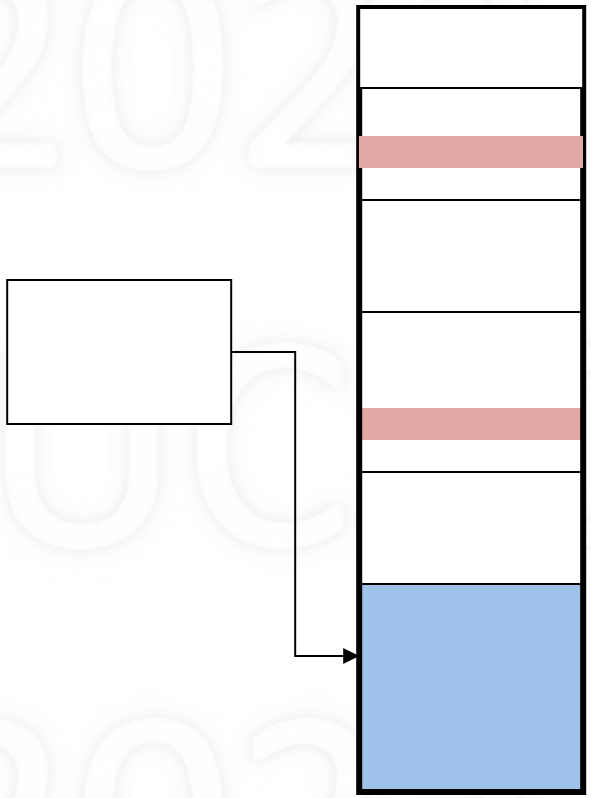
What if No Holes

- There may still be significant unused space
  - External fragments
  - Internal fragments



What if No Holes

- There may still be significant unused space
  - External fragments
  - Internal fragments
- Approaches
  - *Compaction*
    - *Simple idea*
    - *But very time consuming*



What if No Holes

- There may still be significant unused space
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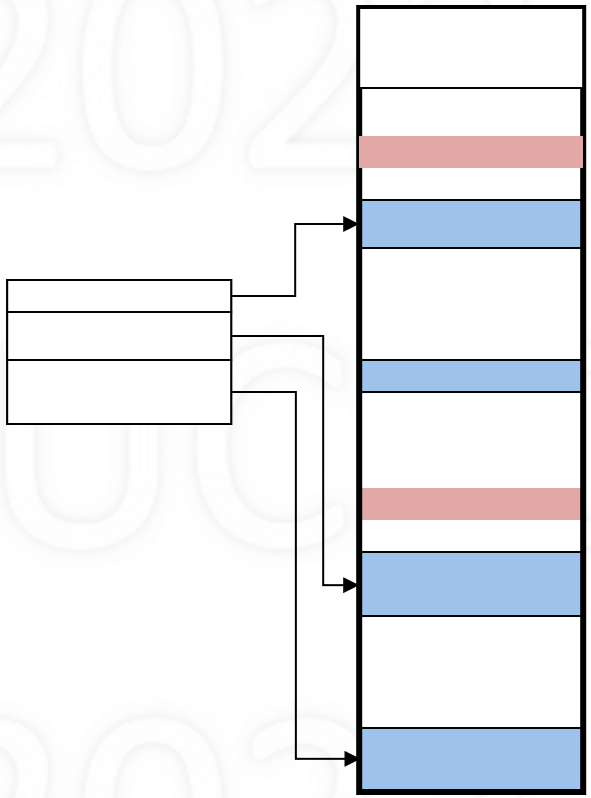
  - Internal fragments
- Approaches
  - Compaction
  - *Break block into sub-blocks*
    - *Easier to fit*
    - *But complex*



What if No Holes

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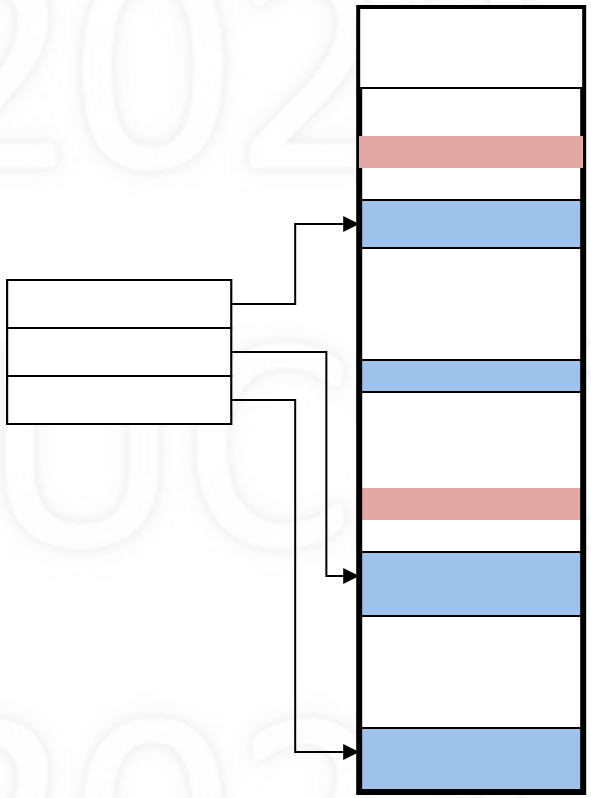

What if No Holes

- There may still be significant unused space
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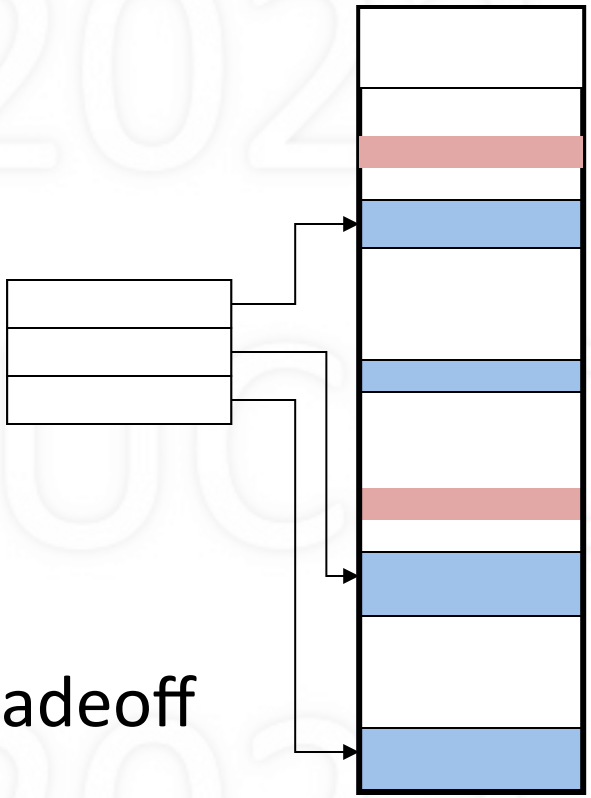
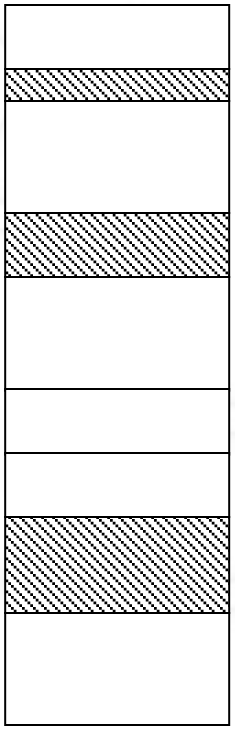
  - Consider time vs. complexity tradeoff



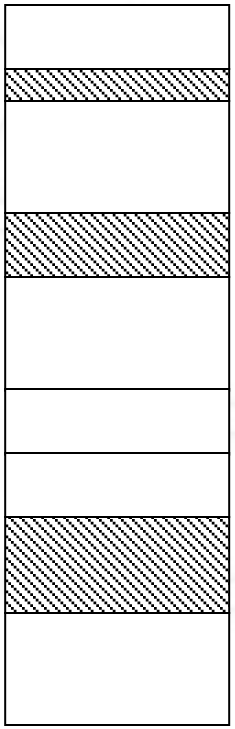
Given *n* blocks, how many holes?

- Assume memory is fragmented
- There are *n* blocks allocated
- There are holes between
- How many holes are there?
  - $m = f(n)$?



50% Rule: $m = n/2$

- Block: an allocated block
- Hole: free space between blocks
- The 50% Rule: $m = n/2$
  - n = number of blocks
  - m = number of holes = $n/2$



Proof of 50% Rule

- Block: an allocated block
- Hole: free space between blocks
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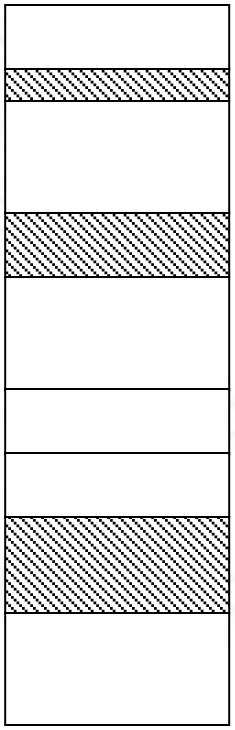
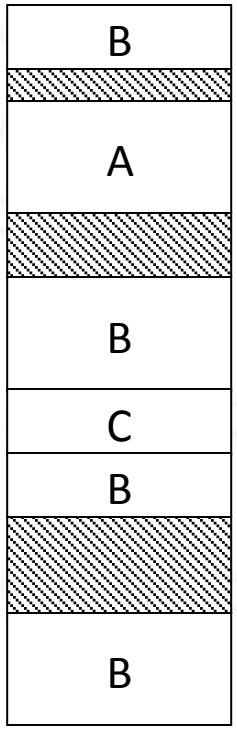


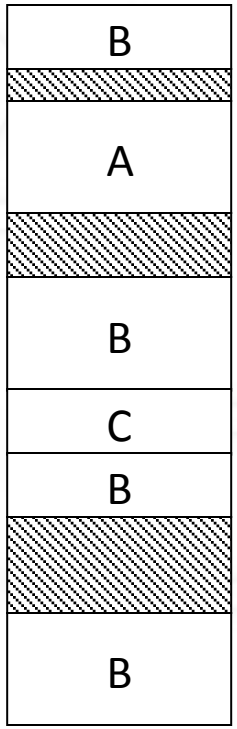
Proof of 50% Rule: Types of Blocks

- Type A: hole on each side
  - Let *a* = number of A blocks
- Type B: hole on just one side
  - Let *b* = number of B blocks
- Type C: no holes on either side
  - Let *c* = number of C blocks
- Total number of blocks: $n = a + b + c$



Proof of 50% Rule: Count Holes

- Number of holes: $m = (2a + b)/2$
  - Each A block is adjacent to 2 holes
  - Each B block is adjacent to 1 hole
  - Each C block has 0 adjacent holes
- Each hole is adjacent to 2 blocks
  - So, to not double count, must divide by 2
- Example: $m = ((2x1) + 4)/2 = 6/2 = 3$
  - where $a = 1$, $b = 4$, $c = 1$



Proof of 50% Rule: Deallocation

- When a block is freed, number of holes
  - Type A: decreases by 1
  - Type B: stays the same
  - Type C: increases by 1
- Probabilities given a block is freed
  - Prob (# holes decrease | block is freed) = a/n
  - Prob (# holes increase | block is freed) = c/n

Proof of 50% Rule: Allocation

- When block is allocated, the number of holes
  - Decreases by 1 if allocated from exact fitting hole
  - Stays the same otherwise
- Let p = probability the hole is not an exact fit
- Probabilities given allocation
  - Prob (# holes decrease | block is allocated) = $1 - p$
  - Prob (# holes increase | block is allocated) = 0

Proof of 50% Rule: Equilibrium

- Equilibrium considerations
  - The system is in equilibrium once a point is reached where the the number of holes and number of allocated blocks stays constant
- Equilibrium assumption implies
  - Prob (block is allocated) = Prob (block is freed)
  - Prob (# holes increase) = Prob (# holes decrease)

Proof of 50% Rule: Use Equilibrium

- Prob (# holes increase) can be expressed as
  - P(incr|free) P(free) + P(incr|alloc) P(alloc)
    = (c/n) P(free) + 0 x P(alloc)
- Prob (# holes decrease) can be expressed as
  - P(decr|free) P(free) + P(decr|alloc) P(alloc)
    = (a/n) P(free) + (1 – p) P(alloc)
- Setting these equal and since P(alloc) = P(free)

  (c/n) = (a/n) + (1 – p), therefore $c = a + n(1 - p)$

Proof of 50% Rule: Final Algebra

- $c = a + n(1 - p) = a + n - np$
- Recall $n = a + b + c$, therefore $c = n - a - b$
- Setting these equal: $a + n - np = n - a - b$
- Therefore $np = 2a + b$
- Recall $m = (2a + b)/2$, therefore $2m = (2a + b)$
- Setting these equal: $np = 2m$
- Therefore $m = (n/2)p$ (recall goal: $m = n/2$)

Proof of 50% Rule: Simplification

- $m = (n/2)p$, this says
  - m, the number of holes, is equal to
  - $n/2$, 50% of the number of blocks, times
  - p, the probability of an imperfect fit
- If $p = 1$ (i.e., all allocations are imperfect fits)
  - $m = n/2$: number of holes is half number of blocks
- If $p = 0$ (i.e., all allocations are perfect fits)
  - $m = 0$: there are no holes, all allocations perfect

How Much Memory Lost to Holes?

- Given we know average sizes for blocks, holes
  - b = average size of blocks
  - h = average size of holes
- What is fraction of memory lost to holes?
  - $0 \leq f(b, h) \leq 1$

Unused Memory Rule: $f = k/(k+2)$

- Let b = average size of blocks
- Let h = average size of holes
- Let $k = h/b$, ratio of average hole-to-block size
- $f = k/(k+2)$ is fraction space lost to holes
  - How to we prove this?

Proof of Unused Memory Rule

- Given a memory of size M
  - $M = mh + nb$
  - $f = mh/M = mh/(mh + nb)$
- Assume that all allocations are imperfect fits
  - $m = n/2$, or $n = 2m$ (this is the 50% rule)
  - $f = mh/(mh + 2mb) = h/(h + 2b)$
  - If $k = h/b$, then $h = kb$, and $f = kb/(kb + 2b)$
- Therefore, $f = k/(k + 2)$

Some Values for $f = k/(k + 2)$

- $k = 1, f = 1/3$
  - avg hole size = avg block size, 33% waste
- $k = 2, f = 1/2$
  - avg hole size = 2x avg block size, 50% waste
- $k = 3, f = 3/5$
  - avg hole size = 3x avg block size, 60% waste
- $k = 8, f = 4/5$
  - avg hole size = 8x avg block size, 80% waste

Limits of $f = k/(k + 2)$

- In general, f increases with increasing k
  - *The larger the avg hole size is to avg block size, the larger is the fraction of wasted memory*
  - as $k \rightarrow \infty$, $f \rightarrow 1$
- *Alternatively,* f decreases with decreasing k
  - *The smaller the avg hole size is to avg block size, the smaller the fraction of wasted memory*
  - as $k \rightarrow 0$, $f \rightarrow 0$

Pre-sized Holes

- Variable-size allocations cause fragmentation
  - So why not have pre-sized holes?
- Same-sized: all holes same, easy allocation
  - Inflexible: may be too small
- Variety of sizes (small, medium, large, …)
  - More flexible, but more complex
  - What should sizes be? How many of each?
- Not adaptable; internal fragmentation

The Buddy System

- Partition into power-of-2 size chunks
- Alloc: given request for size r

```
find chunk of size ≥ r (else return failure)
while (r ≤ sizeof(chunk)/2)
  divide chunk into 2 buddies (each 1/2 size)
allocate the chunk
```

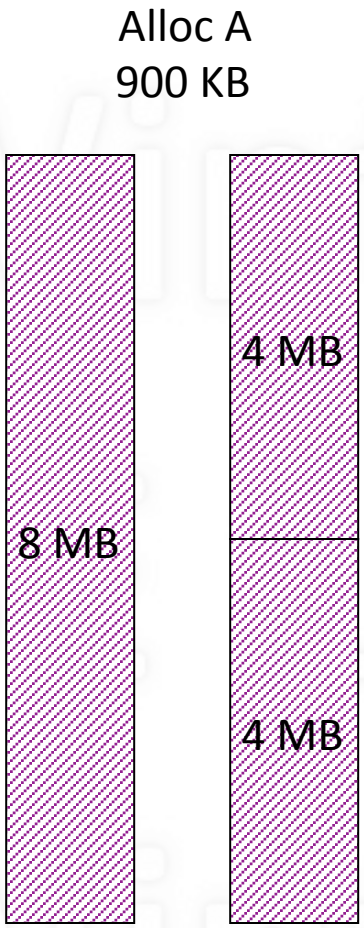
- Free: free the chunk and coalesce with buddy

```
free the chunk
while (buddy is also free)
  coalesce
```

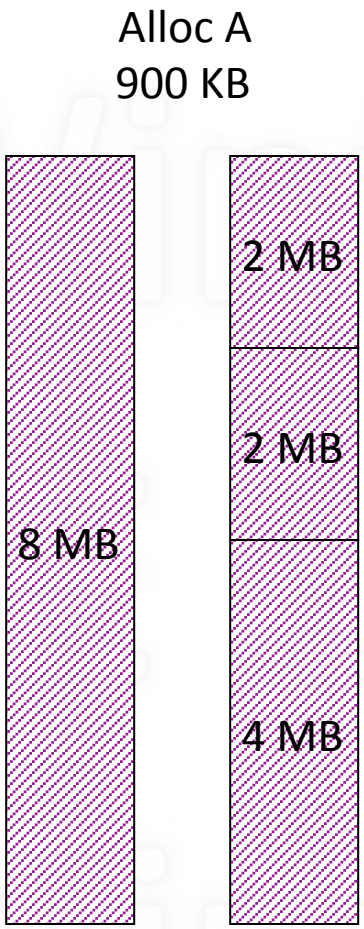
Example of Buddy System

Alloc A
900 KB

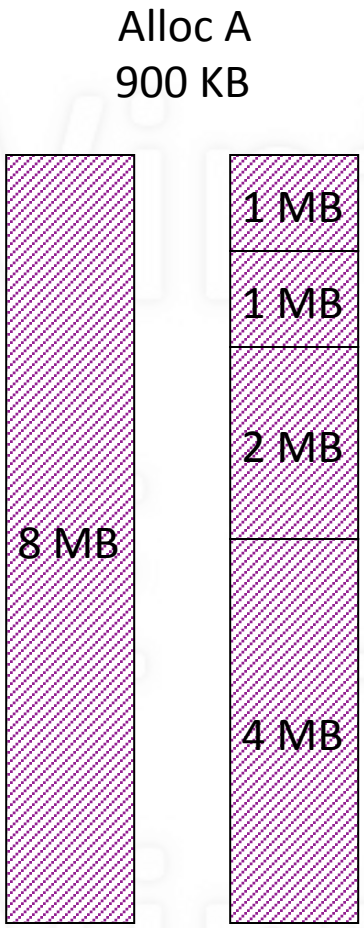
Example of Buddy System



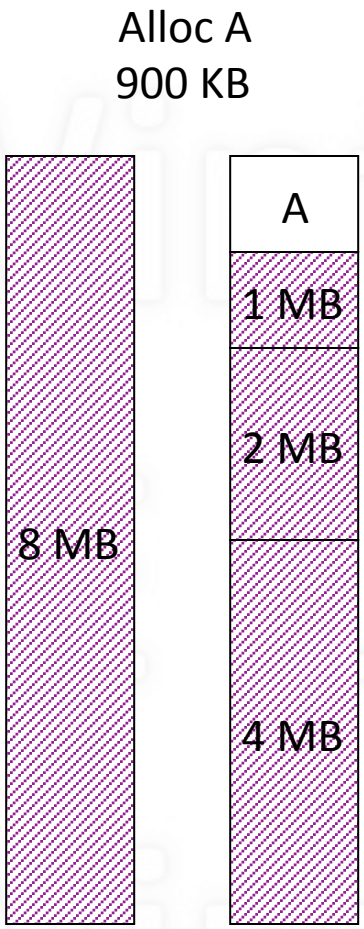
Example of Buddy System



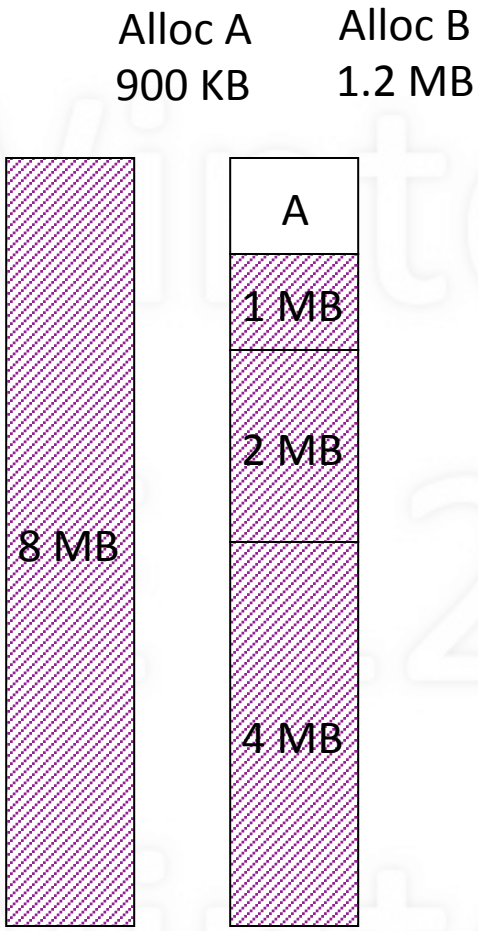
Example of Buddy System



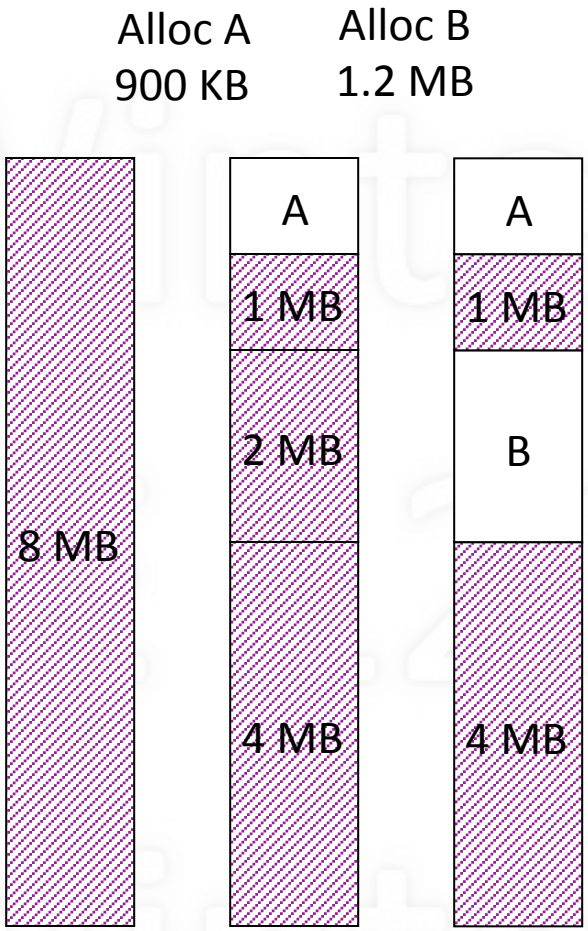
Example of Buddy System



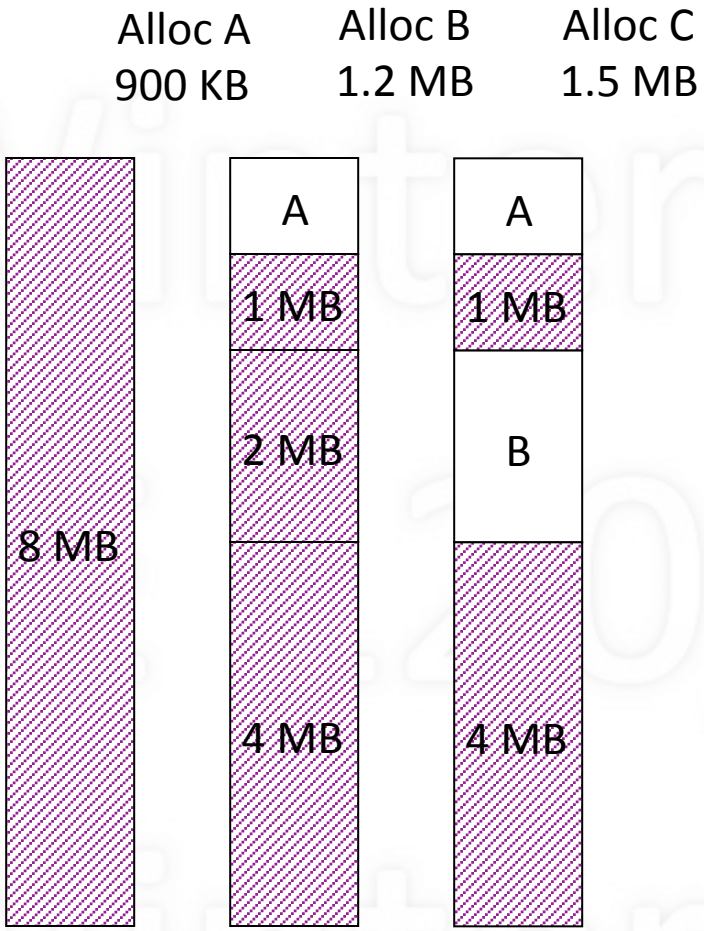
Example of Buddy System



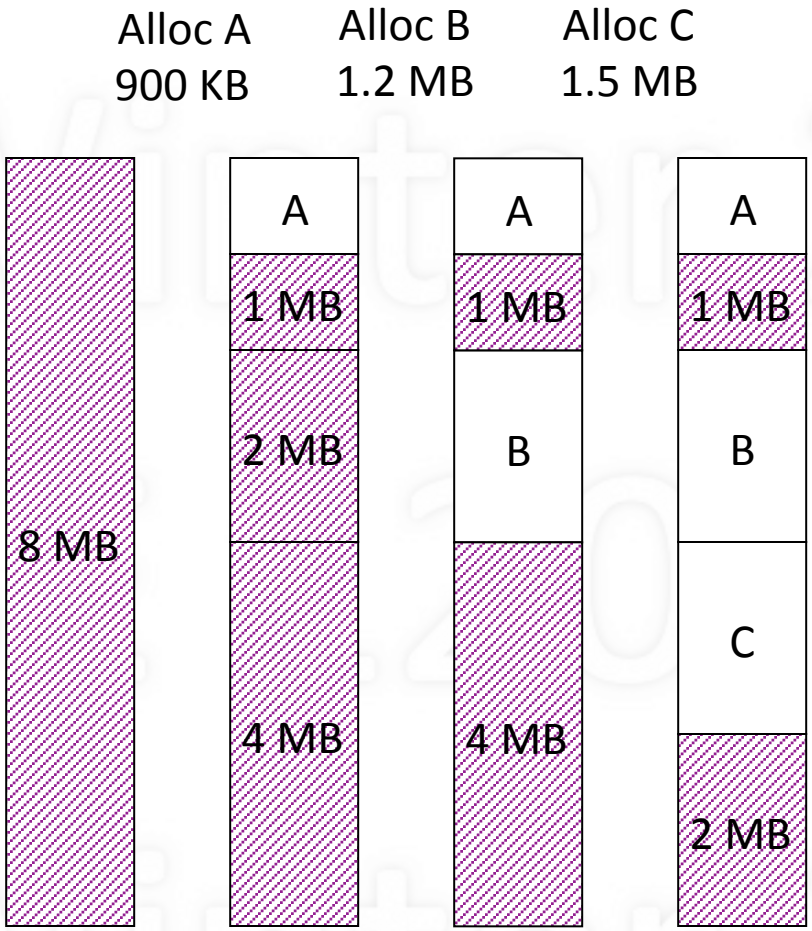
Example of Buddy System



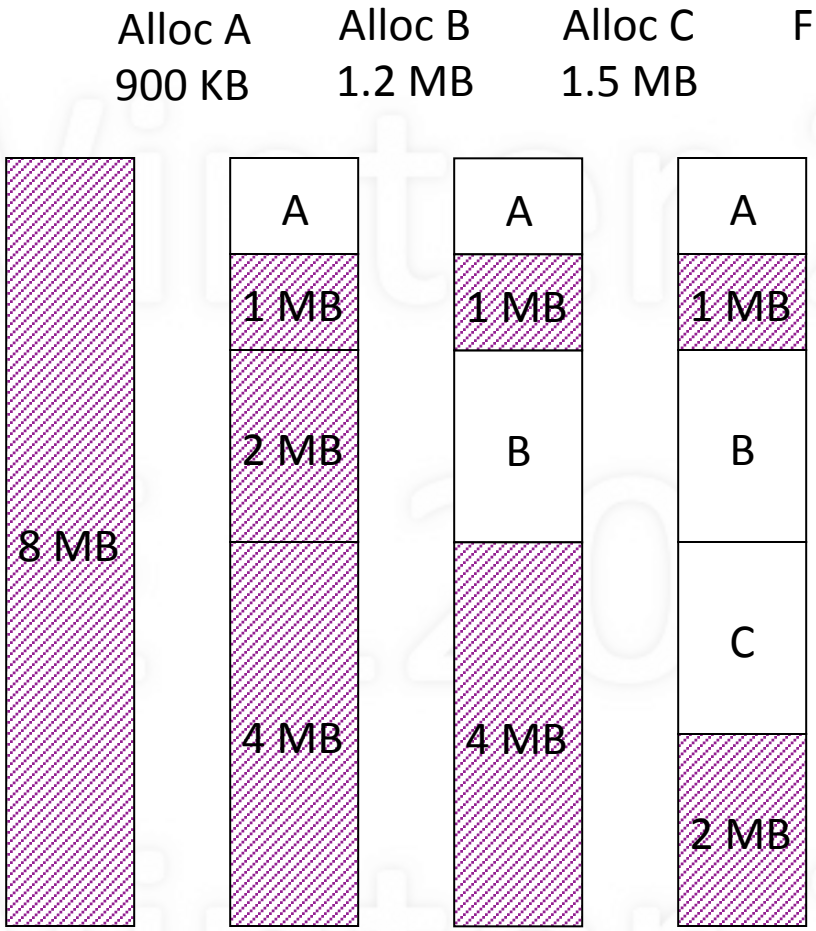
Example of Buddy System



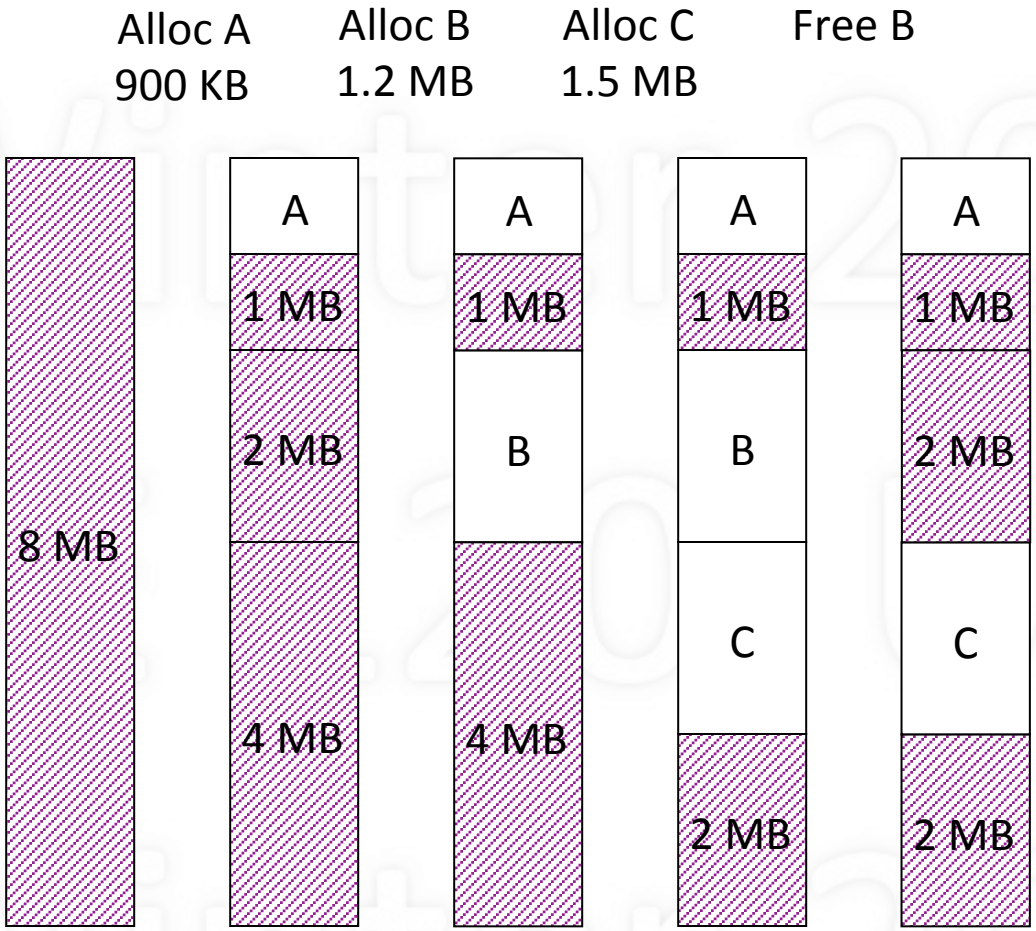
Example of Buddy System



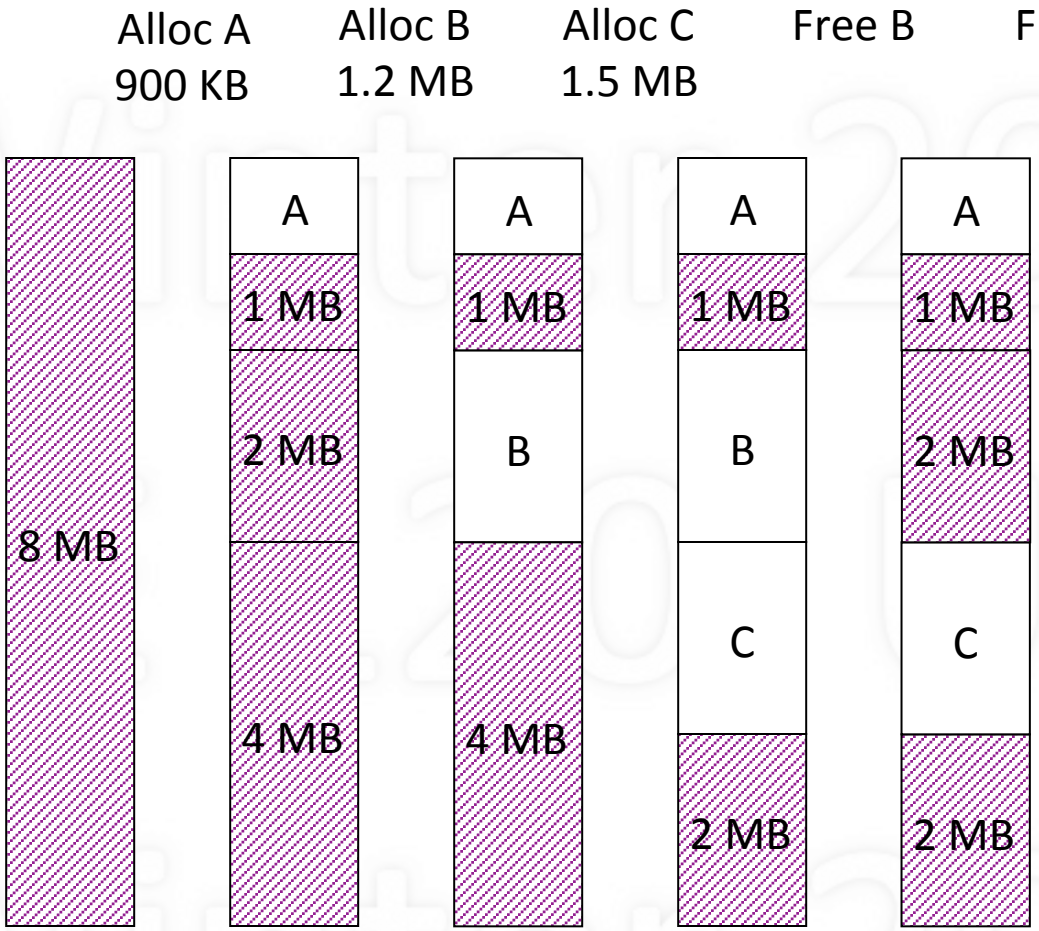
Example of Buddy System



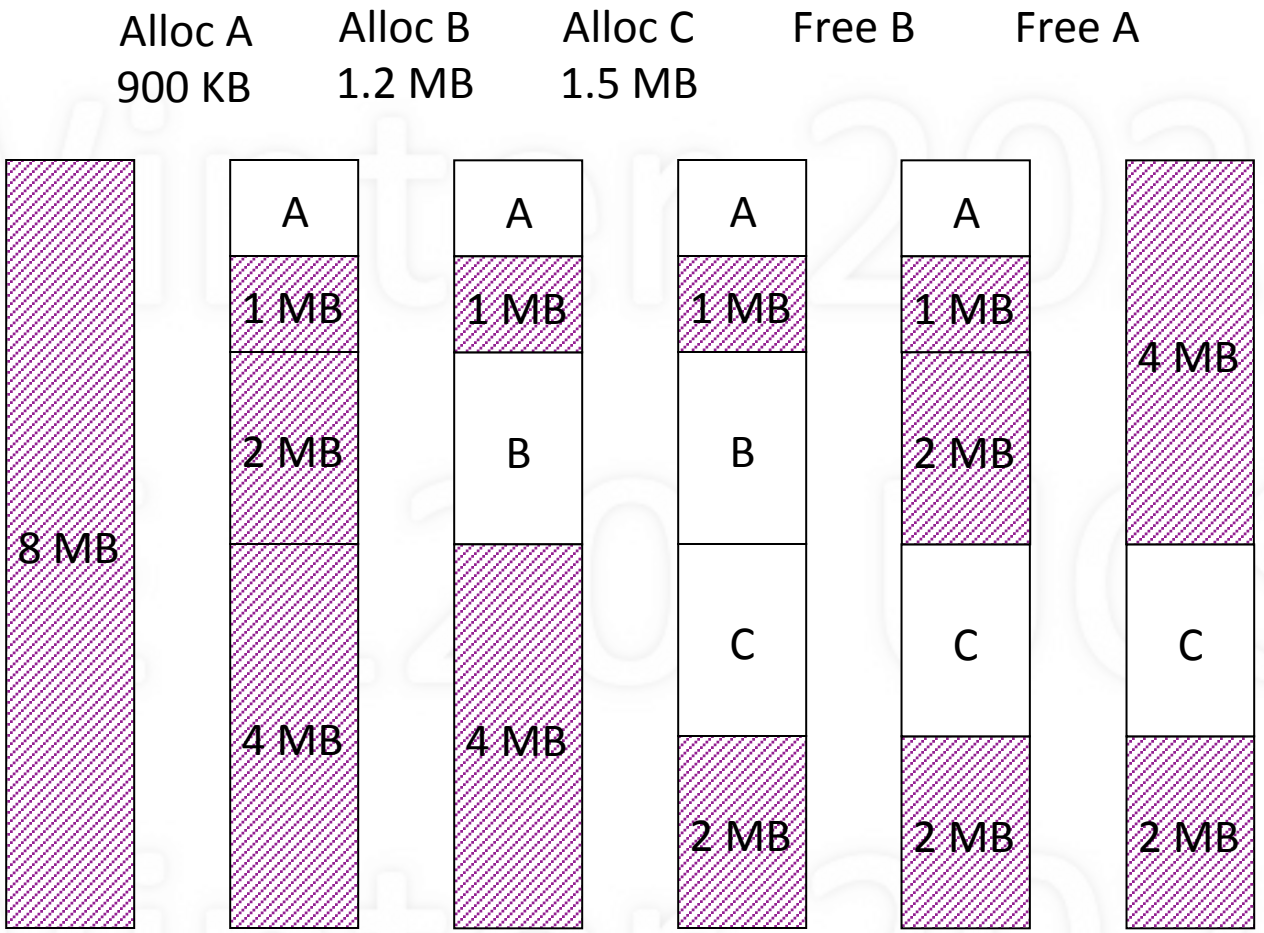
Example of Buddy System



Example of Buddy System

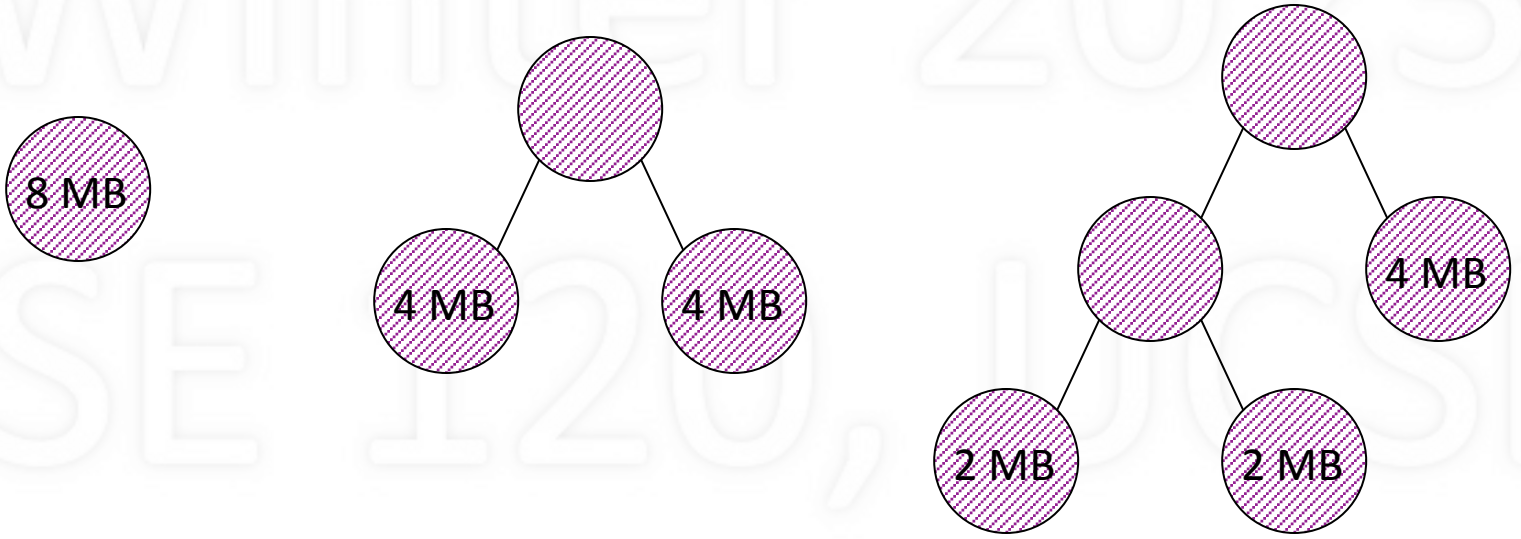


Example of Buddy System



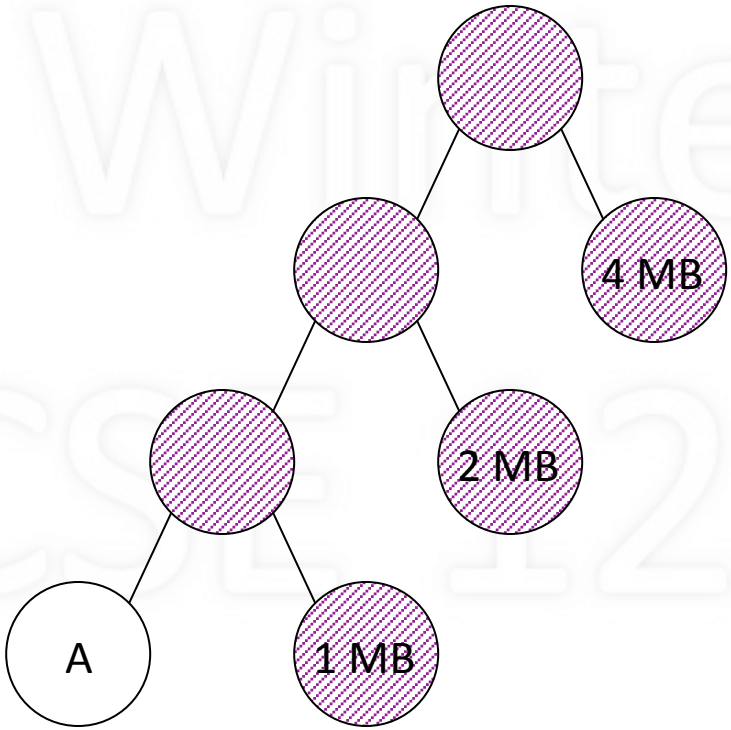
Data Structure for Buddy System

Alloc A: 900 KB



Data Structure for Buddy System

Alloc A: 900 KB



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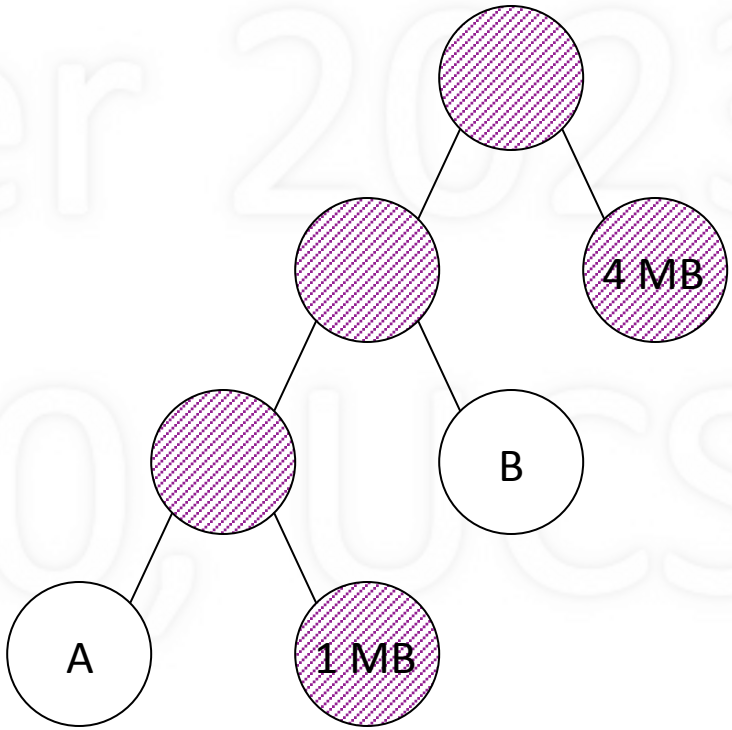
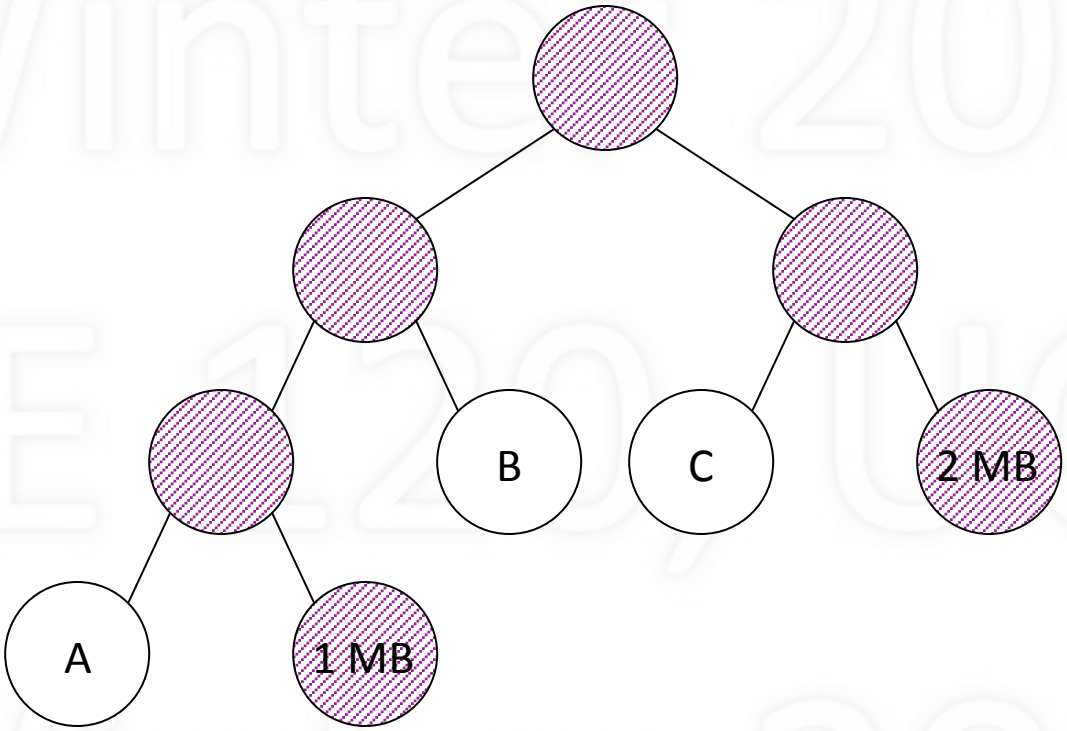
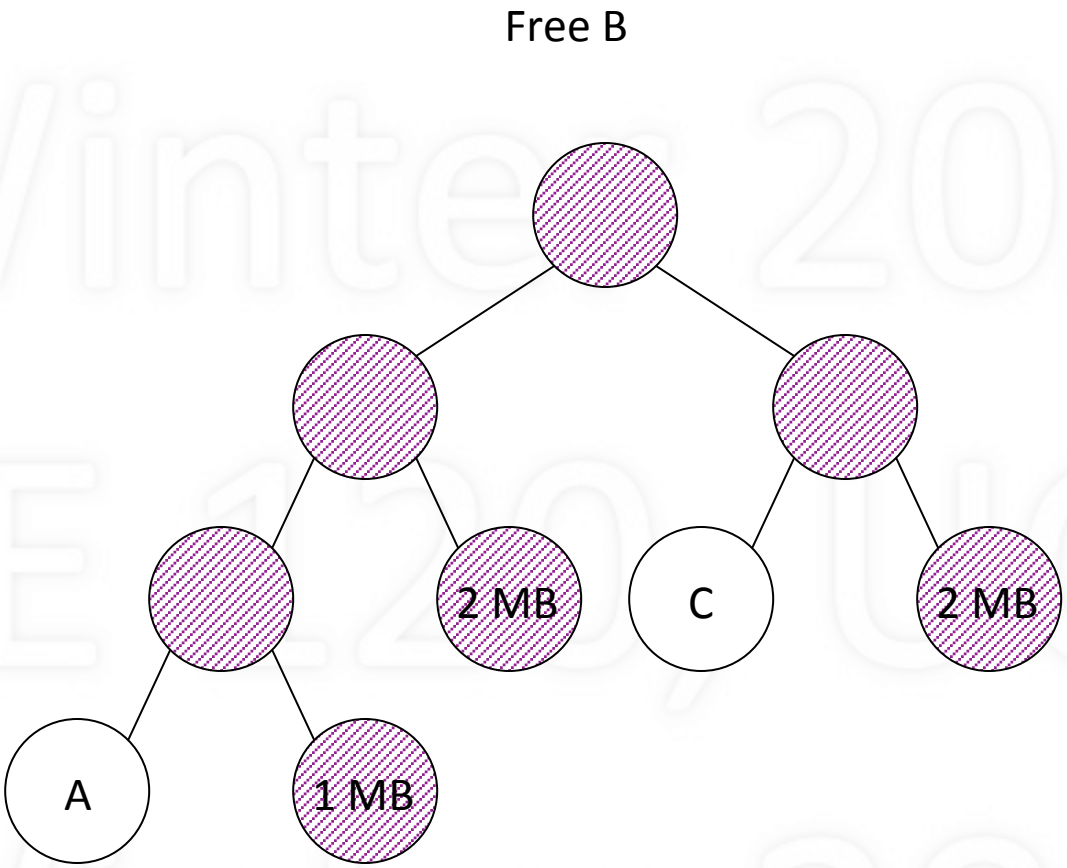


Data Structure for Buddy System

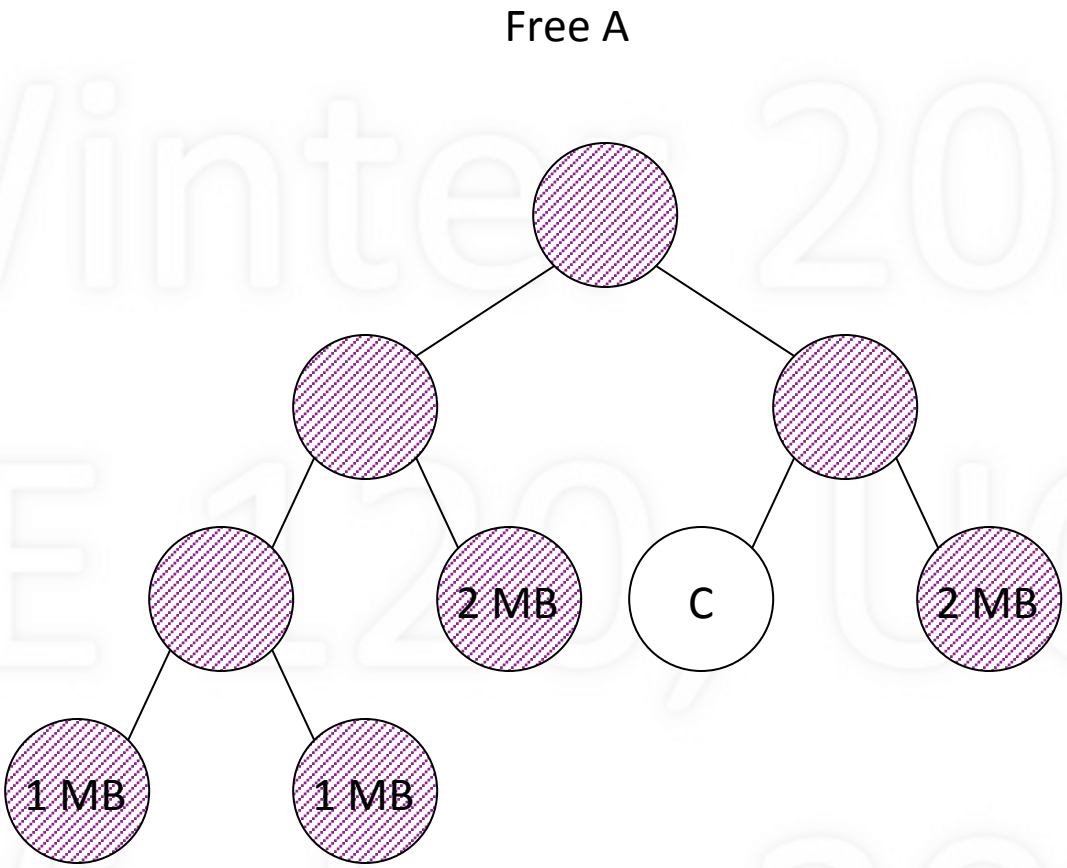
Alloc C: 1.5 MB



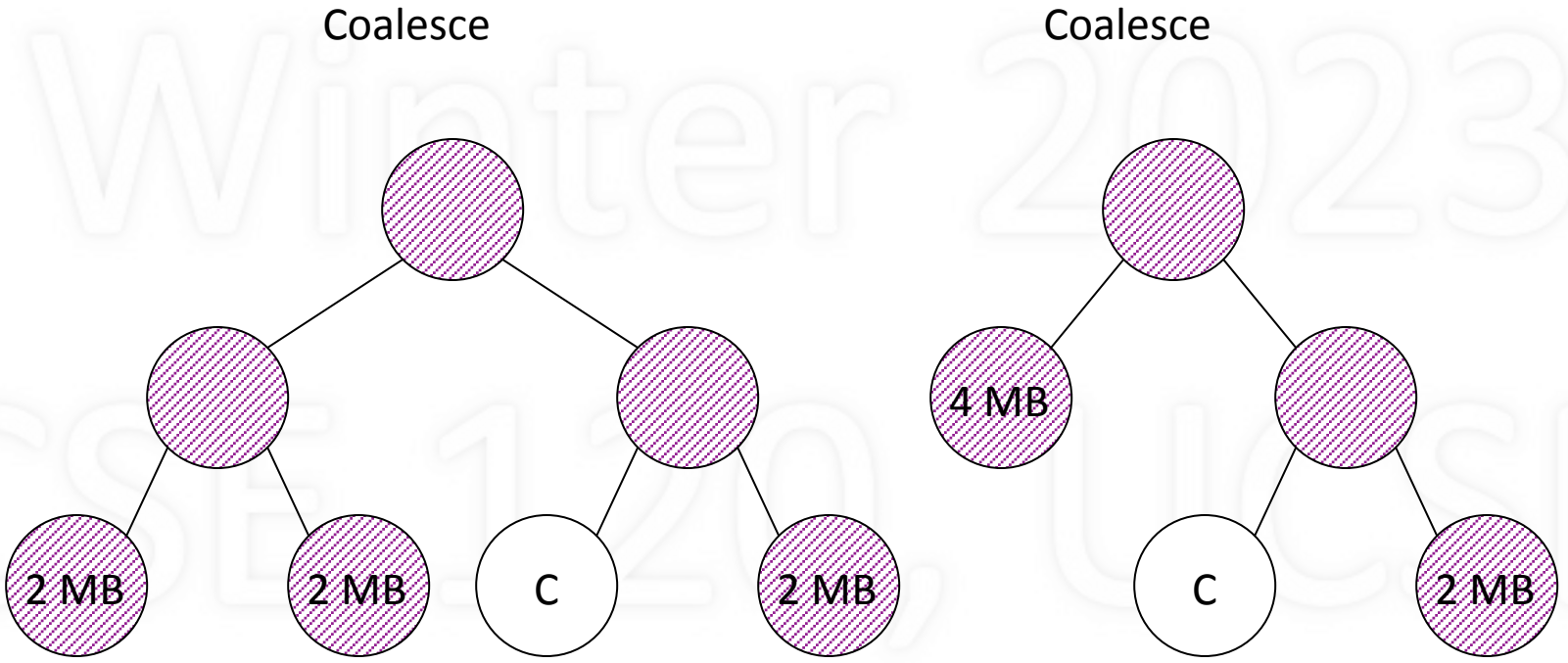
Data Structure for Buddy System



Data Structure for Buddy System



Data Structure for Buddy System



Summary

- Memory allocation: first-fit, best-fit, worst-fit
- Fragmentation: internal and external
- 50% rule: $m = n/2$
- Unused memory rule: $f = k/(k+2)$
  - k is ratio of avg hole size to avg block size
- Buddy System

Textbook

- OSP: Chapter 8
- OSC: Chapter 9 (on Main Memory)
  - Lecture-related: 9.1-9.2, 10.8.1 (buddy system)