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

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Memory Management

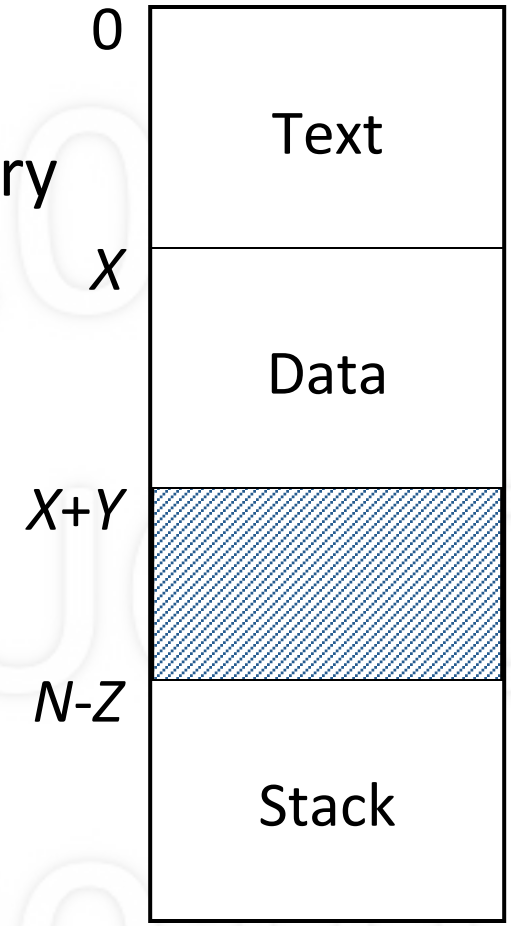
- How to allocate and free portions of memory
- Allocation of memory occurs when
  - new process is created
  - process requests more memory
- Freeing of memory occurs when
  - process exits
  - process no longer needs memory it requested

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

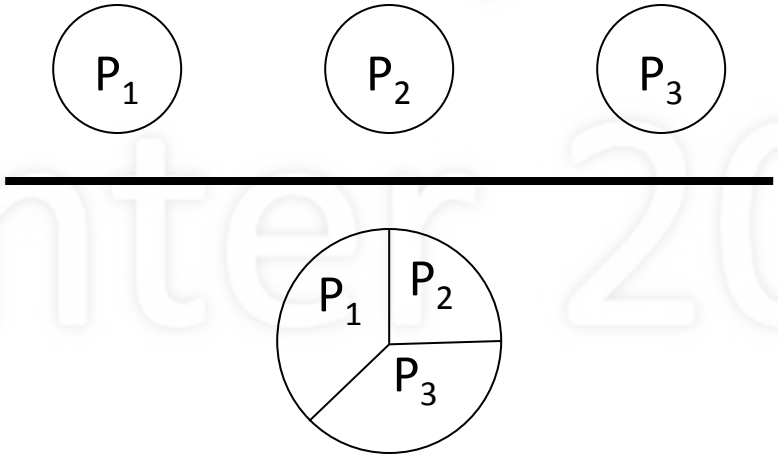
- Address space
  - Set of addresses to access memory
  - Typically, linear and sequential
  - 0 to *N*-1 (for size *N*)
- For process memory of size *N*
  - Text (of size *X*) at 0 to *X*-1
  - Data (of size *Y*) at *X* to *X*+*Y*-1
  - Stack (of size *Z*) at *N*-*Z* to *N*-1



Compiler's Model of Memory

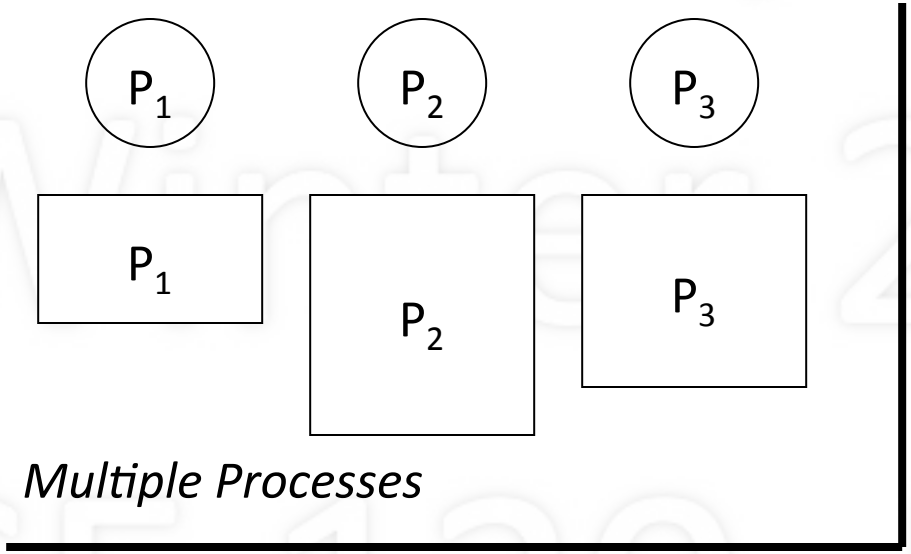
- Compiler generates memory addresses
  - Address ranges for text, data, stack
  - Allow data and stack to grow
- What is not known in compiler
  - Physical memory size (to place stack at high end)
  - Allocated regions of physical memory (to avoid)

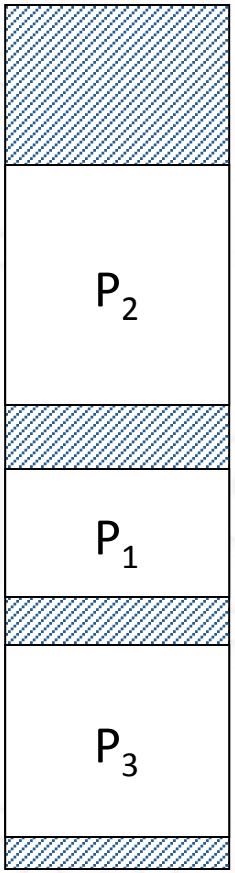
Goal: Support Multiple Processes



- 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





Sharing the Physical Memory

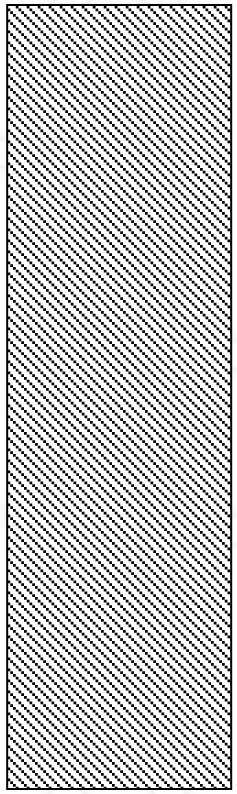
- If process given CPU, must also be in memory
- Problem
  - Context-switching time (CST): 10 µsec
  - Loading from disk: 10 MB/s
  - To load 1 MB process: 100 msec = 10,000 x CST
  - Too much overhead! Breaks illusion of simultaneity
- Solution: keep multiple processes in memory
  - Context switch only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

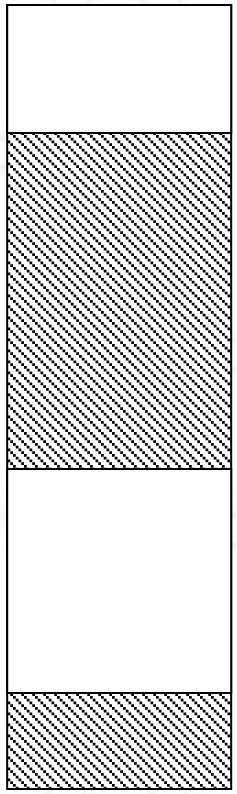
Memory Management Example

- Physical memory starts as one empty “hole”



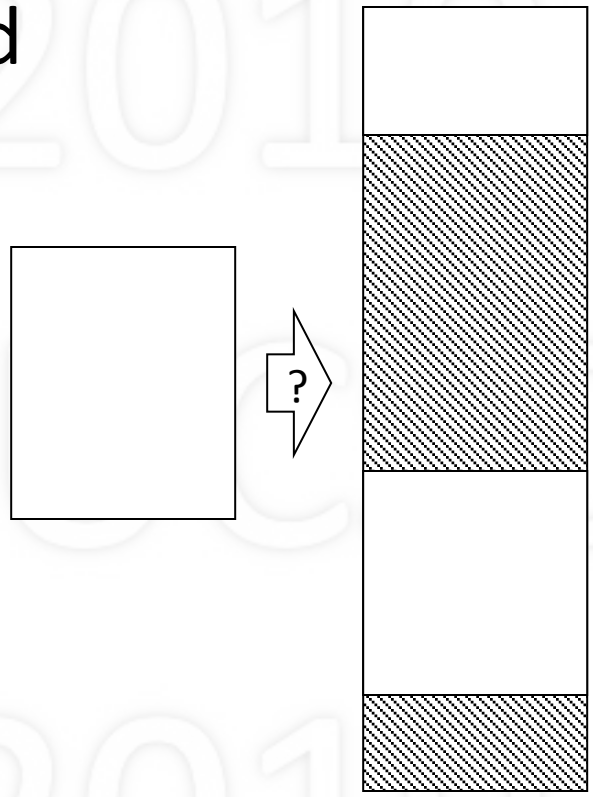
Memory Management Example

- 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”
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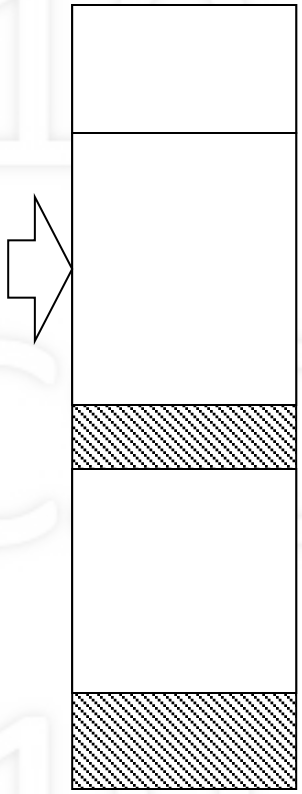
  - Allocate region within hole
  - Typically, leaves (smaller) hole



Memory Management Example

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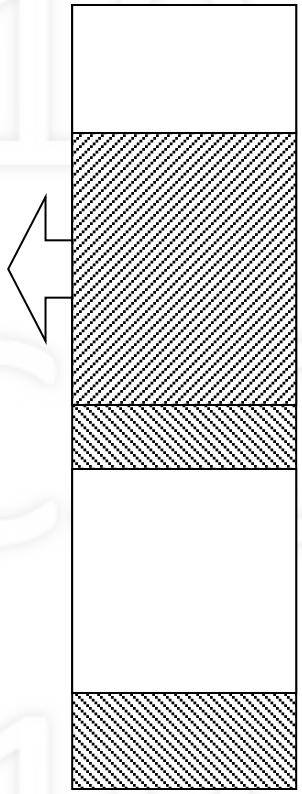
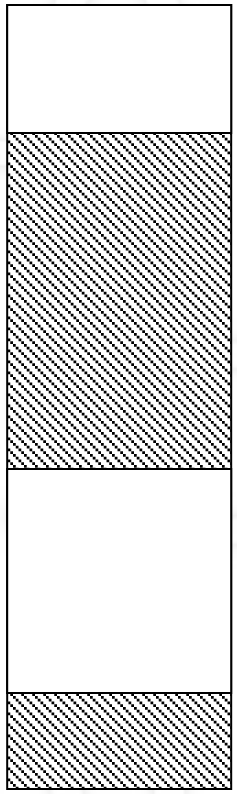
- When no longer needed, release



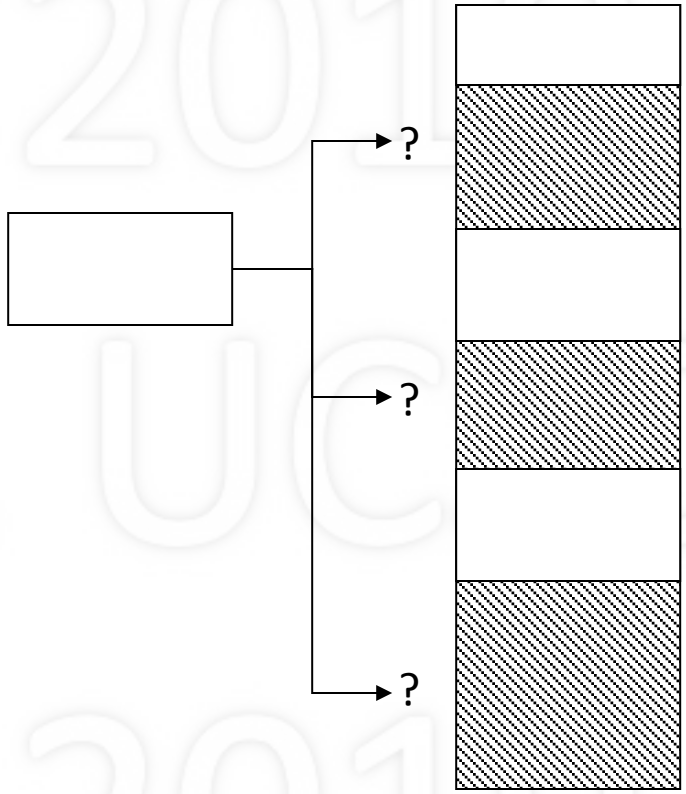
Memory Management Example

- 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



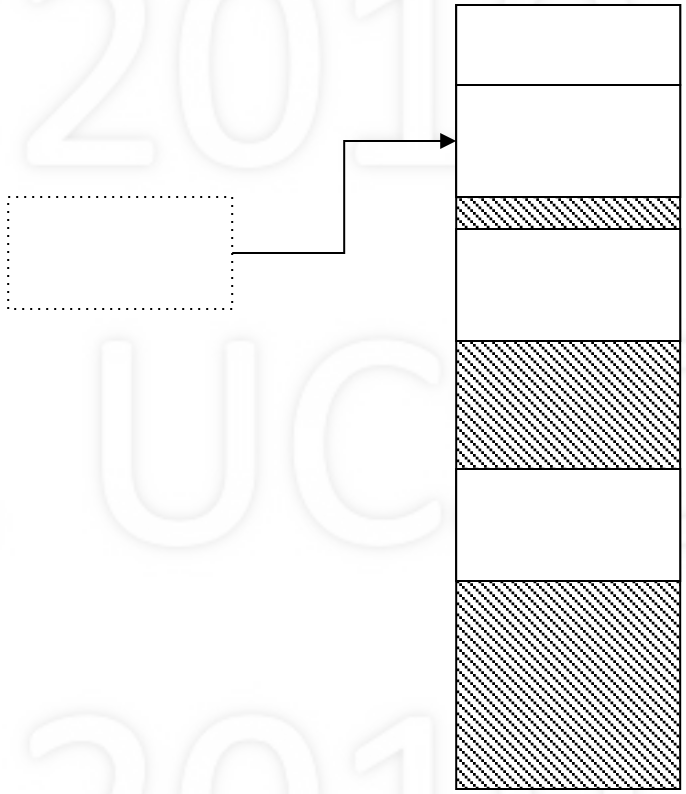
Selecting the Best Hole

- If there are multiple holes, which to select?



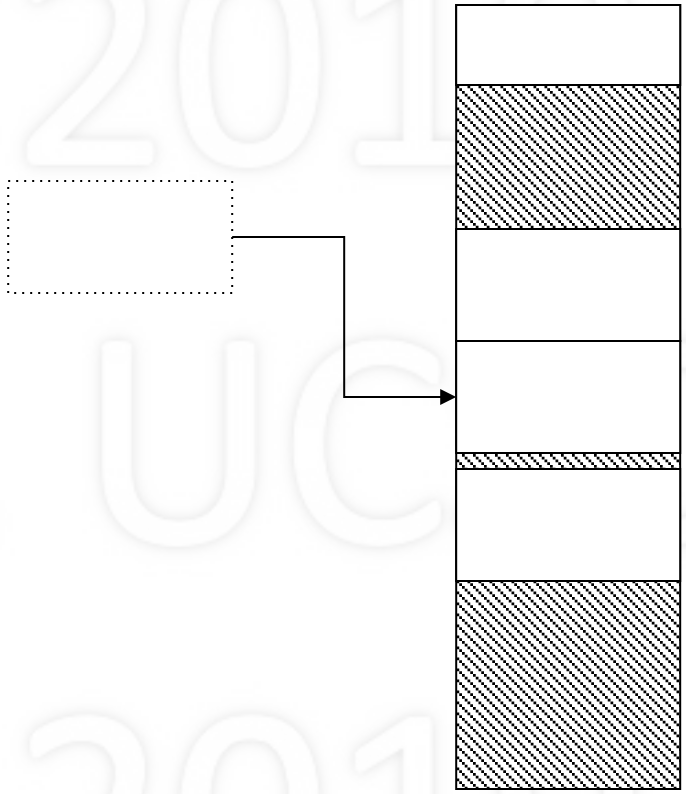
Selecting the Best Hole

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



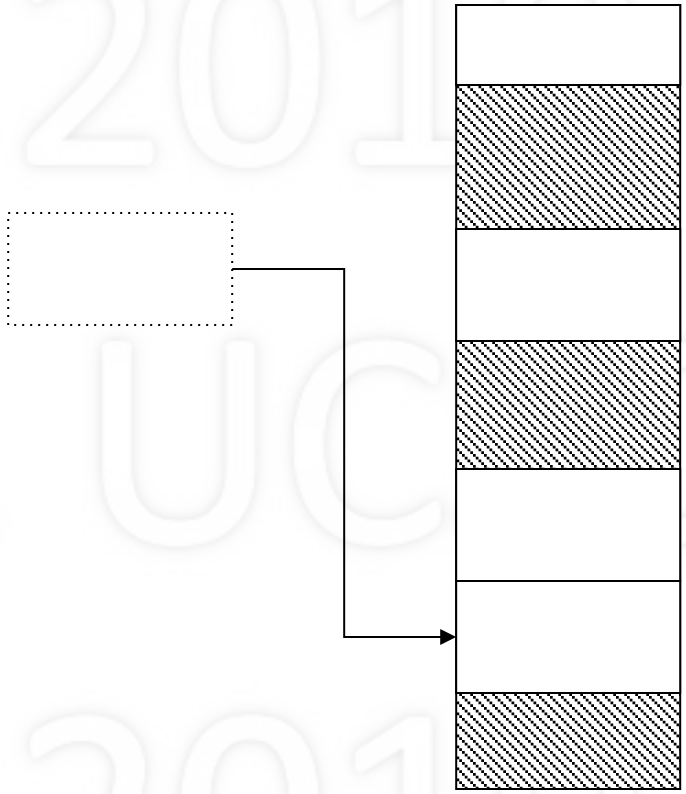
Selecting the Best Hole

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



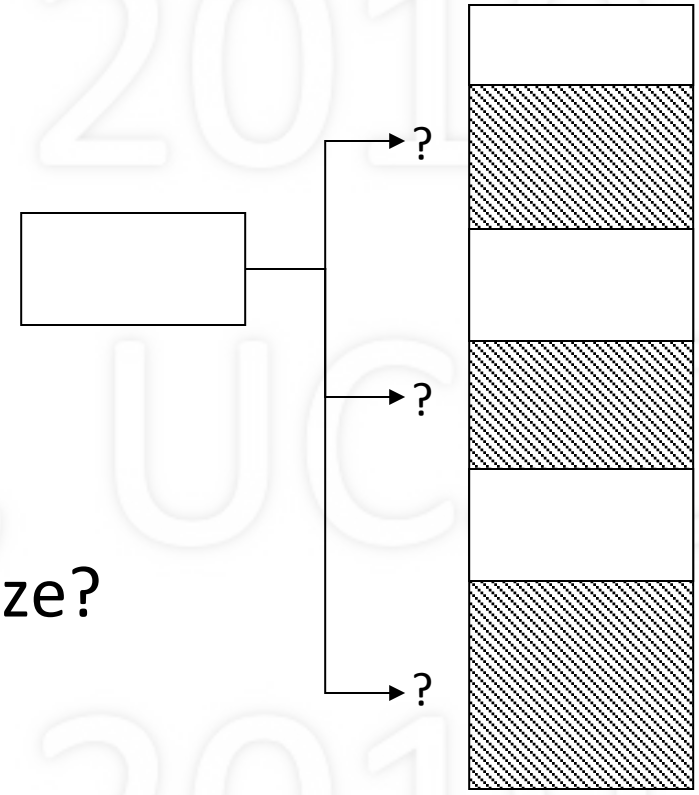
Selecting the Best Hole

- 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
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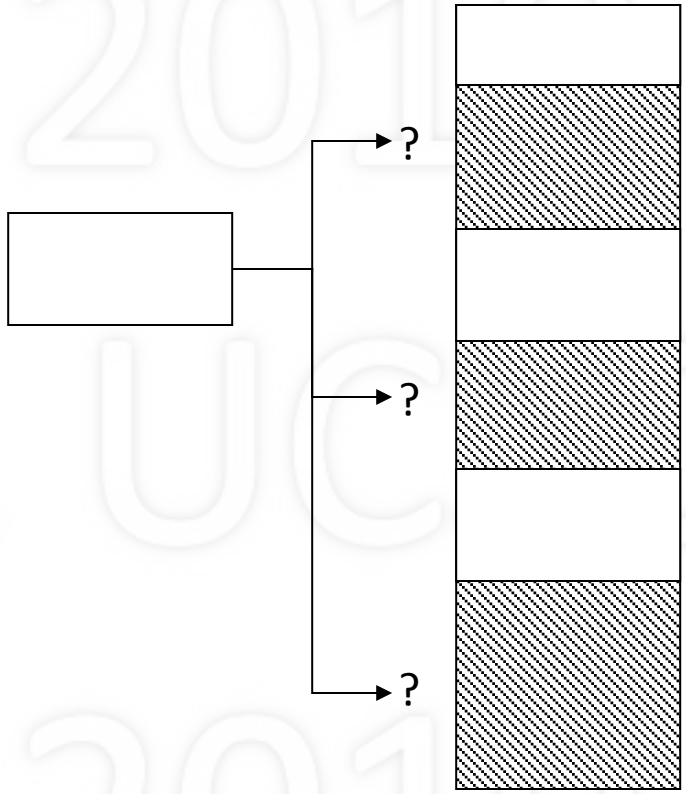
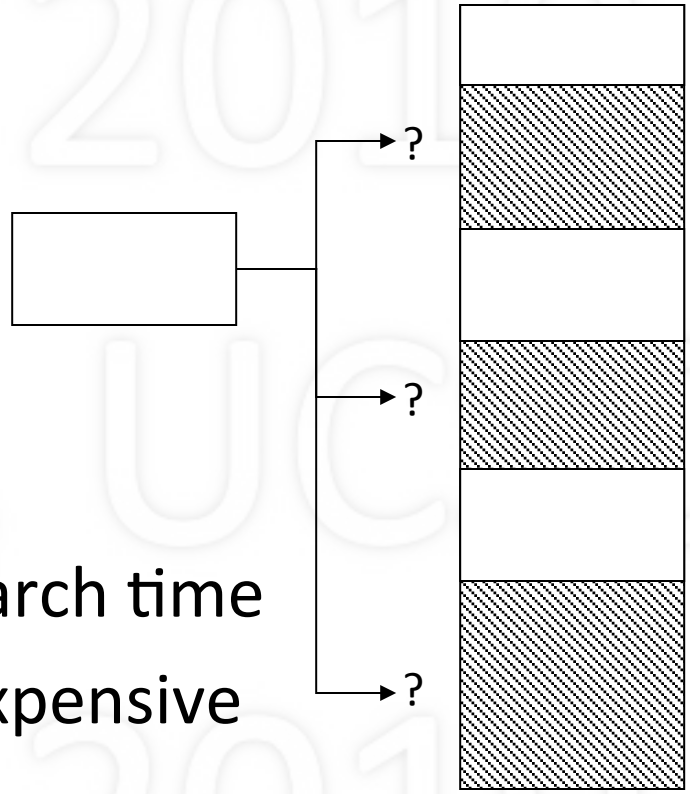
  - Worst fit
- So which is best?



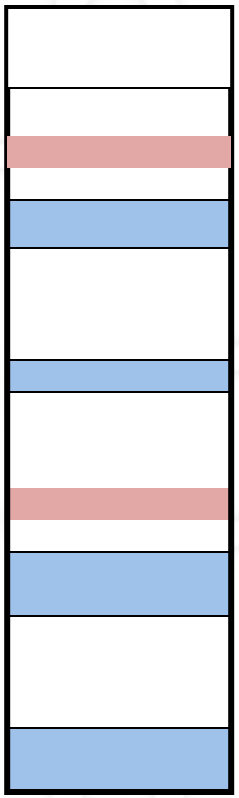
Selecting the Best Hole

- 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



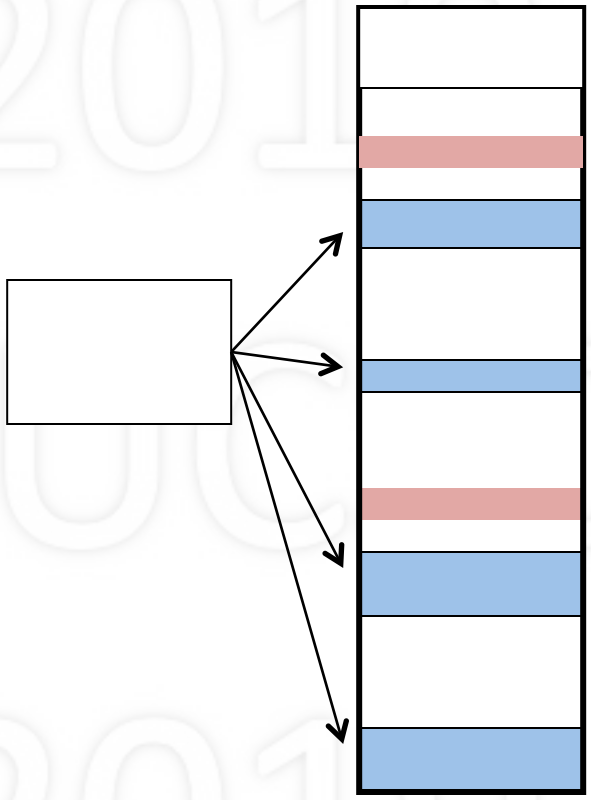
Fragmentation

- 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?)



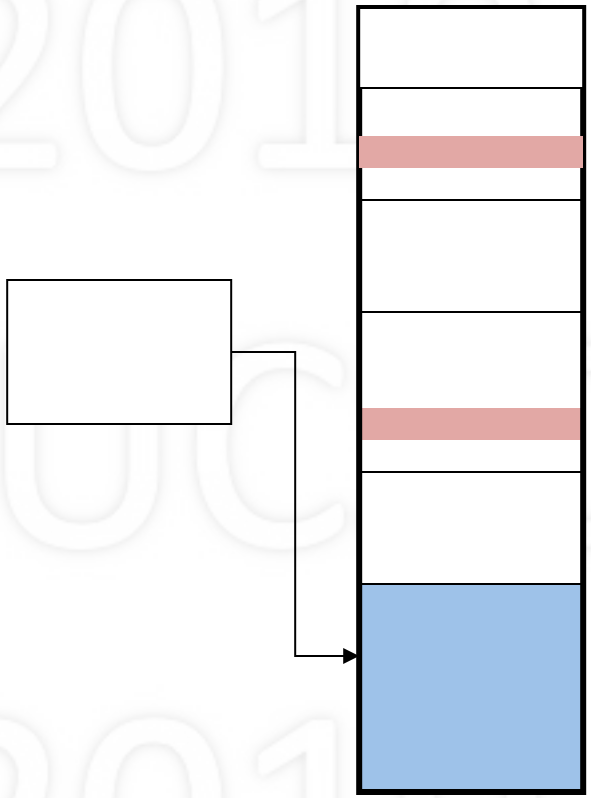
What if No Holes

- 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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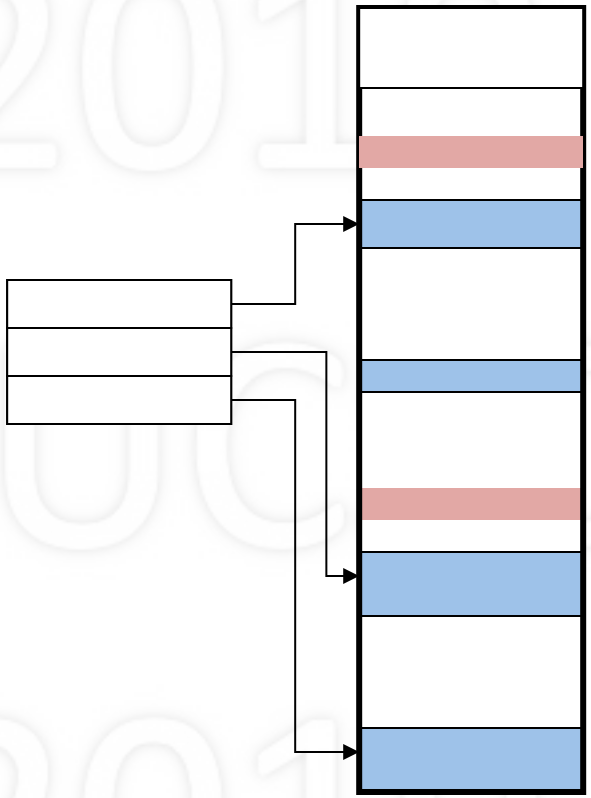
  - Internal fragments
- Approaches
  - Compaction
  - *Break block into sub-blocks*
    - *Easier to fit*
    - *But complex*



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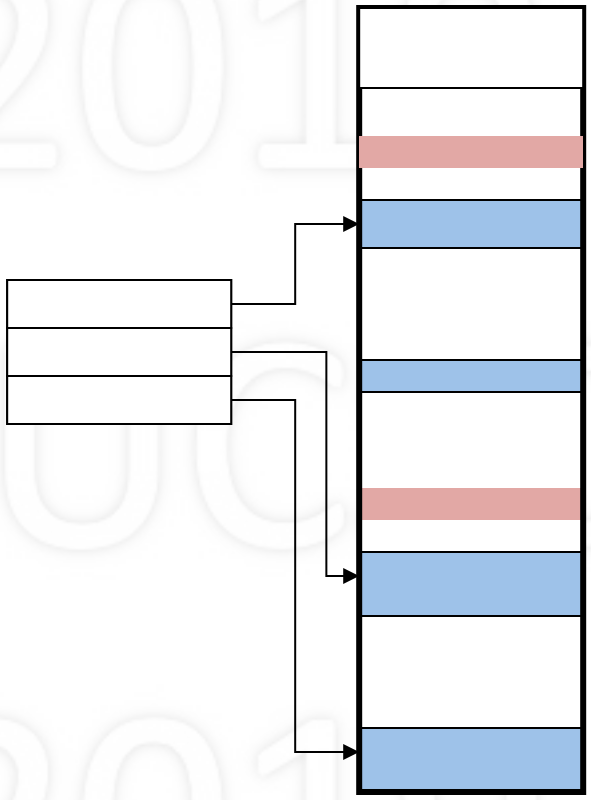

What if No Holes

- There may still be significant unused space
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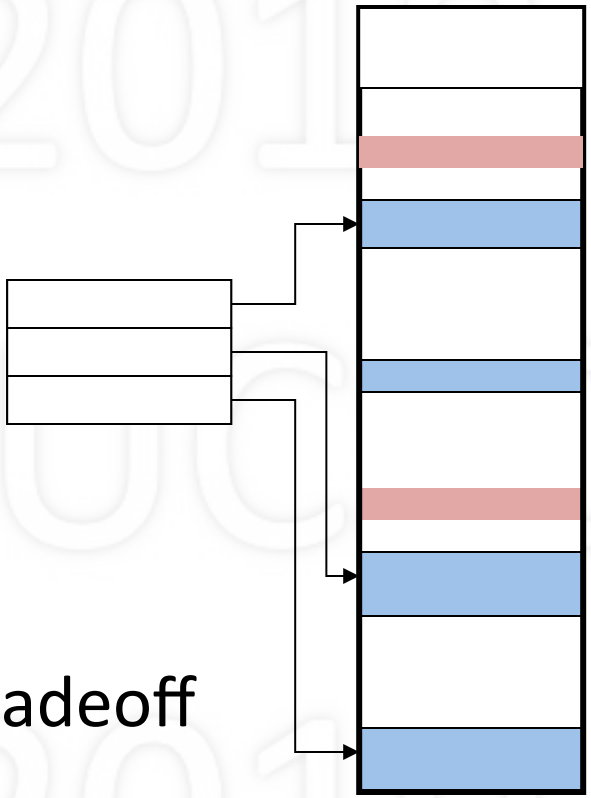
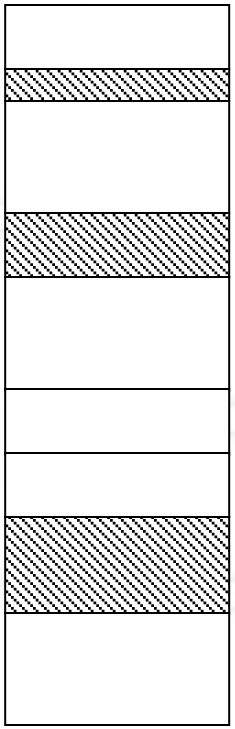
  - Break block into sub-blocks
- So which is best?
  - Consider time vs. complexity tradeoff



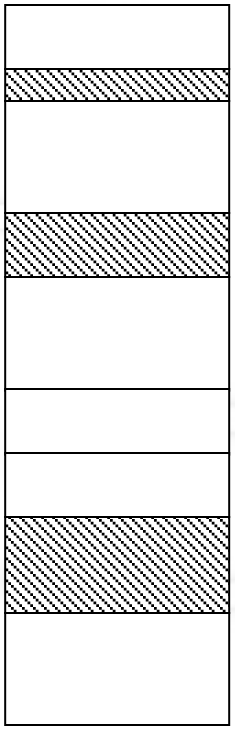
Given *n* blocks, how many holes?

- 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 = $n/2$



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

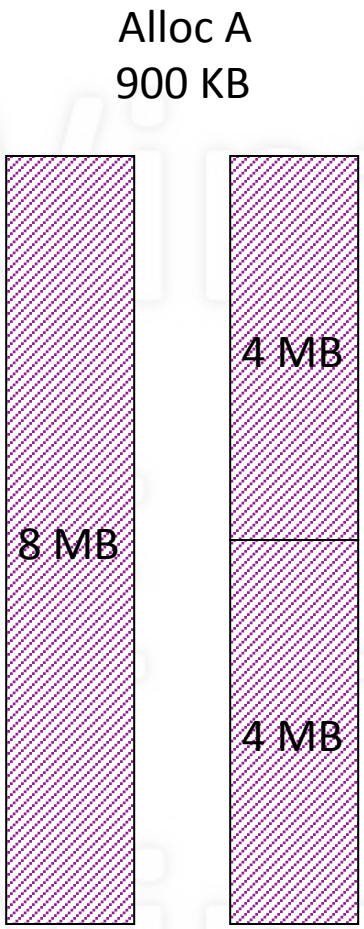
- Free: free the chunk and coalesce with buddy

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

Example of Buddy System

Alloc A
900 KB

Example of Buddy System



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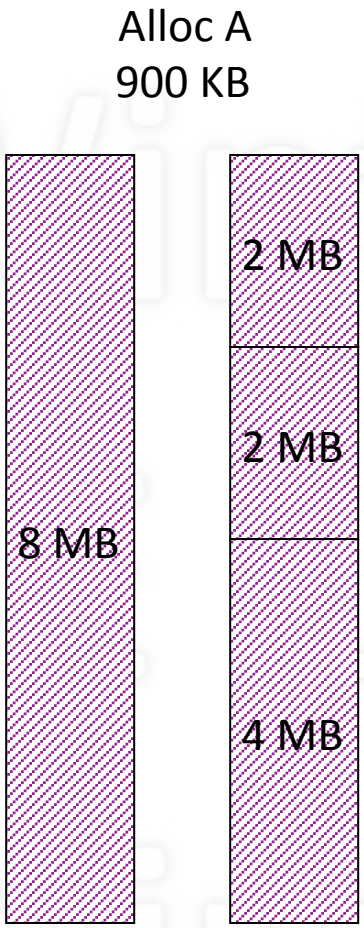

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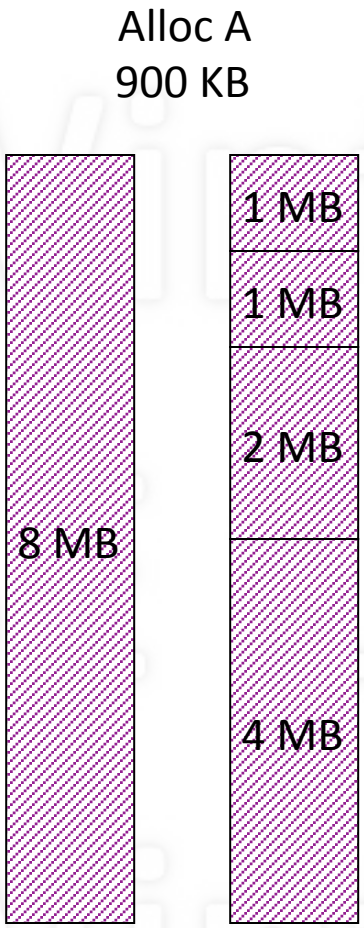

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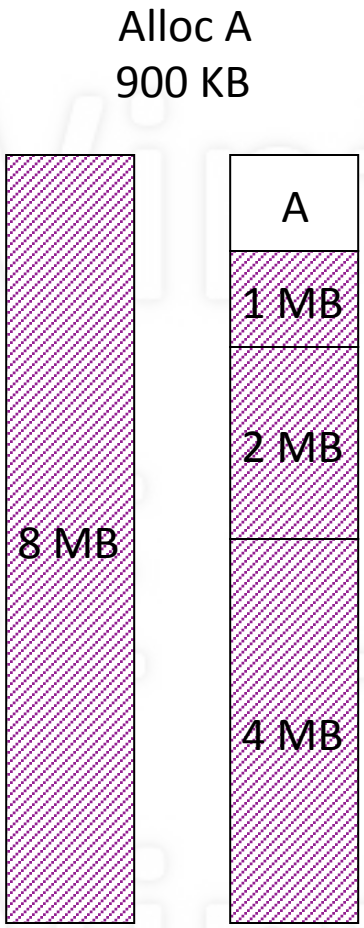

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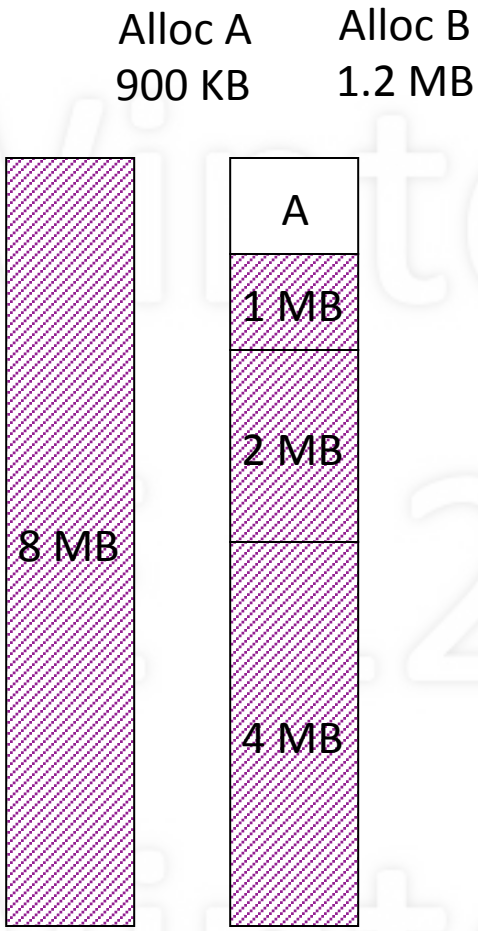

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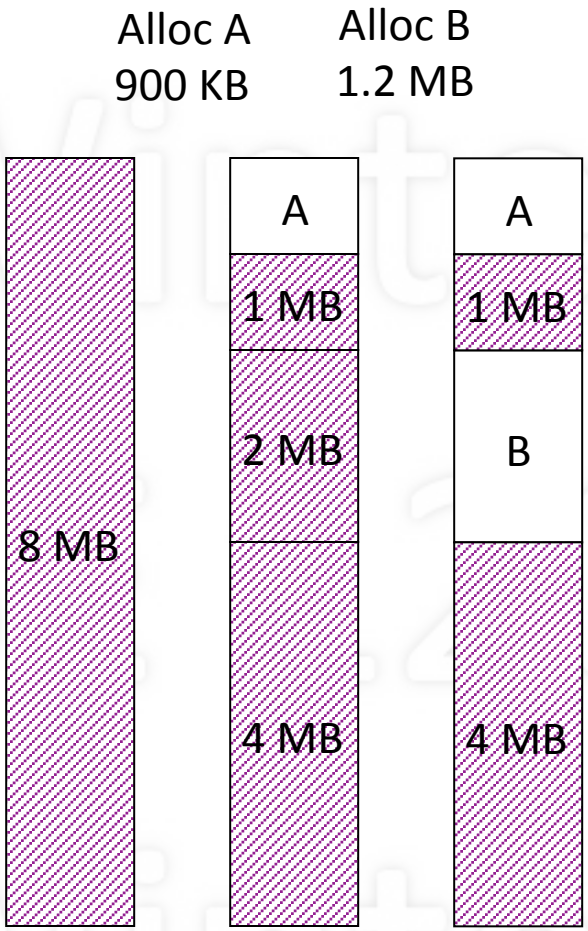

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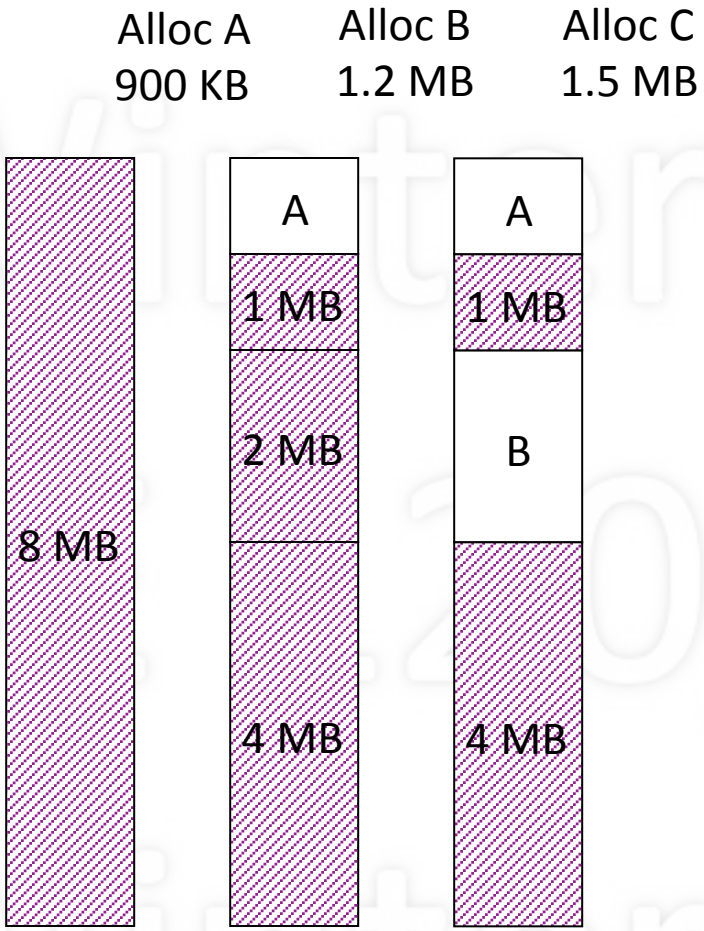

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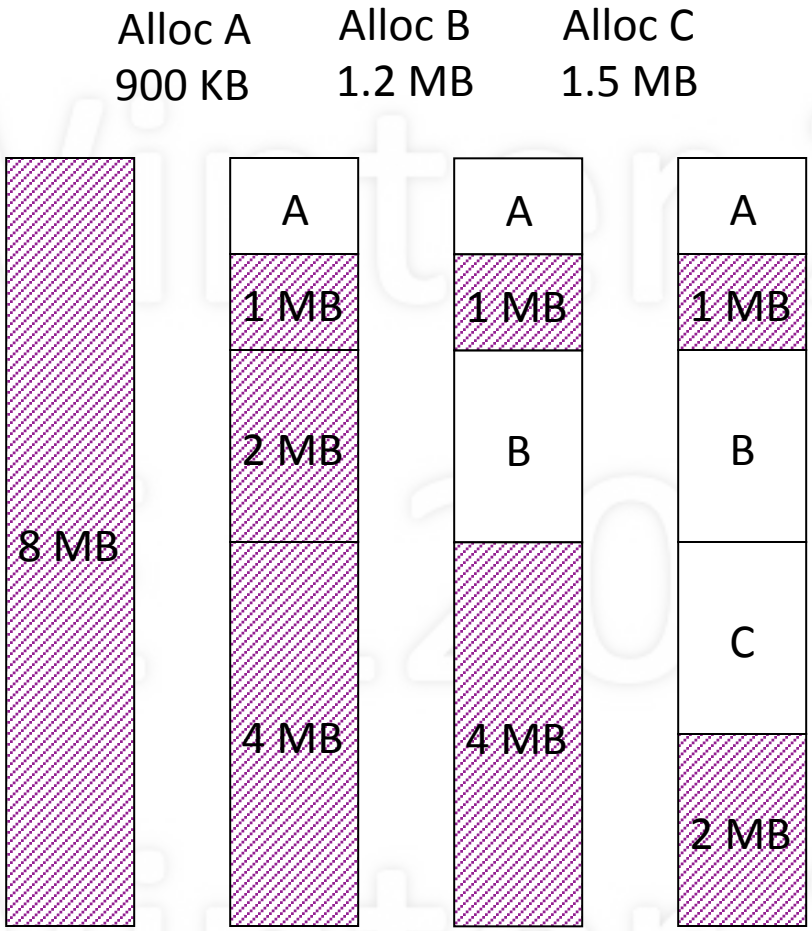

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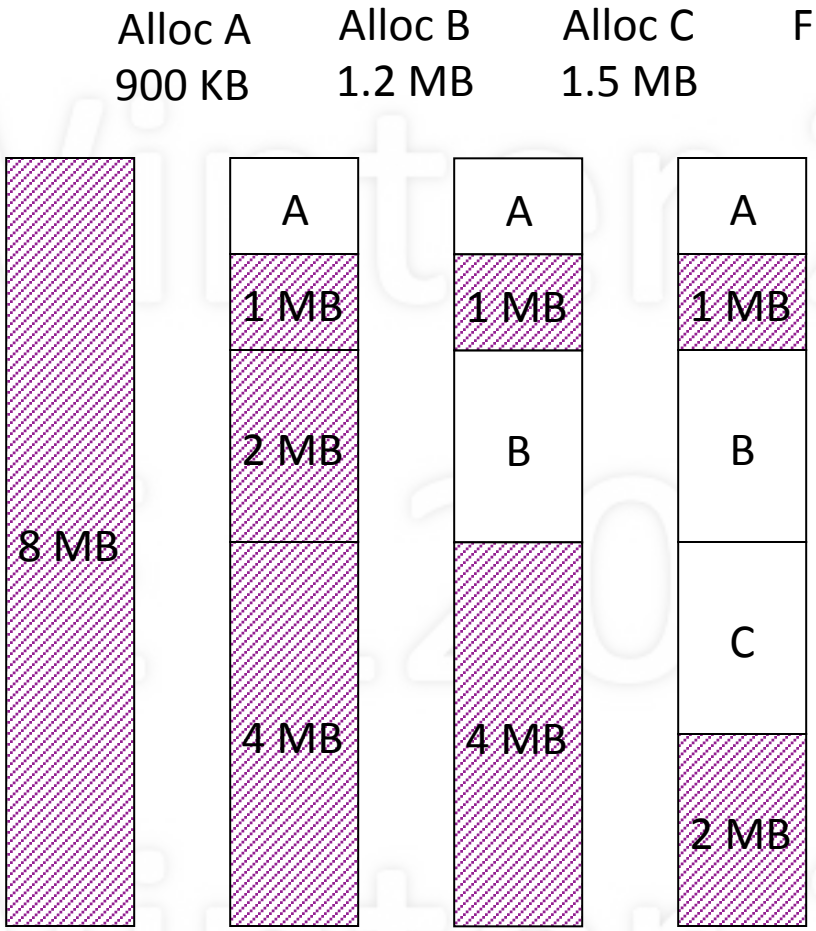

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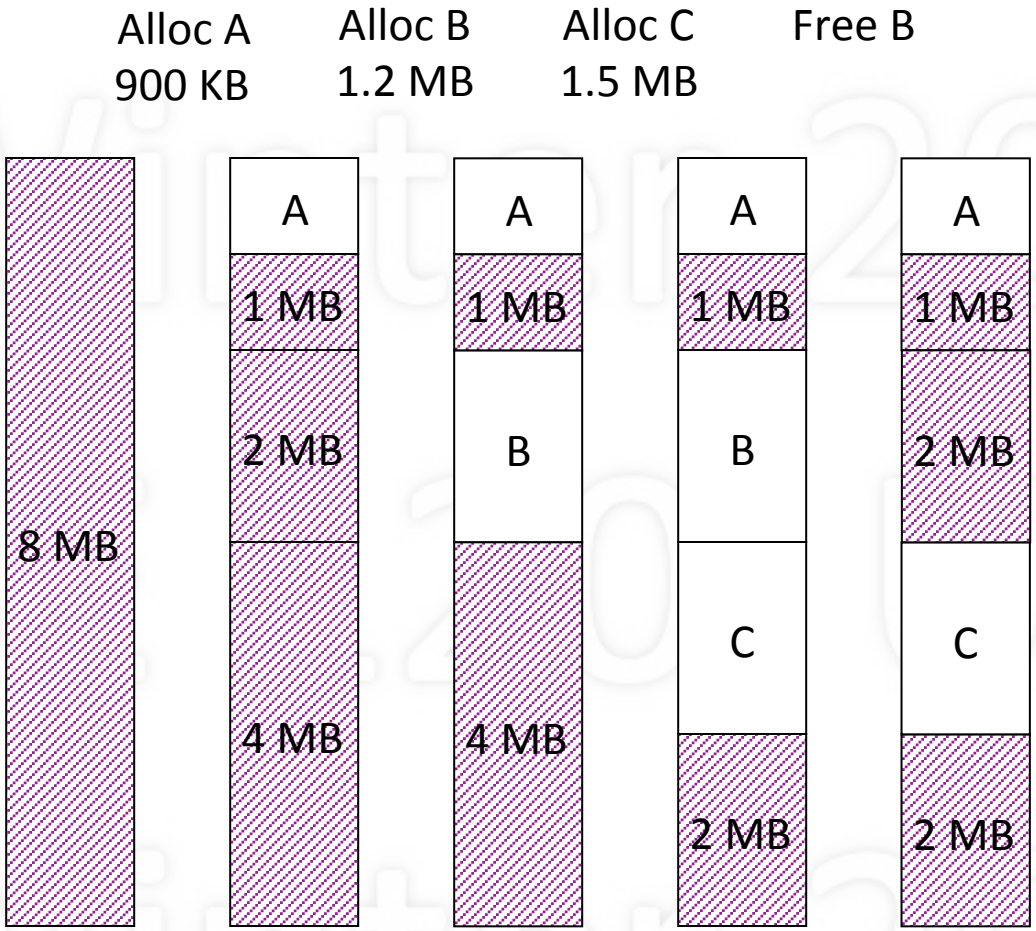

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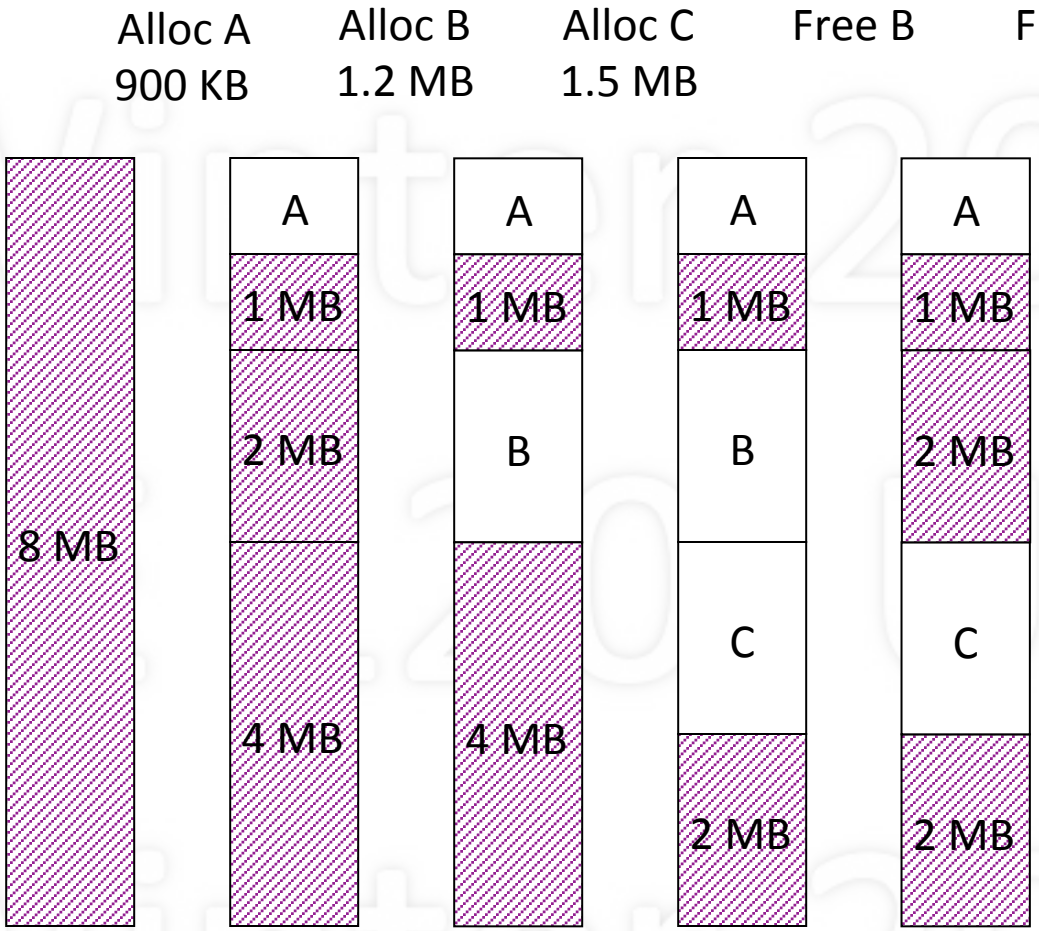
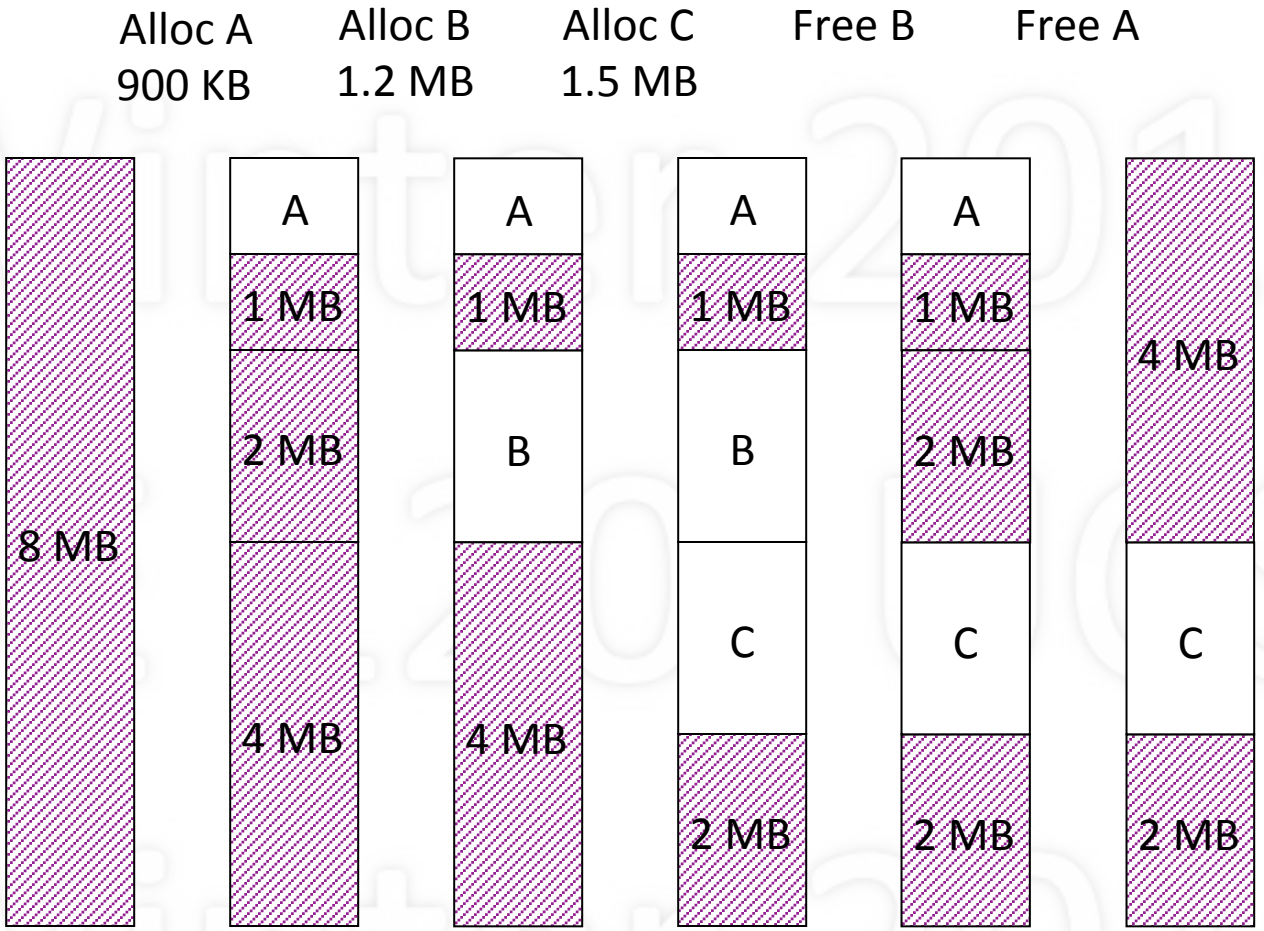
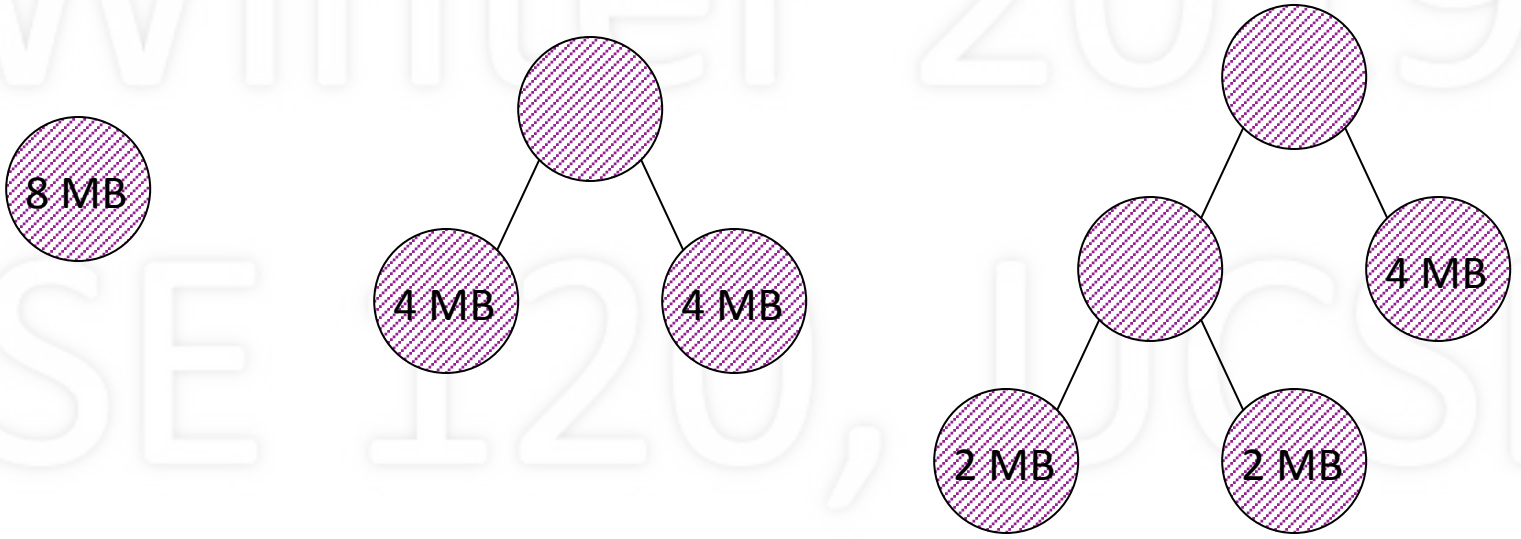


Example of Buddy System



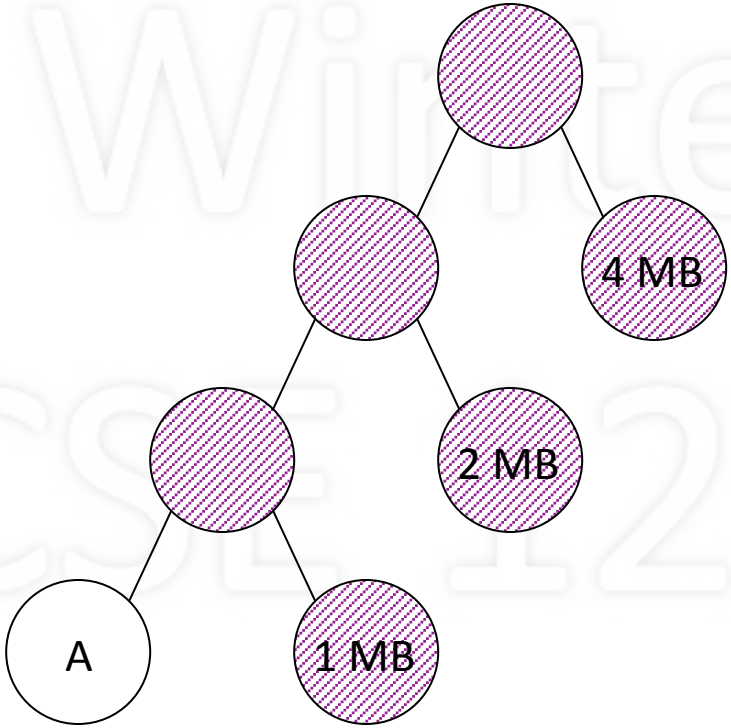
Data Structure for Buddy System

Alloc A: 900 KB

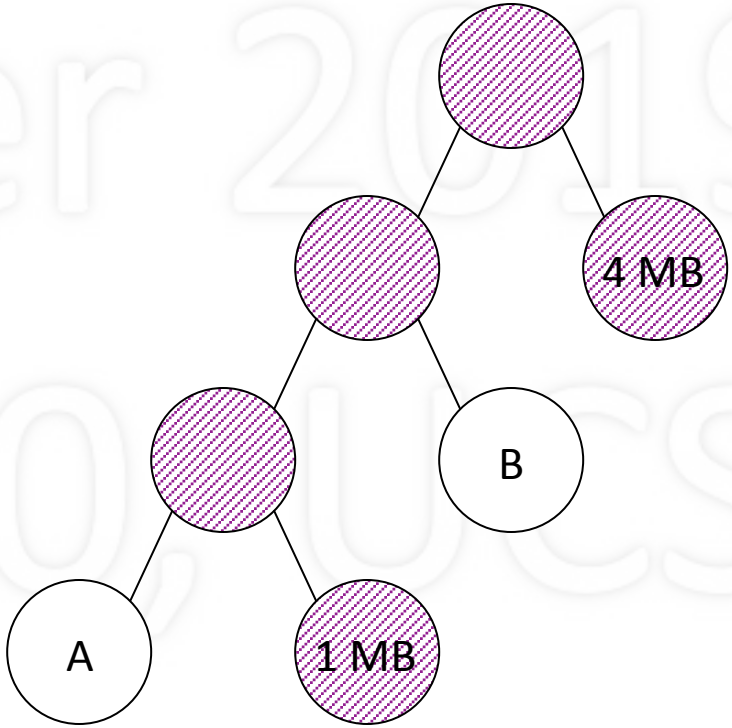


Data Structure for Buddy System

Alloc A: 900 KB

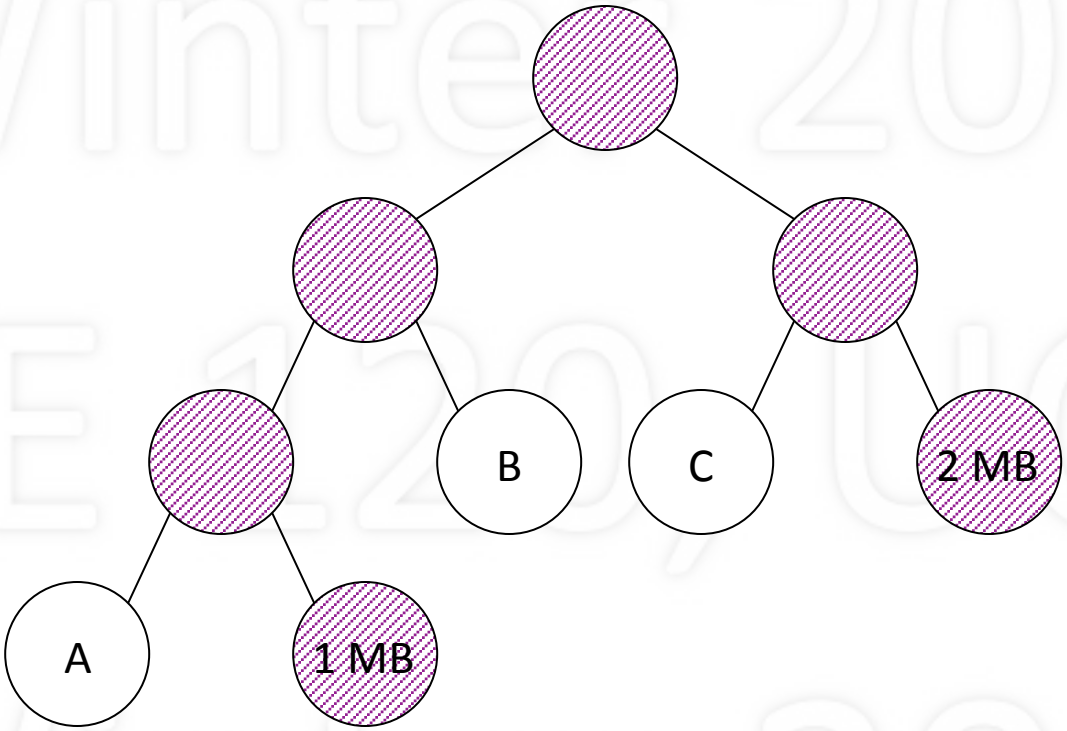


Alloc B: 1.2 MB

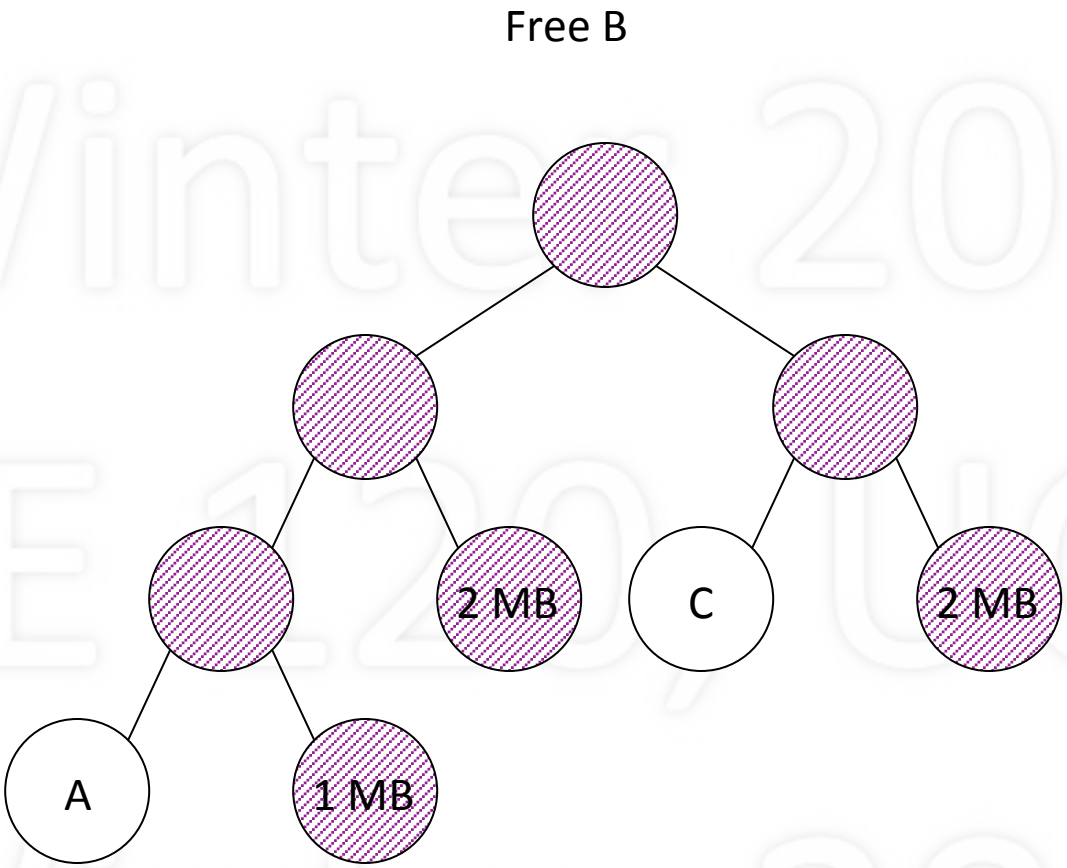


Data Structure for Buddy System

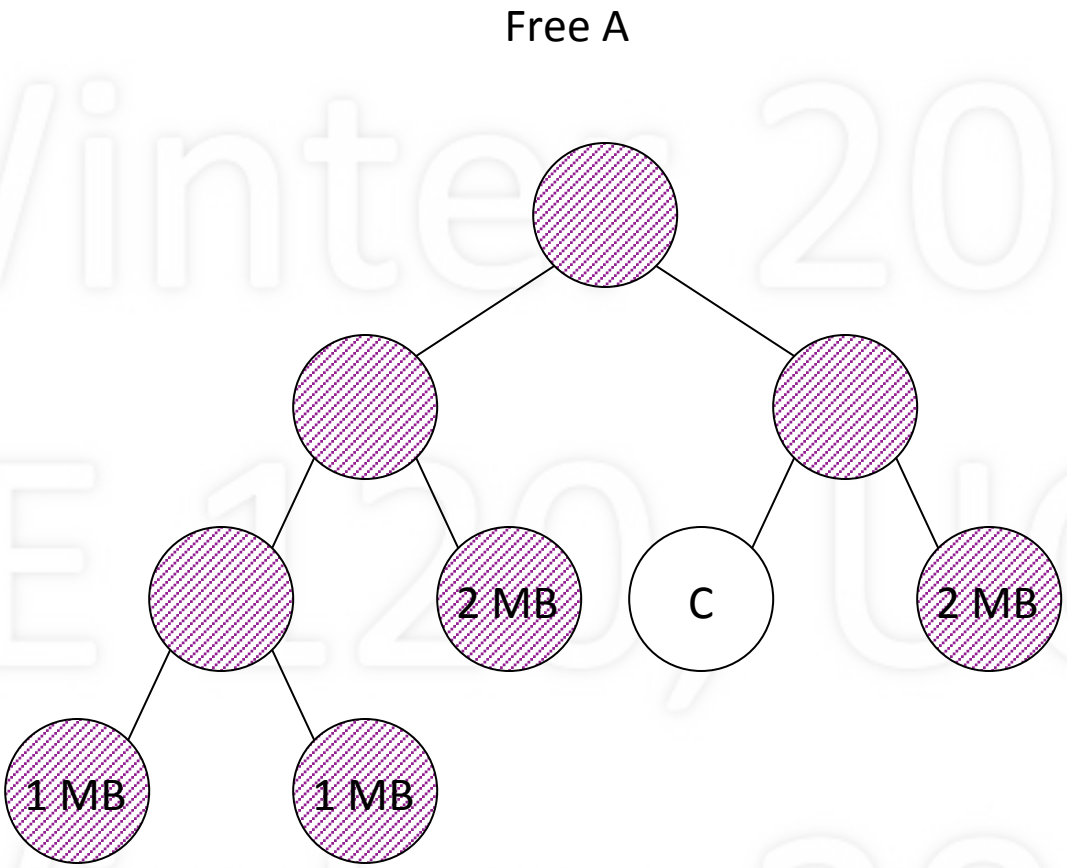
Alloc C: 1.5 MB



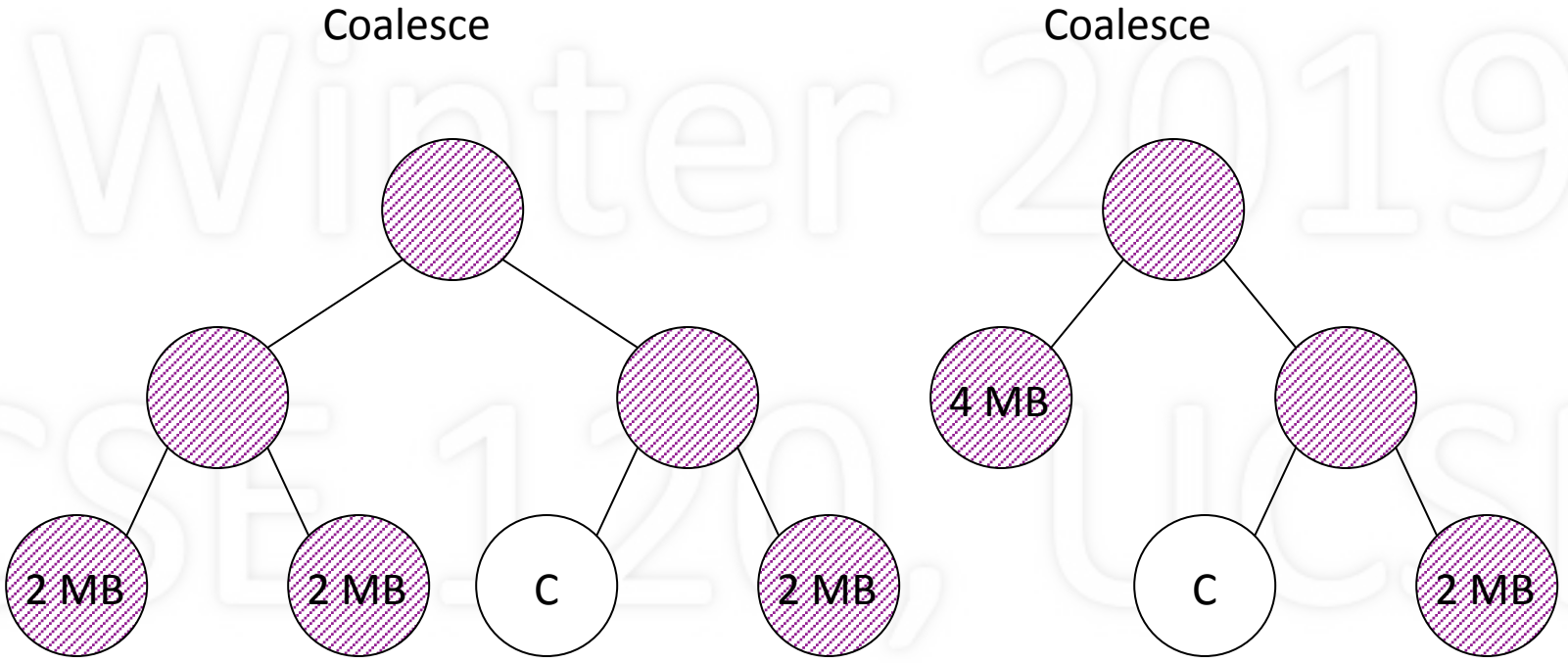
Data Structure for Buddy System



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

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

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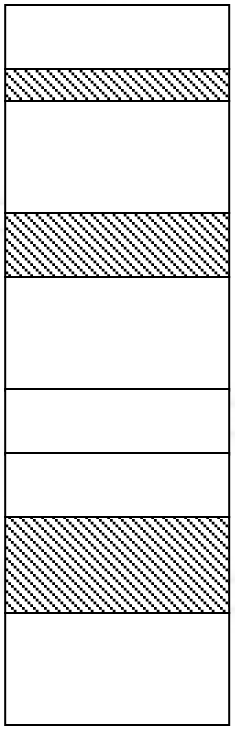
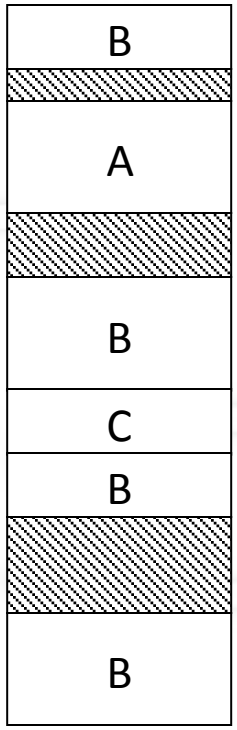
Supplementary: Proof of 50% Rule

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



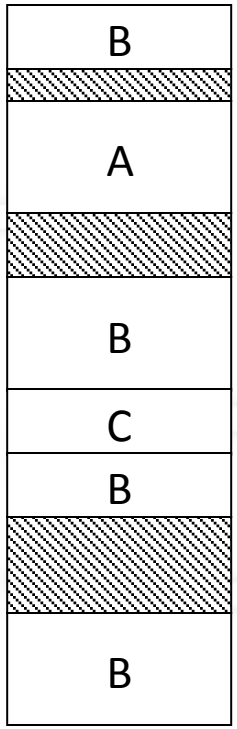
Proof of 50% Rule: Types of Blocks

- 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

Review & Research

- The is meant by “process memory”?
- What is contained in the Text? Data? Stack?
- Why should there be different memory areas? **
- What is an address space?
- Where are the Text, Data, and Stack located in a process’s address space, and for each, why? **

R&R

- What is the compiler's model of memory?*
- How does the memory layout in slide 4 relate to the compiler's model of memory?**
- What are the key aspects of memory NOT known by the compiler, and why are they not known?**

R&R

- How does the goal of supporting multiple processes affect how memory is allocated?**
- How is this related (if at all) to time-sharing? ***
- What is memory management?
- What is meant by a “hole”?
- When a memory region is allocated, how does this affect the number and size of holes?*

R&R

- What is “First fit”, how does it work, and what are its pros and cons?
- What is “Best fit”, how does it work, and what are its pros and cons?
- What is “Worst fit”, how does it work, and what are its pros and cons?
- For each of the above, what effect do variable size memory regions have?***

R&R

- What analysis can be done to determine which memory allocation method is best?**
- What is fragmentation?
- What is internal fragmentation?
- What is external fragmentation?
- Which type of fragmentation do you think is worse, and why?***

R&R

- When trying to allocate memory of a certain size, what if there is no large enough hole?*
- What is compaction, and is it a good idea?**
- What are the pros and cons of breaking up blocks into sub-blocks?*
- What analysis can be done to determine whether compaction or breaking blocks into sub-blocks is best?**

R&R

- Given a memory with n blocks allocation, what is the minimum number of holes there can be?** the maximum?**
- What is the 50% Rule?
- Does the 50% Rule say anything about how much memory is being wasted?*
- What is the proof for the 50% Rule?***

R&R

- What is the Unused Memory Rule, and what does it say?*
- Why is “k” a key parameter for the Unused Memory Rule: what does it mean?*
- How does the amount of wasted memory vary as a function of k, and why (give an intuitive reason)?**
- Can you prove the Unused Memory Rule?***

R&R

- What is the value of pre-sizing holes?*
- What are the pros and cons of pre-sized holes that are all the same size?*
- What are the pros and cons of pre-sized holes that variable size?*
- If memory is divided into pre-sized holes, is it more susceptible to internal fragmentation or external fragmentation, and why?**

R&R

- What is the Buddy System?
- How does the Buddy System work when allocating memory?* when freeing memory?*
- Is the Buddy System more susceptible to internal fragmentation or external fragmentation, and why?**
- What is the rationale for the Buddy System in how it allocates and frees memory?***

R&R

- Why is a binary tree a good data structure for implementing the Buddy System?*

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