CSCI-UA.0201

Computer Systems Organization

Memory Management – Dynamic Allocation

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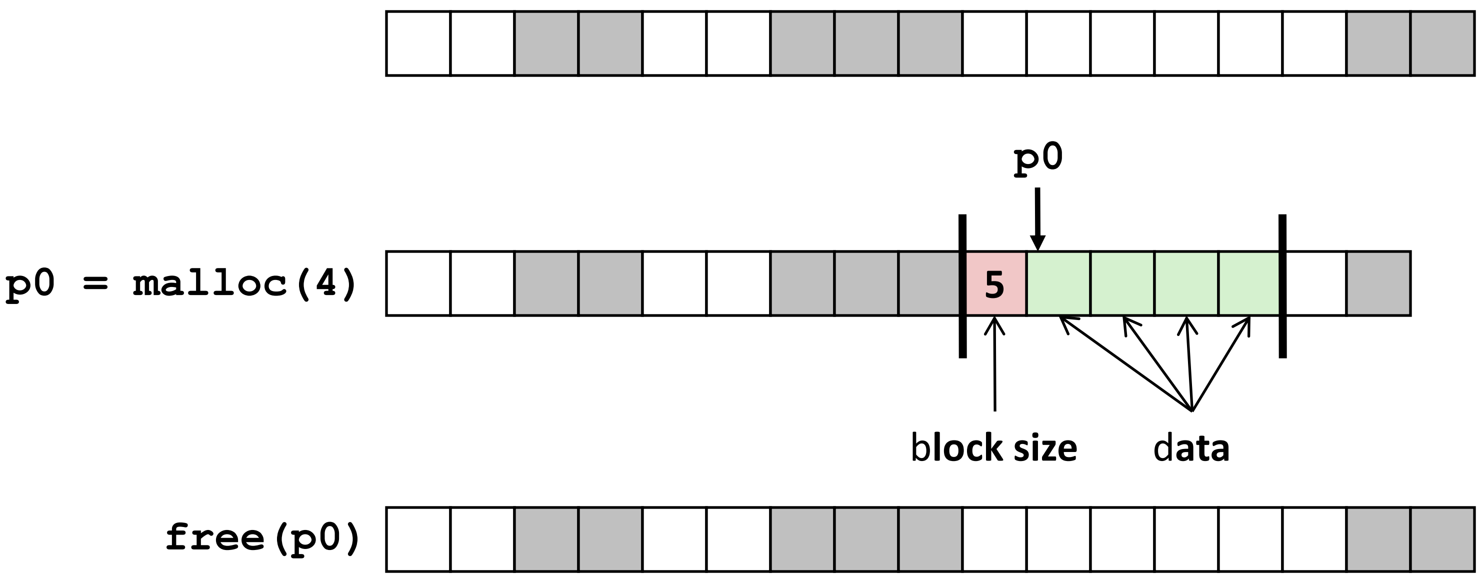
Malloc design choices

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a space that is smaller than the free block it is placed in?
- How do we pick a block to use for allocation -- many might fit?
- How do we reinsert freed block?

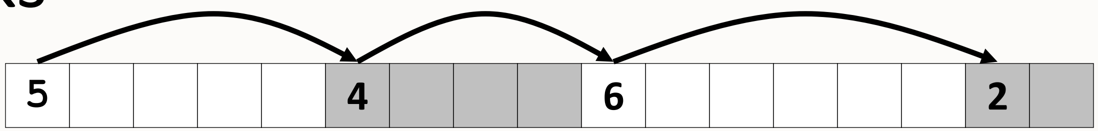
Knowing How Much to Free

- Standard method
  - Keep the length of a block in the header field preceding the block.
  - Requires header overhead for every allocated block



Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



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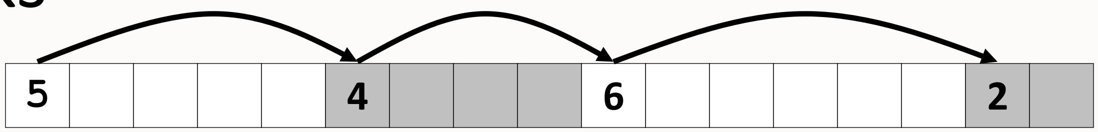
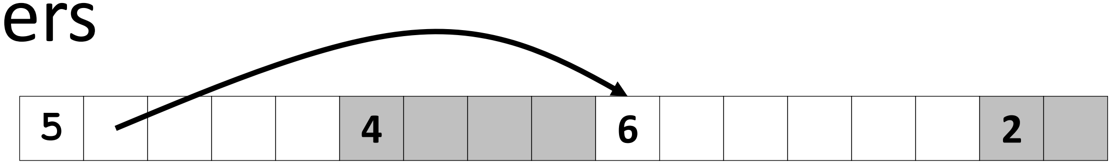


- Method 2: *Explicit list* among the free blocks using pointers



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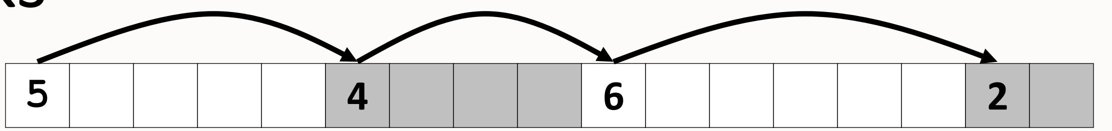

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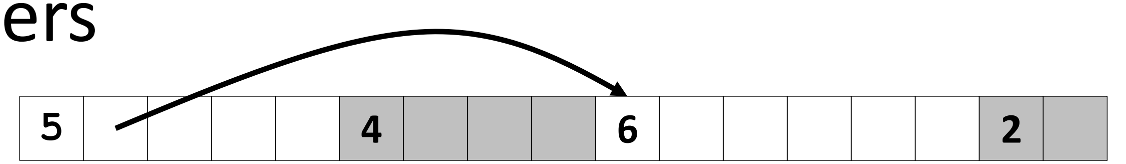
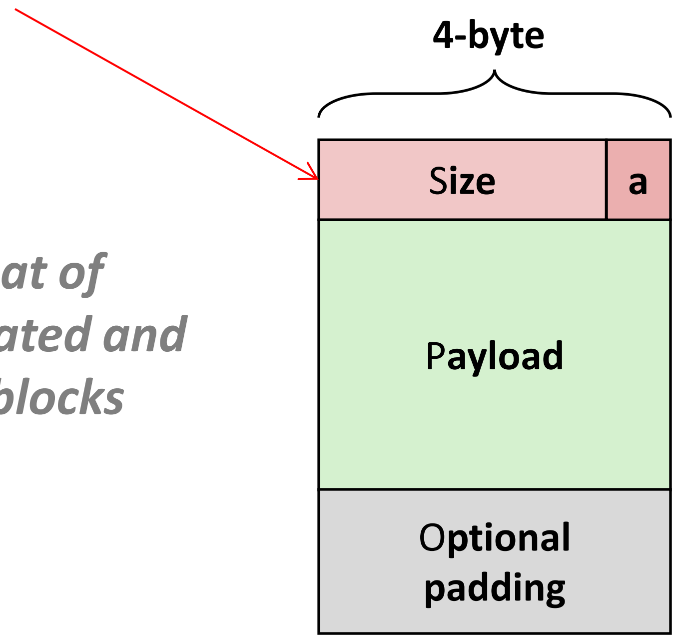


- Method 3: *Segregated free list*
  - Different free lists for different size classes

Method 1: Implicit List

- Malloc grows a contiguous region of heap by calling sbrk()
- Heap is divided into variable-sized blocks
- For each block, we need both size and allocation status

header + payload + padding



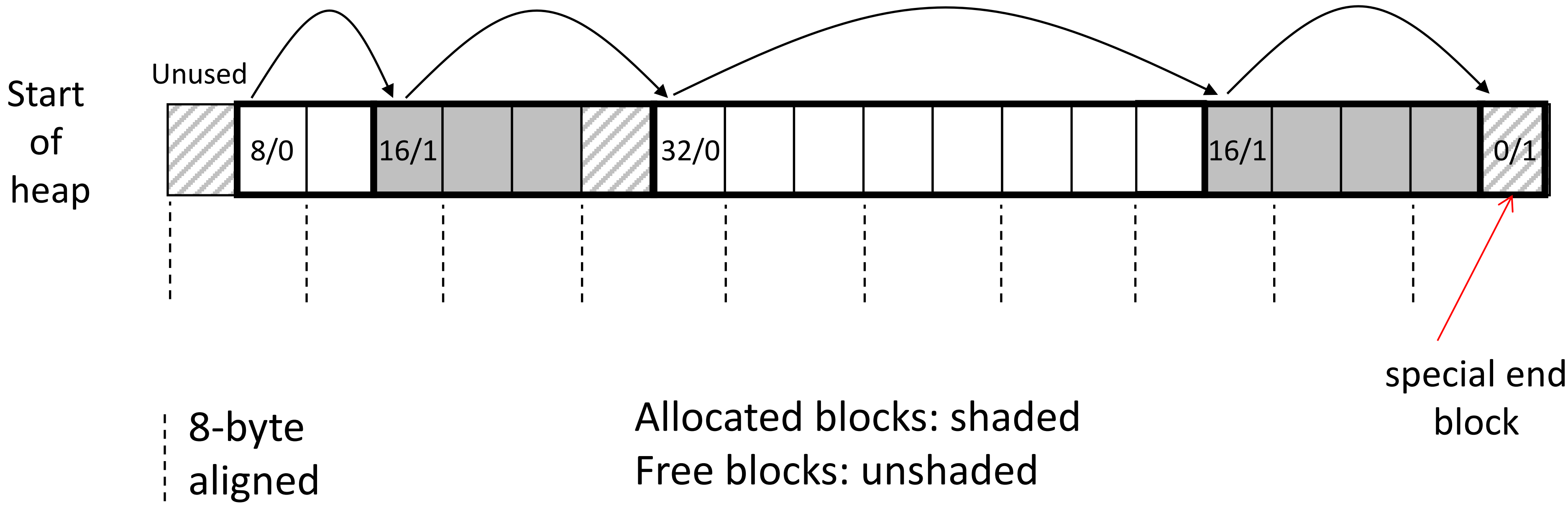
Format of allocated and free blocks

a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example



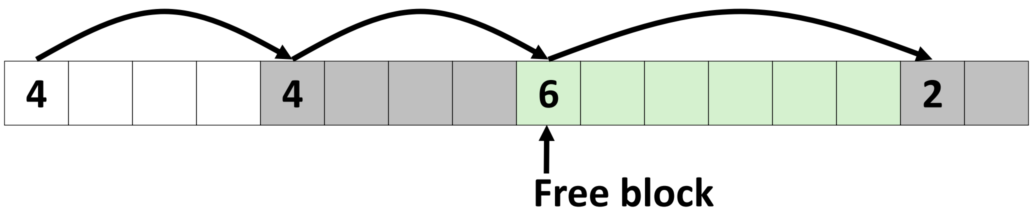
Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit
Each square represents 4 bytes

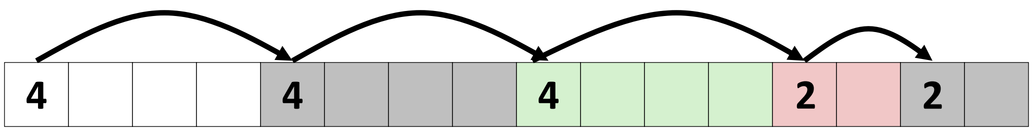
Implicit List: Finding a Free Block

- *First fit:*
  - Search from beginning, choose ***first*** free block that fits:
- *Next fit:*
  - Like first fit, except search starts where previous search finished
- *Best fit:*
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over (i.e. pick the smallest block that is big enough for the payload)
  - Keeps fragments small
  - Will typically run slower than first fit

Implicit List: Allocating in Free Block

- Allocating in a free block: *splitting*
  - Since allocated space might be smaller than free space, we might want to split the block

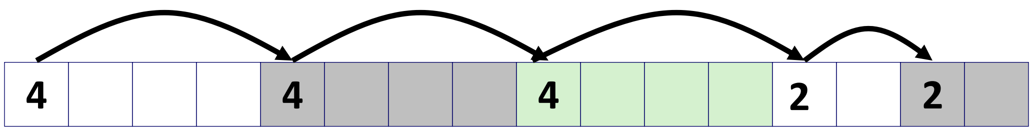




After malloc(4)

Implicit List: Freeing a Block

- Simplest implementation:
  - Need only clear the "allocated" flag
  - But can lead to "false fragmentation"



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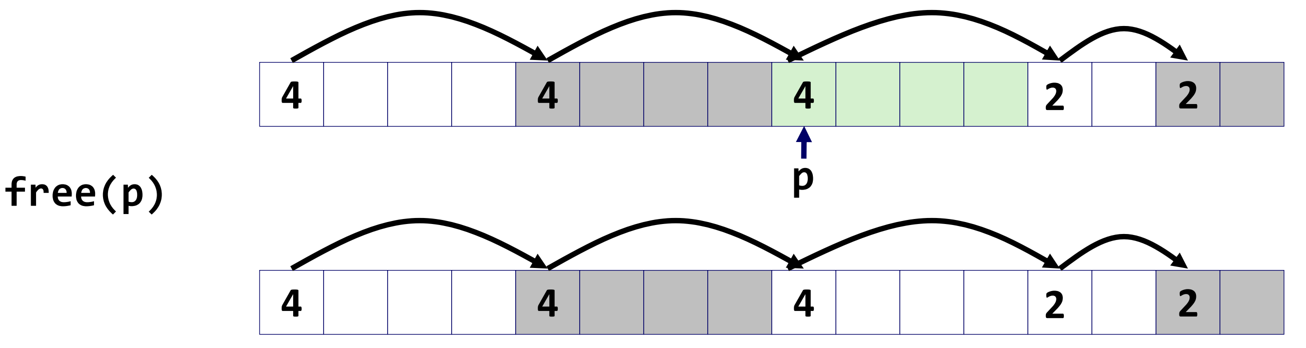

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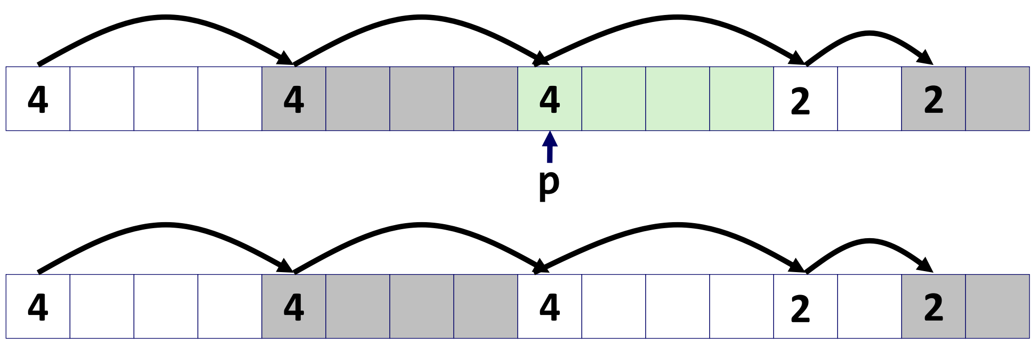
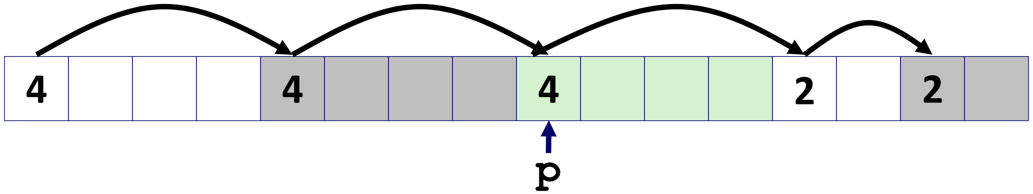


`free(p)`

`malloc(5)` ***Oops!***

Implicit List: Coalescing

- Join *(coalesce)* with next/previous blocks, if they are free
  - Coalescing with next block



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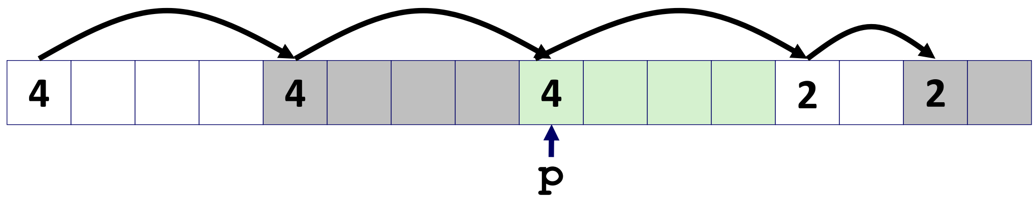

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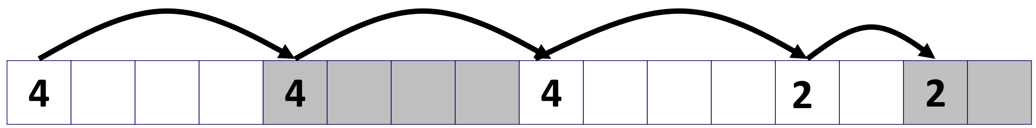

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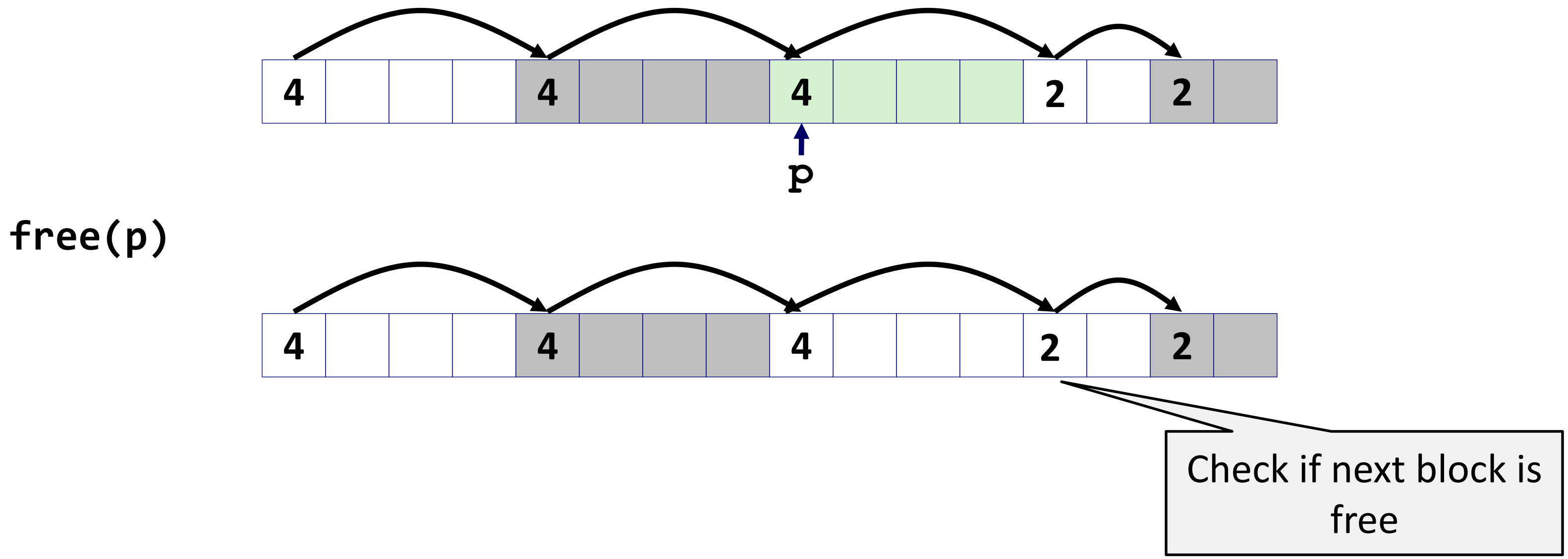

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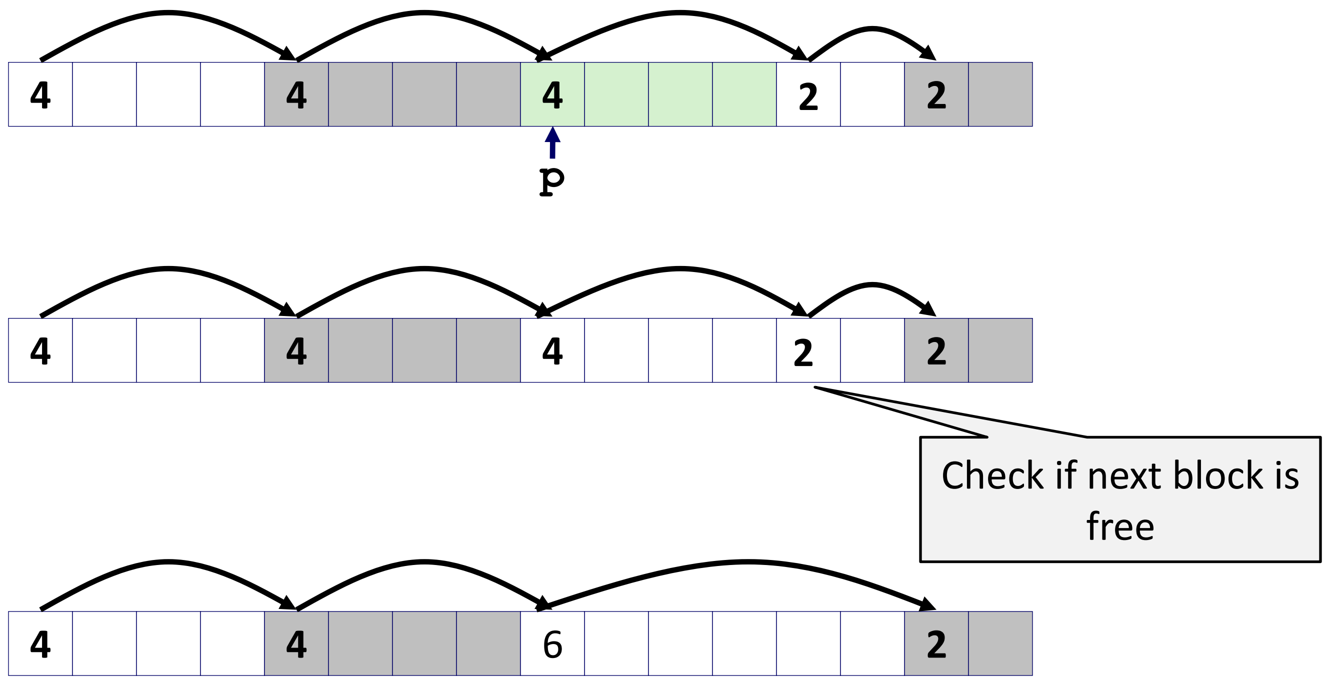

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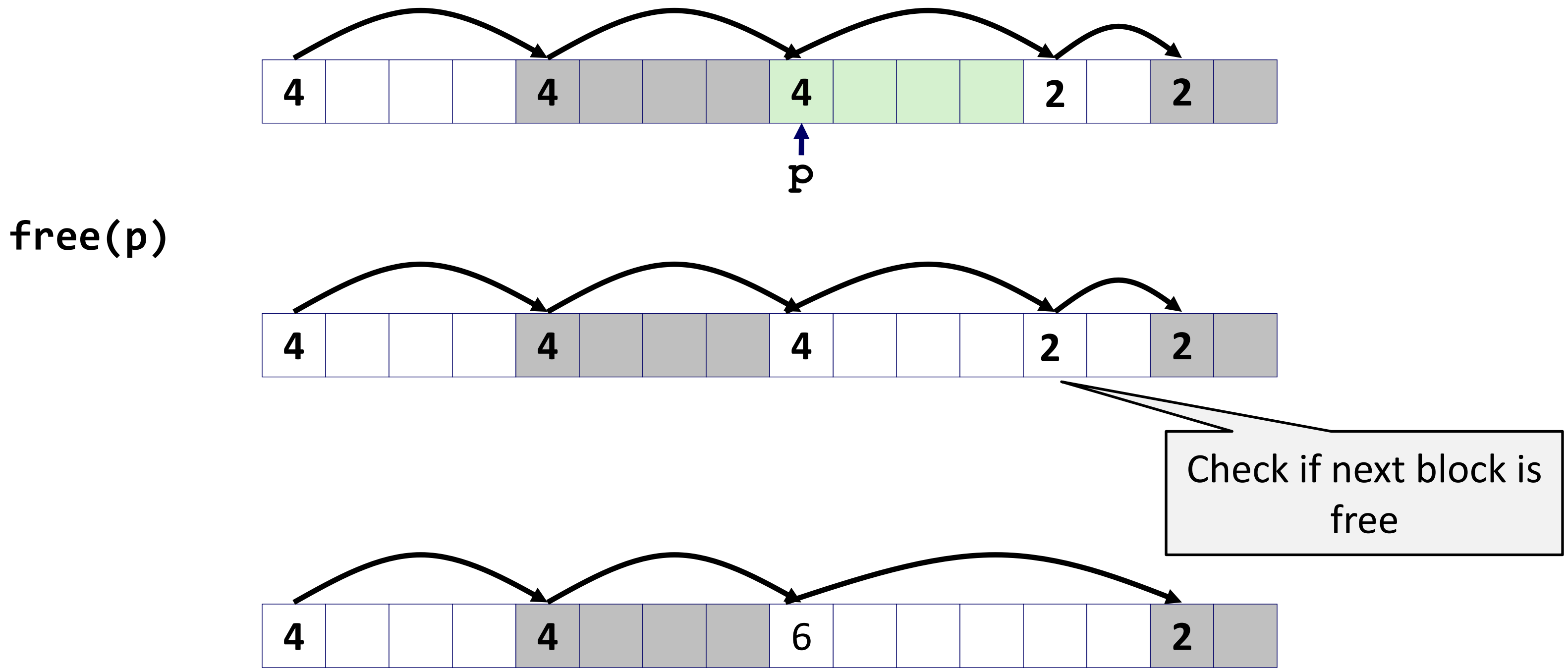
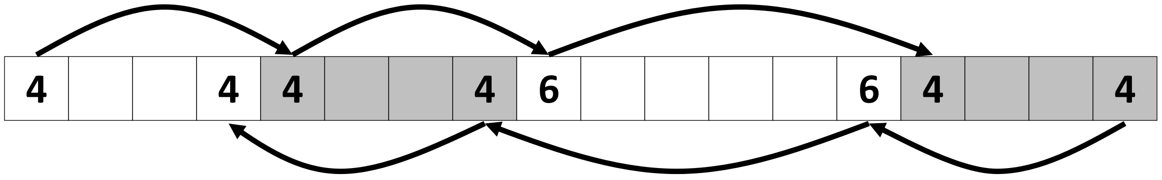


How to coalesce with a previous block?

Implicit List: Bidirectional Coalescing

- *Boundary tags* [Knuth73]
  - Replicate size/allocated header at "bottom" (end) of blocks
  - Allows us to traverse the "list" backwards, but requires extra space



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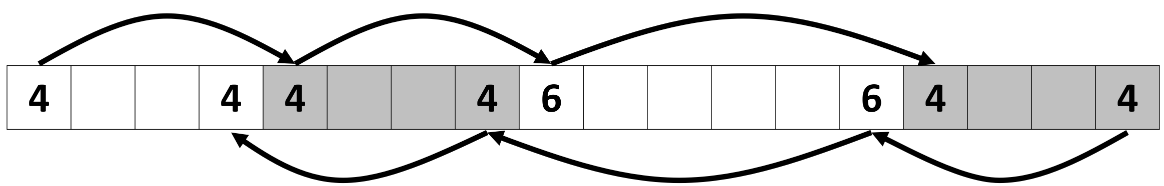
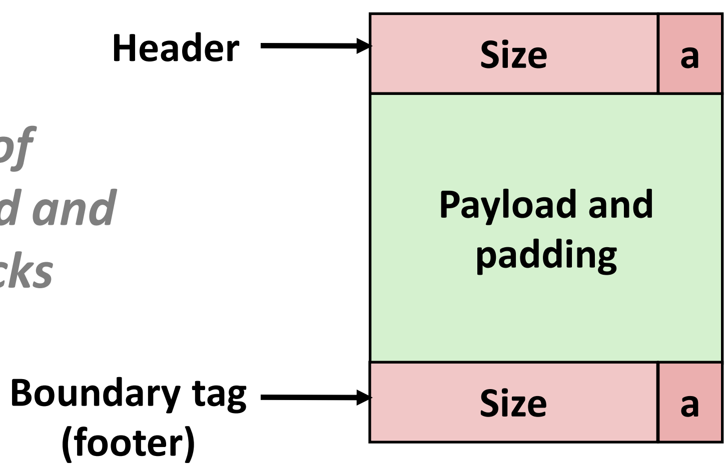


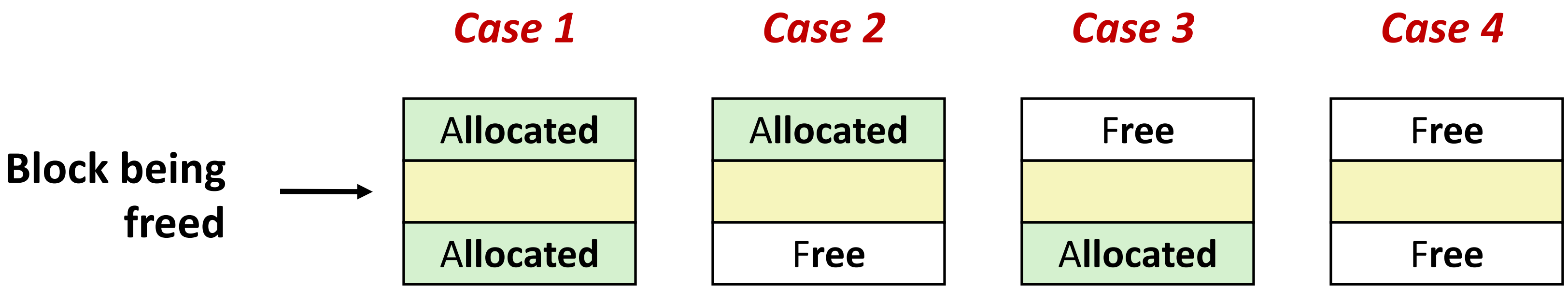
Format of allocated and free blocks



a = 1: Allocated block
a = 0: Free block

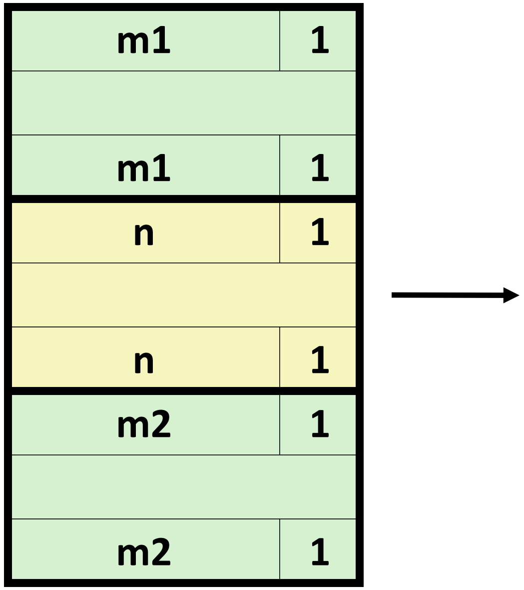
Size: Total block size

Coalescing



Case 1
Case 2
Case 3
Case 4
Block being freed
Allocated
Allocated
Allocated
Free
Free
Allocated
Free
Free

Coalescing (Case 1)



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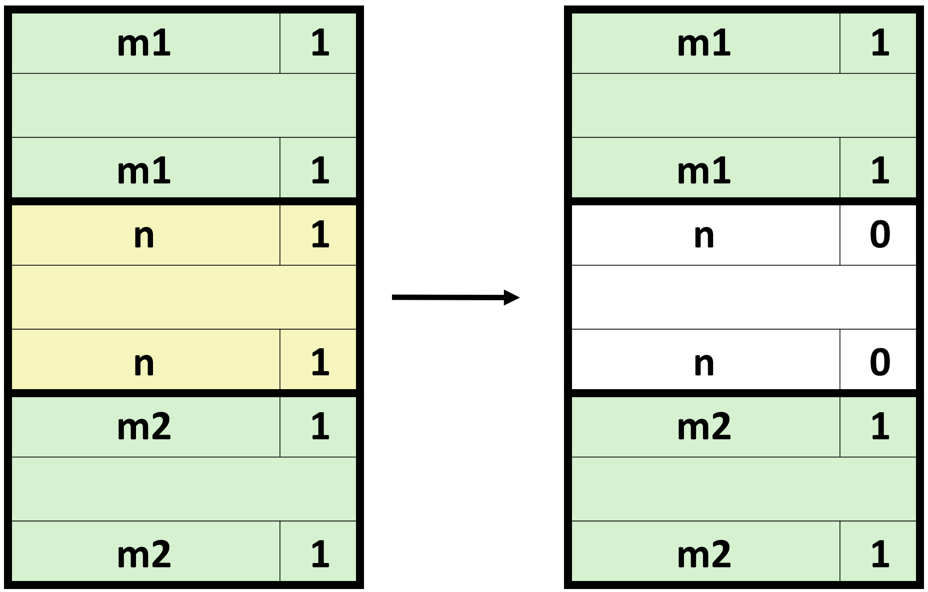
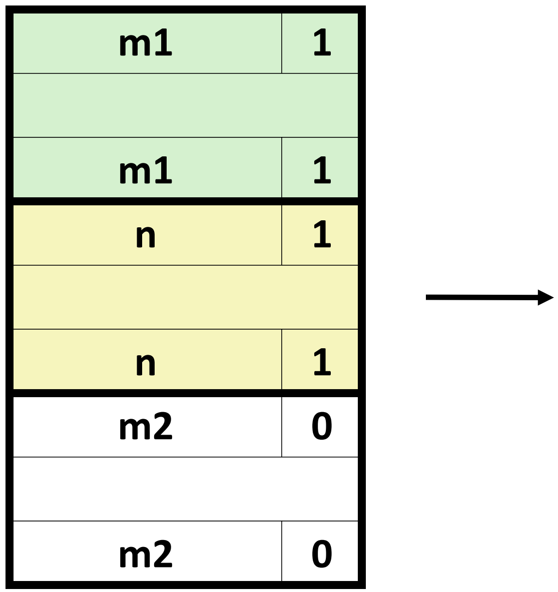


Coalescing (Case 2)



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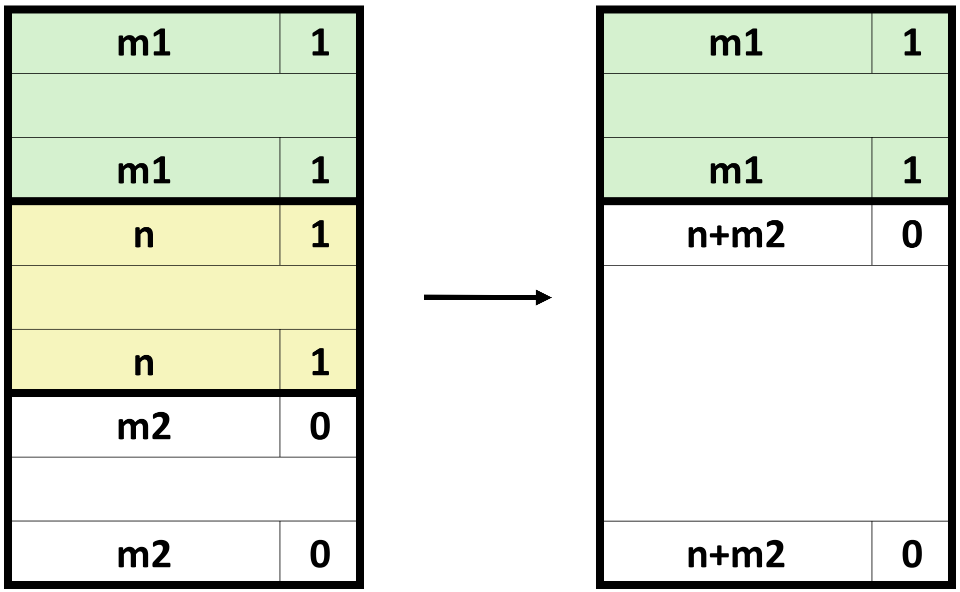
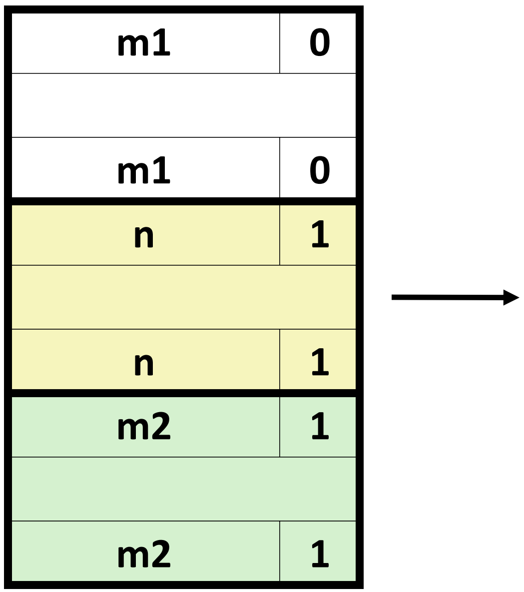


Coalescing (Case 3)



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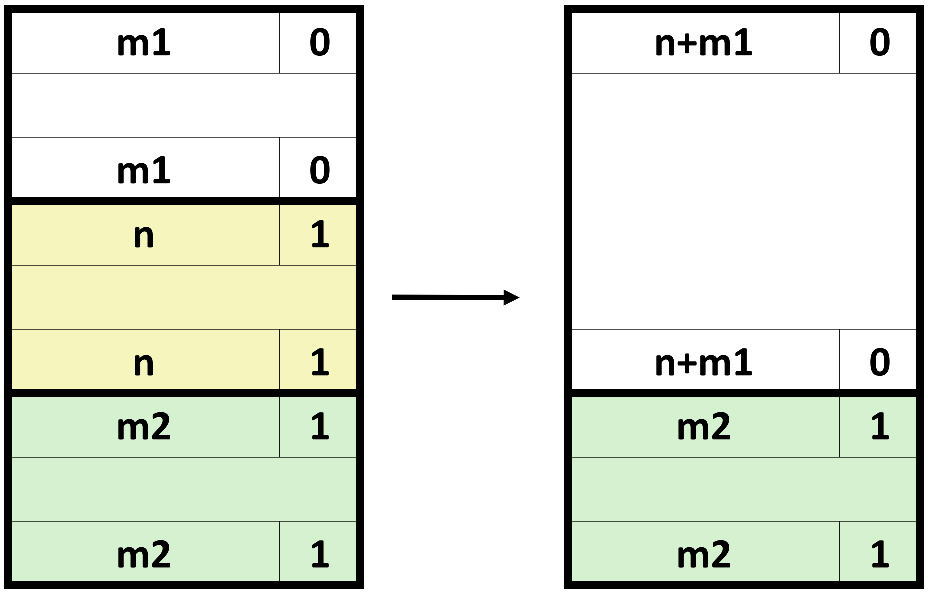
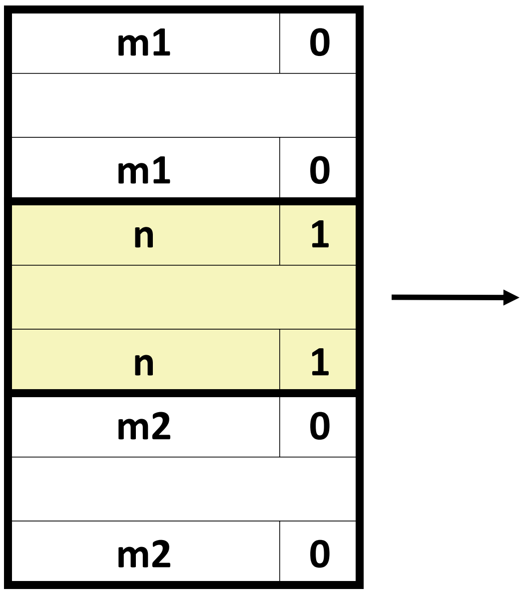


Coalescing (Case 4)



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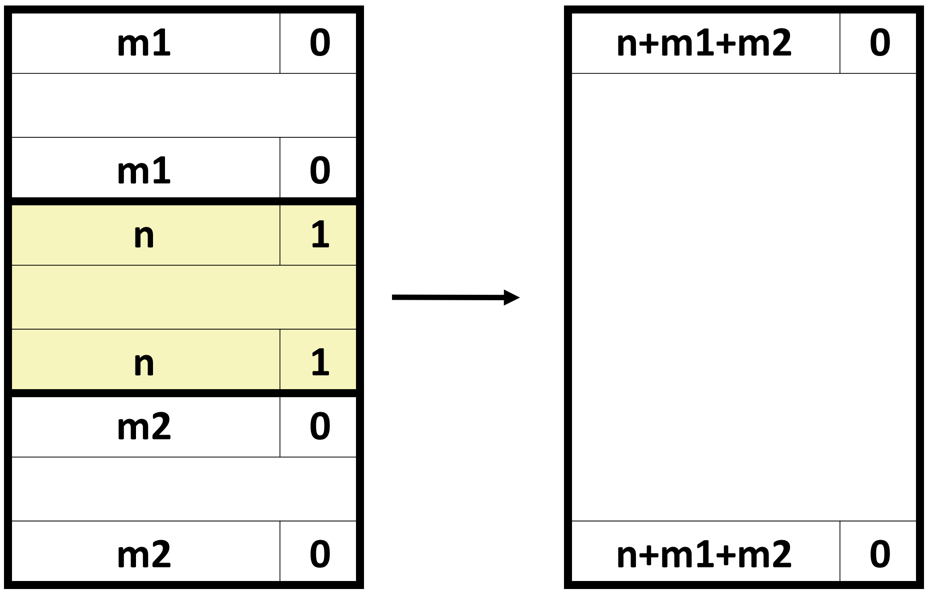


When to coalesce?

- Immediate coalescing: coalesce each time `free()` is called
- Deferred coalescing: try to improve performance of `free` by deferring coalescing until needed.

  Examples:
  - Coalesce as you scan the free list for `malloc()`
  - Coalesce when the amount of external fragmentation reaches some threshold

Implicit Lists: Summary

- Implementation: very simple
- Allocate cost:
  - linear time worst case
- Free cost:
  - constant time worst case, even with coalescing
- Memory usage:
  - will depend on first-fit, next-fit or best-fit

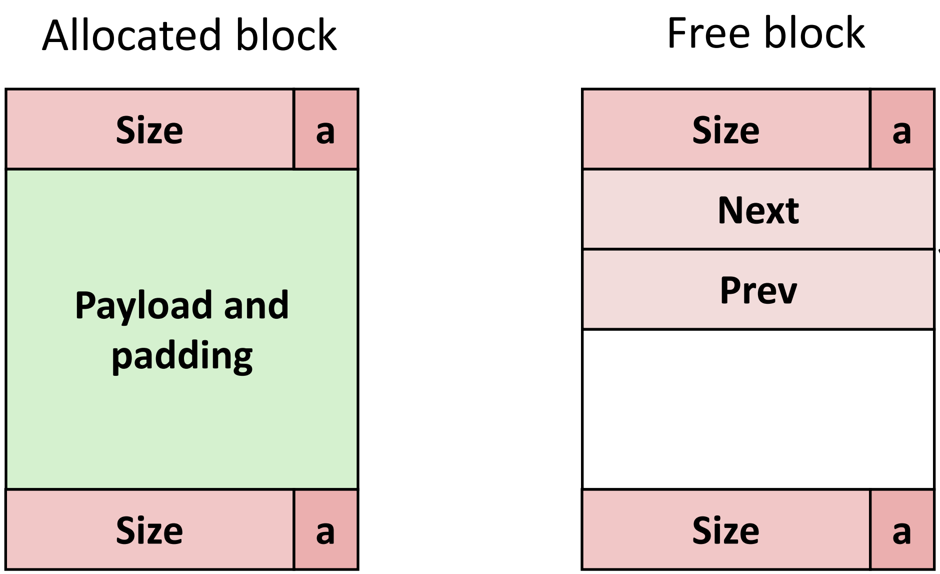
- Not used in practice for `malloc/free` because of high runtime cost for allocation
  - used in many special purpose applications

Explicit Free list

- Maintain list(s) of free blocks instead of all blocks

- Need to store forward/back pointers in each free block, not just sizes
  - because free blocks may not be contiguous in heap.

Explicit Free Lists



Store next/prev pointers in "payload" of free block.

Does this increase space overhead?

Freeing With Explicit Free Lists

- Where in the free list to put a newly freed block?
  - Insert freed block at the beginning of the free list (LIFO)
    - ***Pro:*** simple and constant time
  - Insert freed blocks to maintain address order:

    addr(prev) < addr(curr) < addr(next)
    - ***Pro:*** may lead to less fragmentation than LIFO

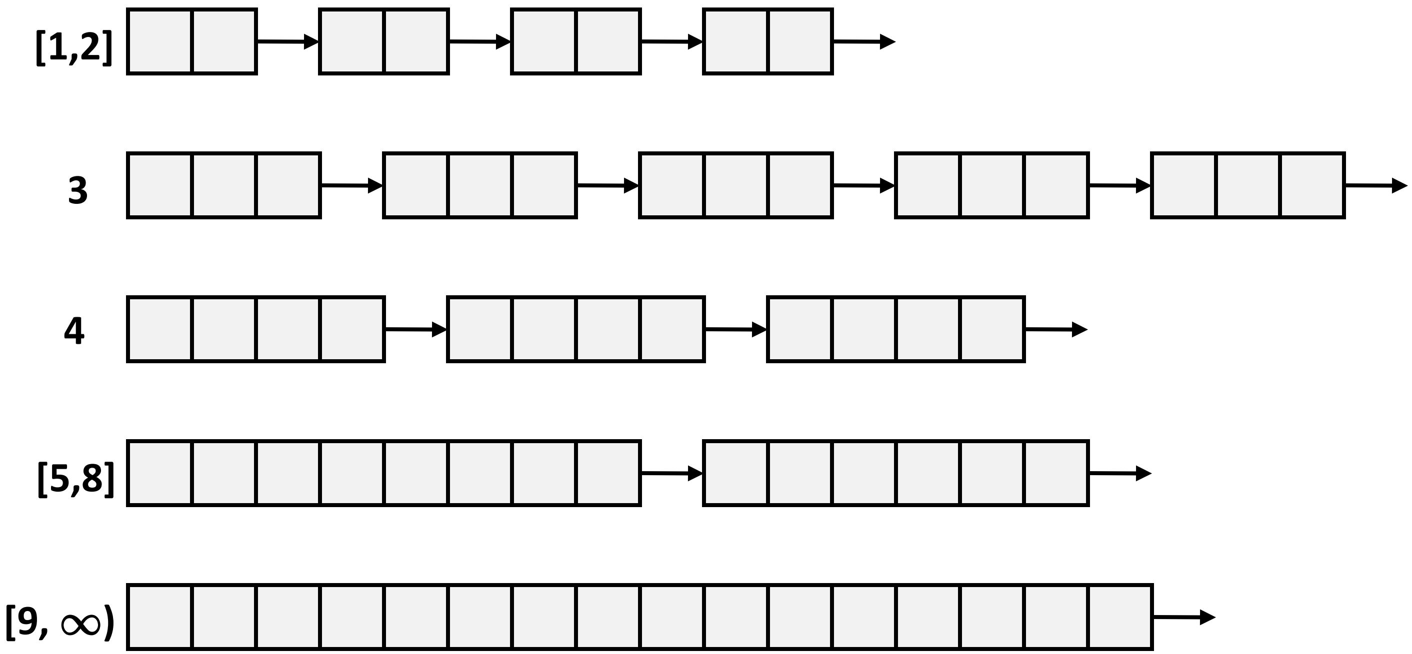
Explicit List

- ✓ Allocation is linear time in # of ***free*** blocks instead of ***all*** blocks

- Still expensive to find a free block that fits
  - How about keeping multiple linked lists of different size classes?

Segregated List (Seglist) Allocators

- Multiple free lists each linking free blocks of similar sizes



Seglist Allocator

- Given an array of free lists, each one for some size class

- To allocate a block of size *n*:
  - Search in appropriate free list containing size n
  - Split found block and place fragment on appropriate list
  - try next larger class if no blocks found

- If no block is found:
  - Request additional heap memory from OS
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in largest size class.

Seglist Allocator (cont.)

- To free a block:
  - Coalesce and place on appropriate list

- Advantages of seglist allocators
  - Fast allocation
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap

A Word About Garbage Collection

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- A garbage collection is a dynamic storage allocator that automatically frees allocated blocks that are no longer needed by the program.
- Allocated blocks that are no longer needed are called garbage.

A Word About Garbage Collection

- In systems that support garbage collection (e.g. Java, Perl, Mathematica, …)
  - Applications explicitly allocate heap blocks
  - But never free them!
- The garbage collector periodically identifies garbage and make appropriate calls to free.

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How does the garbage collector recognizes blocks that are no longer needed?

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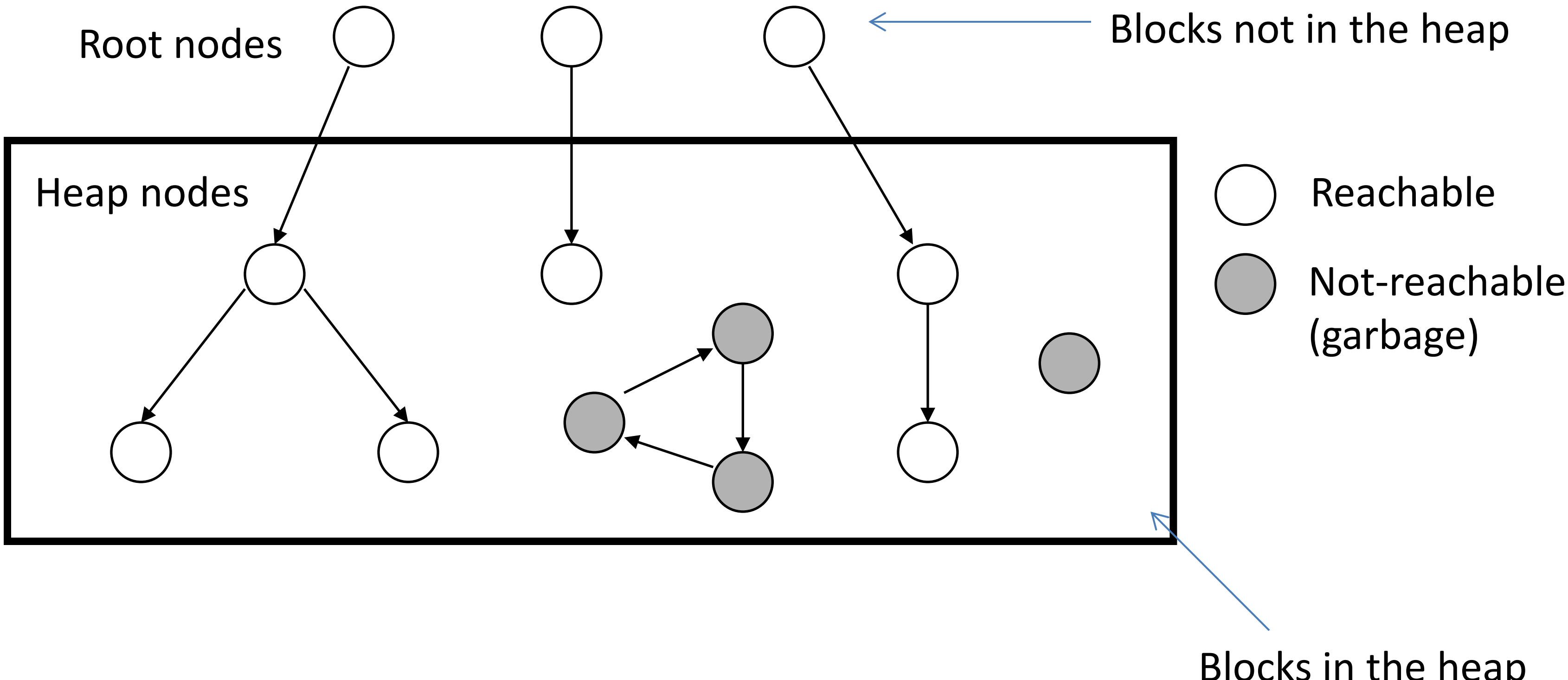


Reachability Graph

Conclusions

- Dynamic memory allocator manages the heap.
- Dynamic memory allocator is part of the user-space
- The allocator has two main goals:
  - reaching higher throughput (operations per second)
  - better memory utilization (i.e. reduces fragmentation).

Conclusions (cont'd)

- Explicit allocator
  - Works in terms of blocks
  - Keeping track of free blocks
    - Implicit list
    - Explicit list
    - segregated list
    - blocks sorted by size
- Implicit allocator

Virtual Memory and Isolation

Isolation

User applications

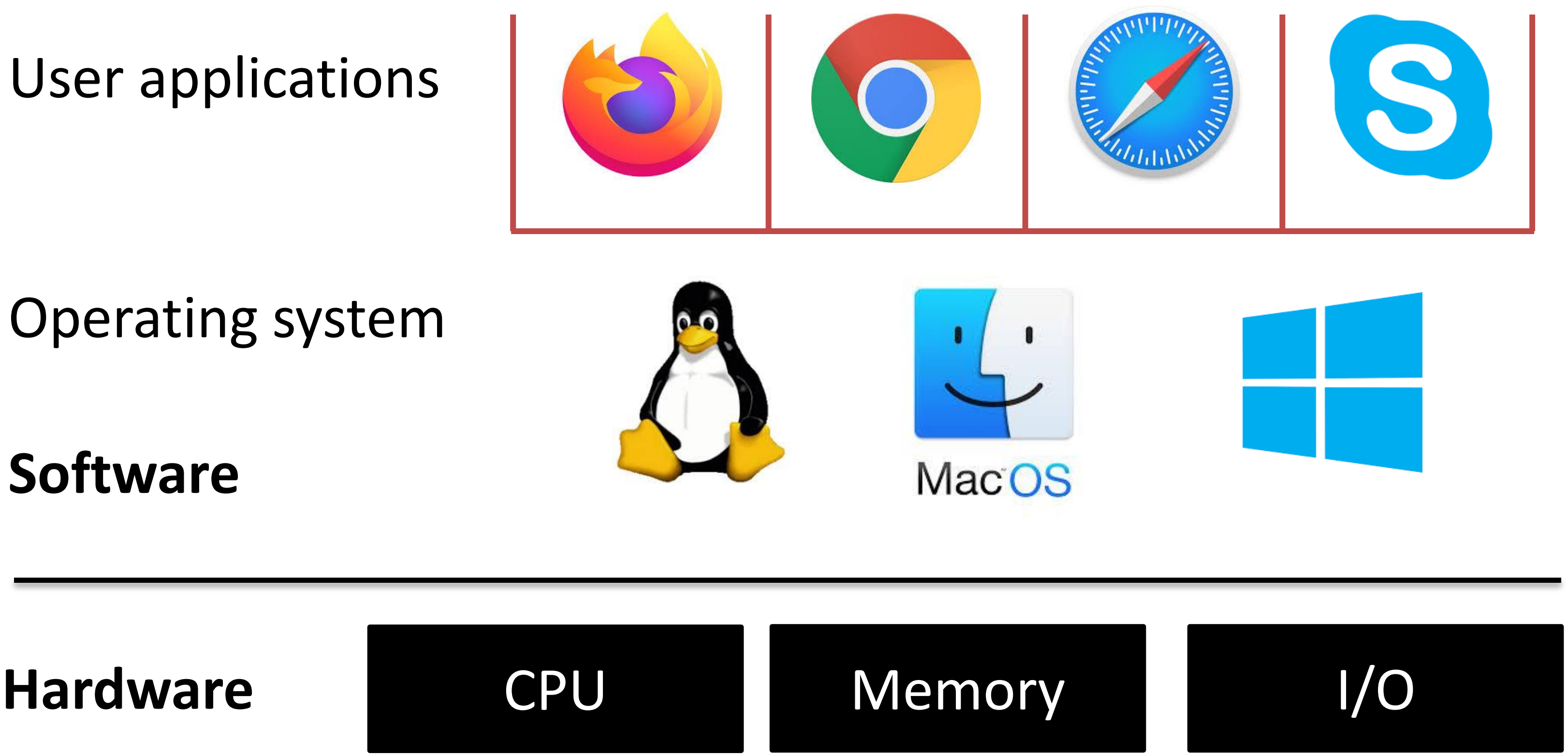
Operating system

Software

Hardware

CPU	Memory	I/O

Isolation


User applications
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Isolation

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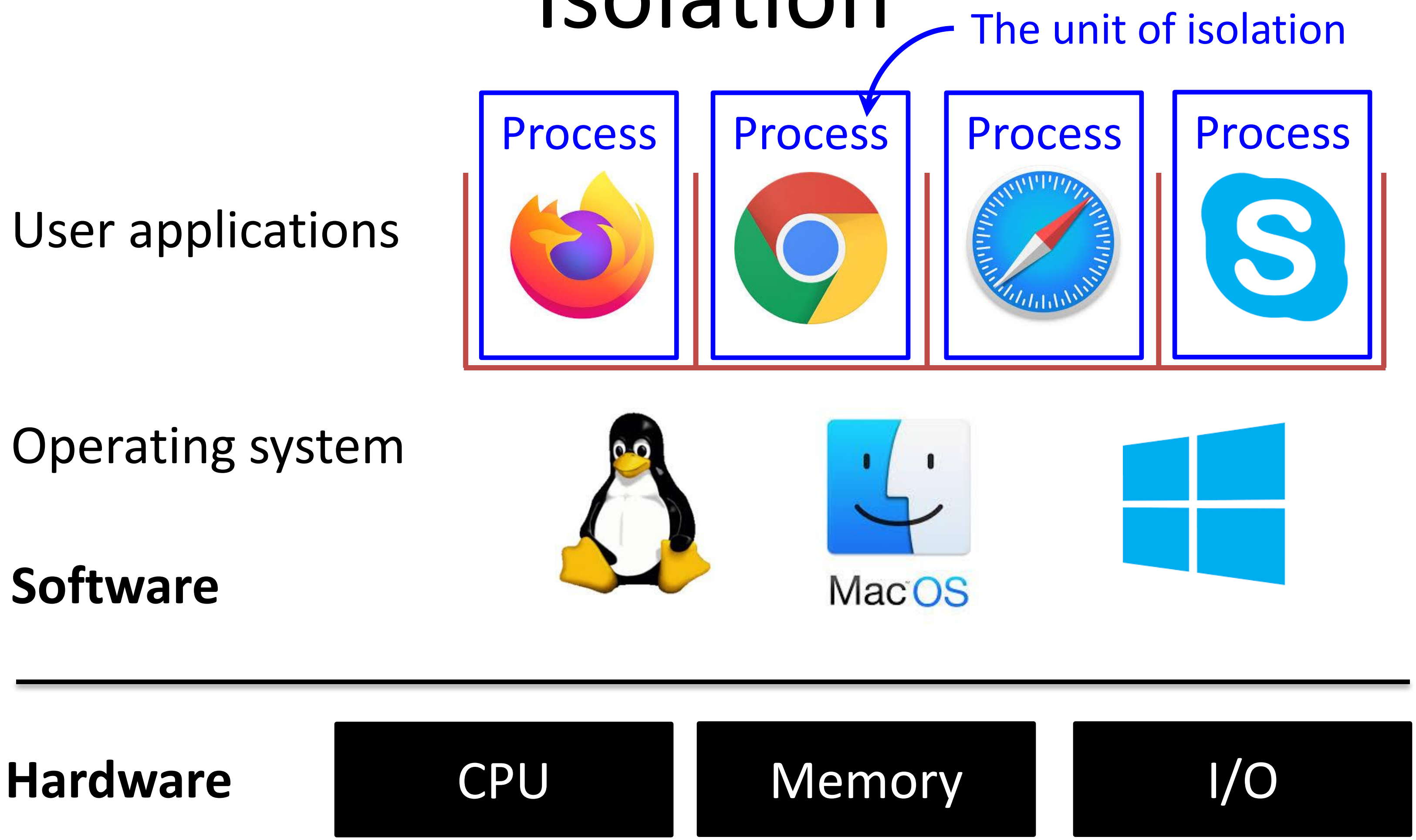
Isolation – Enforced separation to contain effects of failures

Isolation

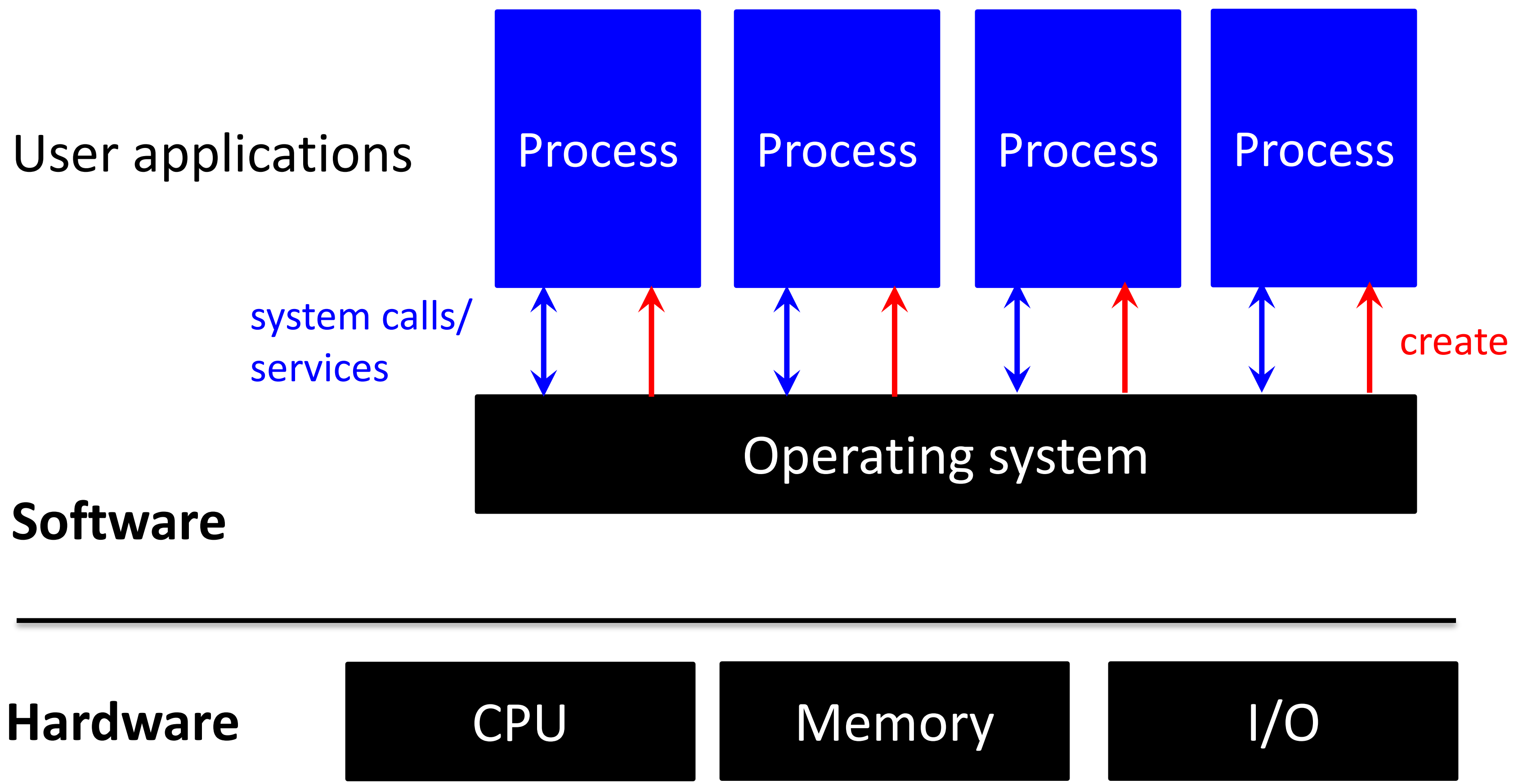


Isolation – Enforced separation to contain effects of failures

Process

- An instance of a computer program that is being executed
- Program vs. Process
  - Program: a passive collection of instructions
  - Process: the actual execution of those instructions
- Different processes have different process id
  - `getpid()`: function that returns id of current process
  - Command `ps`: list all processes

Isolation



To run a program, OS starts a process and provide services through system calls (`getpid()`, `fopen()`).