Memory Management
CS 111
Summer 2025
Operating System Principles
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Outline

- What is memory management about?
- Memory management strategies:
  - Fixed partition strategies
  - Dynamic partitions
  - Buffer pools
  - Garbage collection
  - Memory compaction

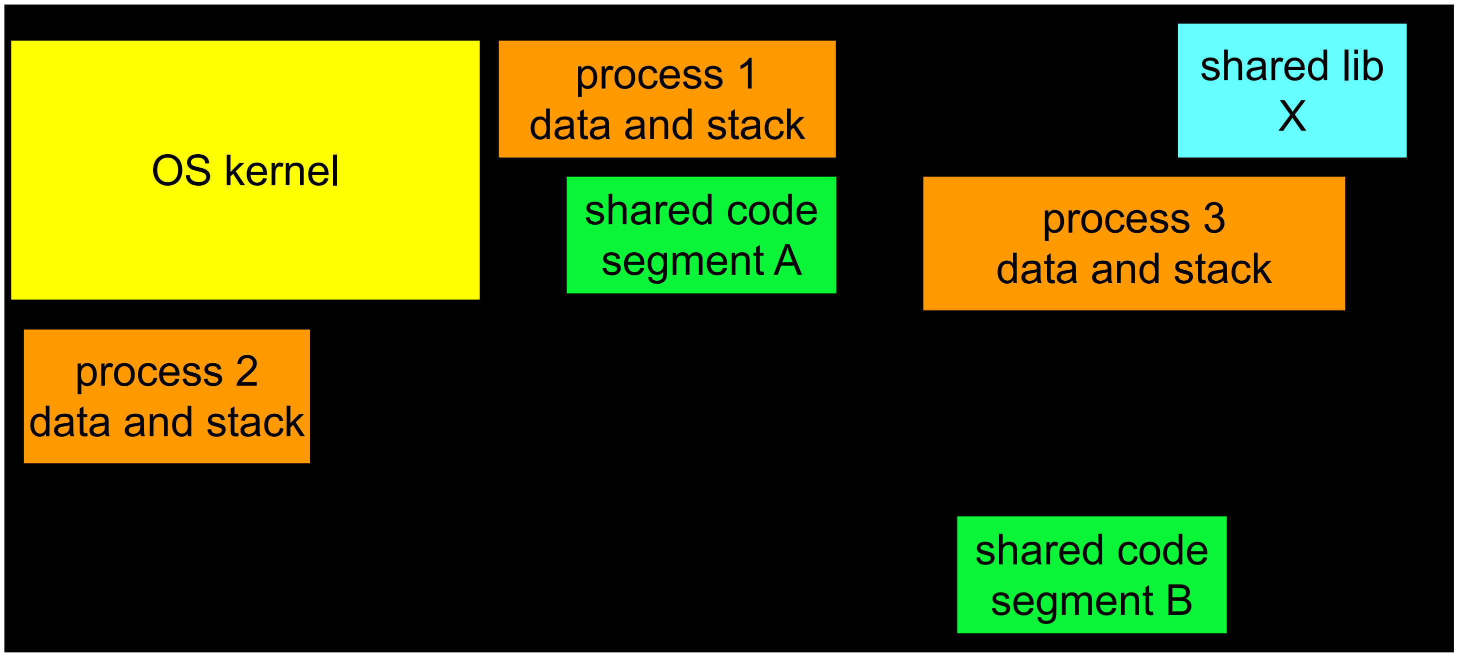
Memory Management

- Memory is one of the key assets used in computing
- In particular, memory abstractions that are usable from a running program
  – Which, in modern machines, means RAM
- We have a limited amount of it
- Lots of processes need to use it
- How do we manage it?

Memory Management Goals

1. Transparency
   – Each process sees only its own address space
   – Each process is unaware memory is being shared
2. Efficiency
   – High effective memory utilization
   – Low run-time cost for allocation/relocation
3. Protection and isolation
   – Private data will not be corrupted
   – Private data cannot be seen by other processes

Physical Memory Allocation



Physical memory is divided between the OS kernel, process private data, and shared code segments.

Physical and Virtual Addresses

- A RAM cell has a particular physical address
  - Essentially a location on a memory chip
- Decades ago, that address was used by processes to name memory locations
- Now processes use virtual addresses
  - Which are <u>not</u> locations on a memory chip
  - And usually aren't the same as the actual physical addresses
- More flexibility in memory management, but requires virtual to physical translation

Aspects of the Memory Management Problem

- Most processes can’t perfectly predict how much memory they will use
- The processes expect to find their existing data when they need it where they left it
- The entire amount of data required by all processes may exceed amount of available physical memory
- Switching between processes must be fast
  - Can’t afford much delay for copying data
- The cost of memory management itself must not be too high

Memory Management Strategies

- Fixed partition allocations
- Dynamic partitions
- Relocation

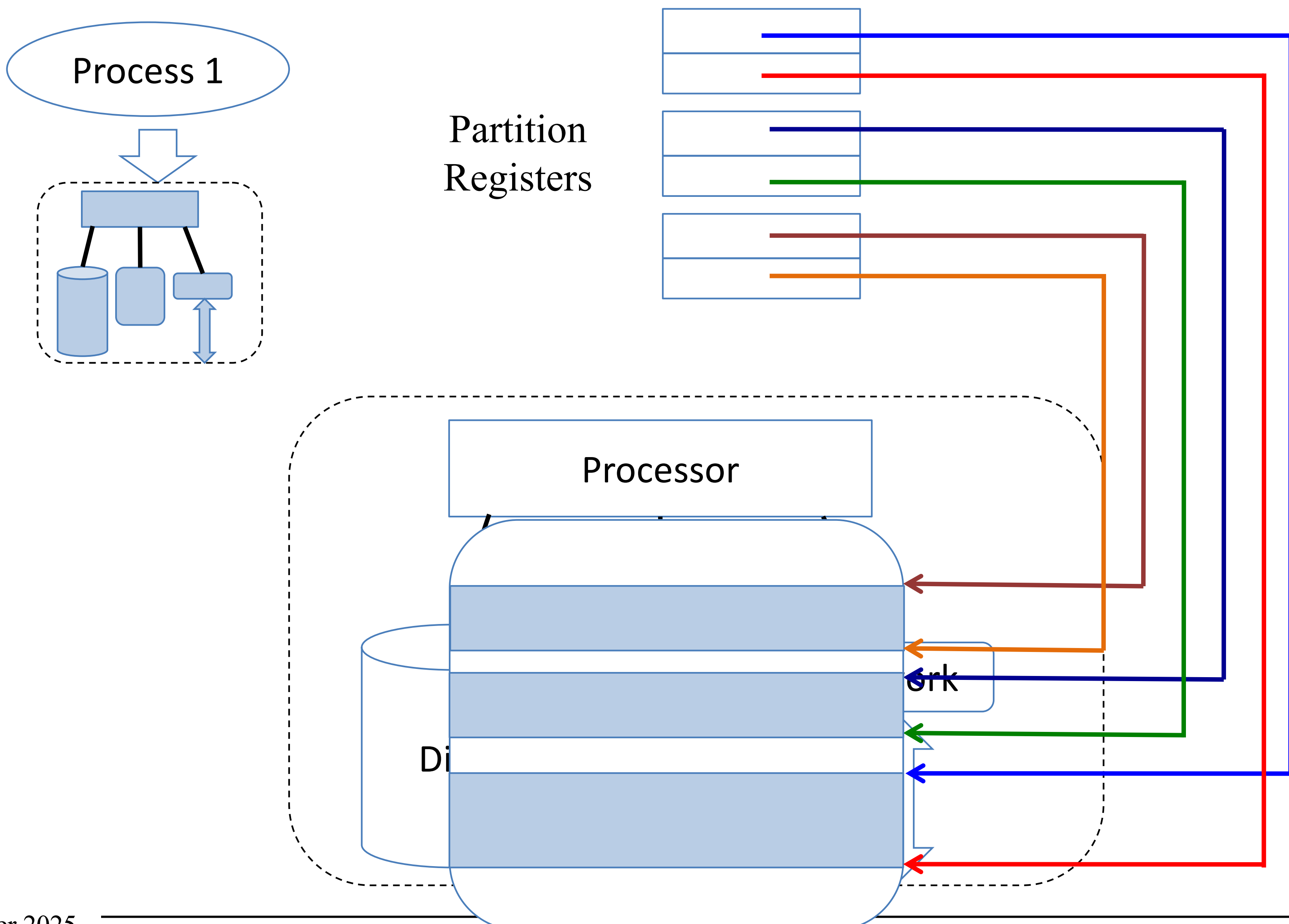
Fixed Partition Allocation

- Pre-allocate partitions for *n* processes
  - One or more per process
  - Usable only by owning process
  - Reserving space for largest possible process
- Partitions come in one or a few set sizes
- Very easy to implement
  - Common in old batch processing systems
  - Allocation/deallocation very cheap and easy
- Well suited to well-known job mix

Memory Protection and Fixed Partitions

- Need to enforce partition boundaries
  - To prevent one process from accessing another's memory
- Could use hardware for this purpose
  - Special registers that contain the partition boundaries
  - Only accept addresses within the register values
- Basic scheme doesn't use virtual addresses

The Partition Concept



Problems With Fixed Partition Allocation

- Presumes you know how much memory will be used ahead of time
- Limits the number of processes supported to the total of their memory requirements
- Not great for sharing memory
- *Fragmentation* causes inefficient memory use

Fragmentation

- A problem for all memory management systems
  - Fixed partitions suffer it especially badly
- Causes unallocated memory to be unusable
- Because of inefficiencies in memory allocation
- With too much fragmentation,
  - You can’t provide memory for as many processes as you theoretically could

Fragmentation Example

Let's say there are three processes, A, B, and C

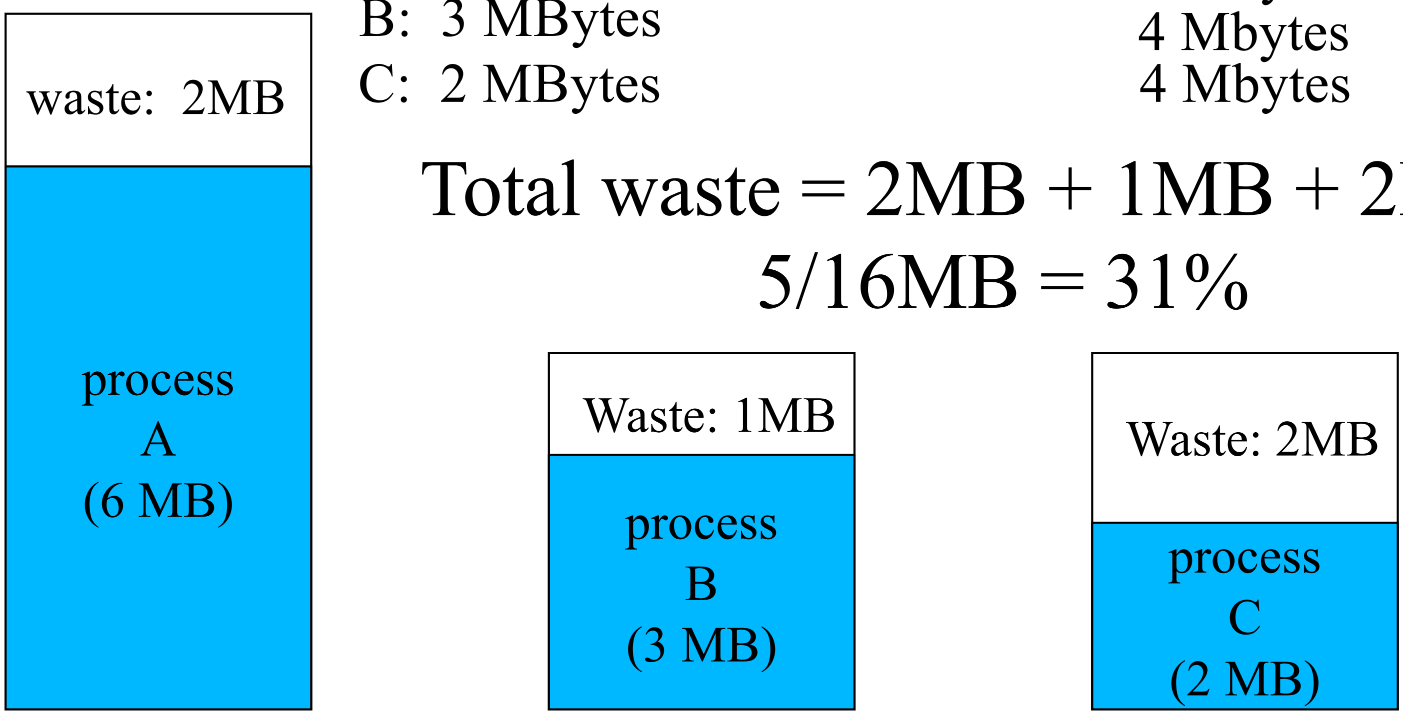
Their memory requirements:

A: 6 MBytes
B: 3 MBytes
C: 2 MBytes

Available partition sizes:

8 Mbytes
4 Mbytes
4 Mbytes

Total waste = 2MB + 1MB + 2MB = 5/16MB = 31%



Partition 1 8MB

Partition 2 4MB

Partition 3 4MB

If someone asks for a 3MB partition, you can't provide it

Even though there's 5 MB unused

Internal Fragmentation

- Fragmentation comes in two kinds:
  - Internal and external
- This is an example of *internal fragmentation*
  - We'll see external fragmentation later
- Wasted space *inside* fixed sized blocks
  - The requestor was given more than he needed
  - The unused part is wasted and can't be used for others
- Internal fragmentation can occur whenever you force allocation in fixed-sized chunks

More on Internal Fragmentation

- Internal fragmentation is caused by a mismatch between
  - The chosen size of a fixed-sized block
  - The actual sizes that processes use
- Average waste: 50% of each block

Summary of Fixed Partition Allocation

- Very simple
- Inflexible
- Subject to a lot of internal fragmentation
- Not used in many modern systems
  - But a possible option for special purpose systems, like embedded systems
  - Where we know exactly what our memory needs will be

Dynamic Partition Allocation

- Like fixed partitions, except
  - Variable sized, usually almost any size requested
- Each partition has contiguous addresses
- Processes have access permissions for the partitions
- Potentially shared between processes
- Each process could have multiple partitions
  - With different sizes and characteristics
- In basic scheme, still only physical addresses

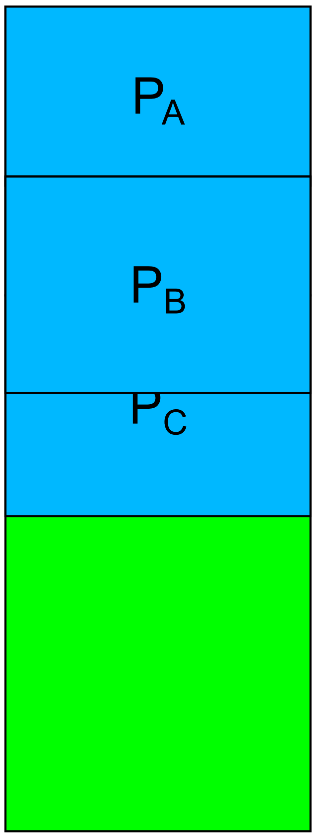
Problems With Dynamic Partitions

- Not relocatable
  - Once a process has a partition, you can't easily move its contents elsewhere
- Not easily expandable
- Impossible to support applications with larger address spaces than physical memory
  - Also can't support several applications whose total needs are greater than physical memory
- Also subject to fragmentation
  - Of a different kind . . .

Relocation and Expansion

- Partitions are tied to particular address ranges
  - At least during an execution
- Can’t just move the contents of a partition to another set of addresses
  - All the pointers in the contents will be wrong
  - And generally you don’t know which memory locations contain pointers
- Hard to expand because there may not be space “nearby”

Illustrating the Expansion Problem



Now Process B wants to expand its partition size

But if we do that, Process B steps on Process C's memory

We can't move C's partition out of the way

And we can't move B's partition to a free area

We're stuck, and must deny an expansion request that we have enough memory to handle

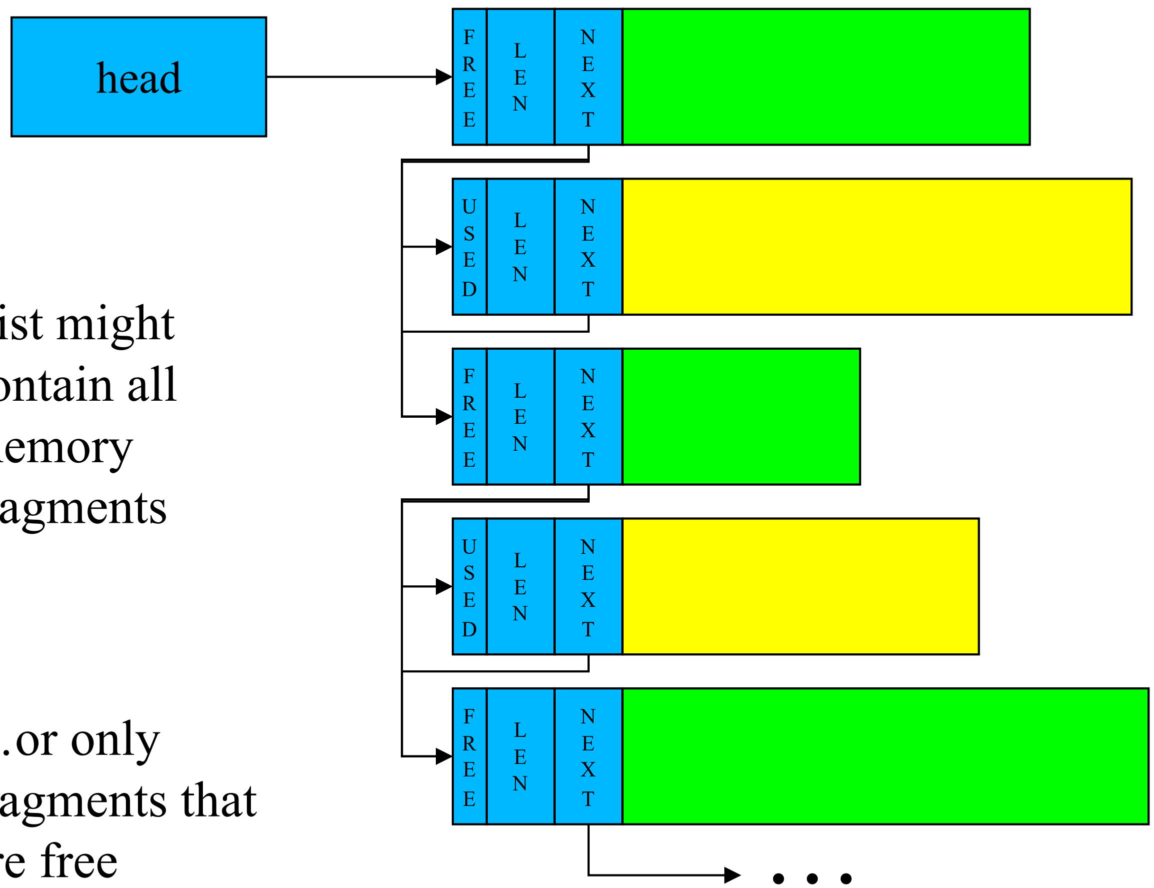
How To Keep Track of Variable Sized Partitions?

- Start with one large "heap" of memory
- Maintain a *free list*
  - Systems data structure to keep track of pieces of unallocated memory
- When a process requests more memory:
  - Find a large enough chunk of memory
  - Carve off a piece of the requested size
  - Put the remainder back on the free list
- When a process frees memory
  - Put freed memory back on the free list

Managing the Free List

- Fixed sized blocks are easy to track
  - A bit map indicating which blocks are free
- Variable chunks require more information
  - A linked list of descriptors, one per chunk
  - Each descriptor lists the size of the chunk and whether it is free
  - Each has a pointer to the next chunk on list
  - Descriptors often kept at front of each chunk
- Allocated memory may have descriptors too

The Free List

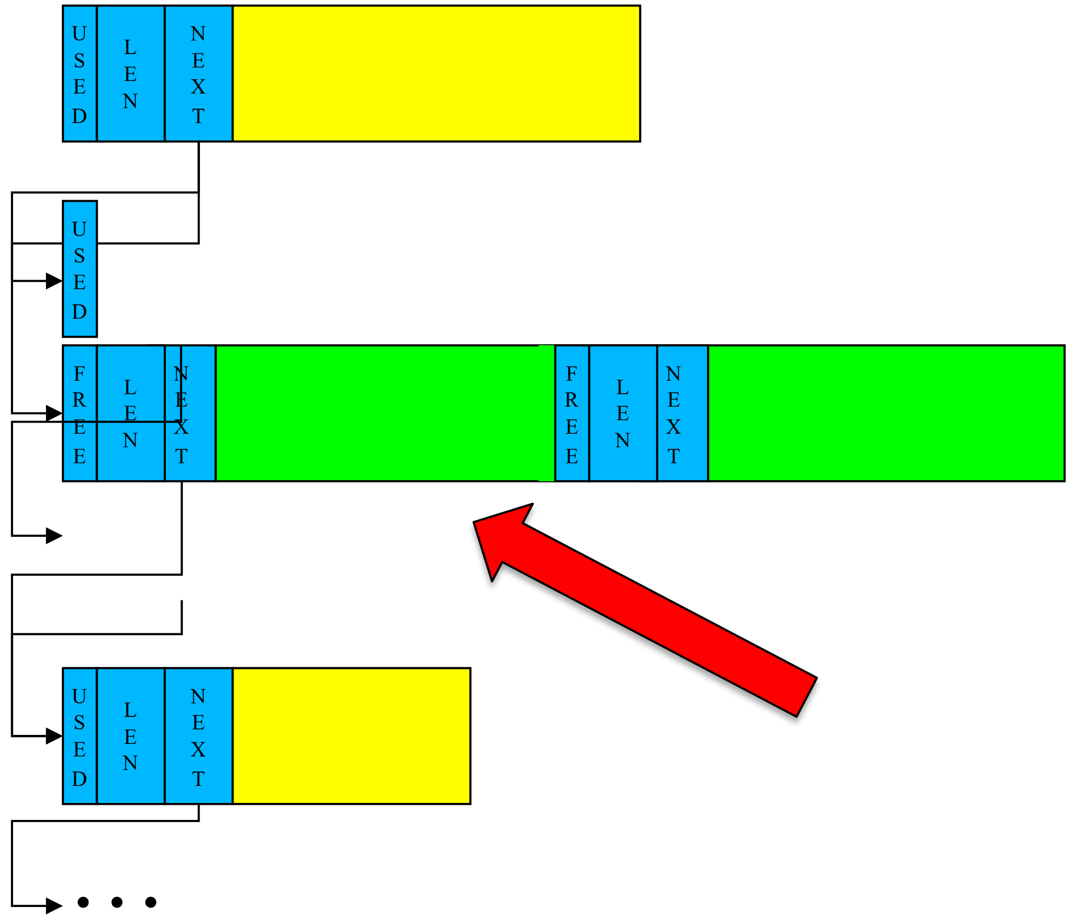


List might contain all memory fragments

…or only fragments that are free

Free Chunk Carving

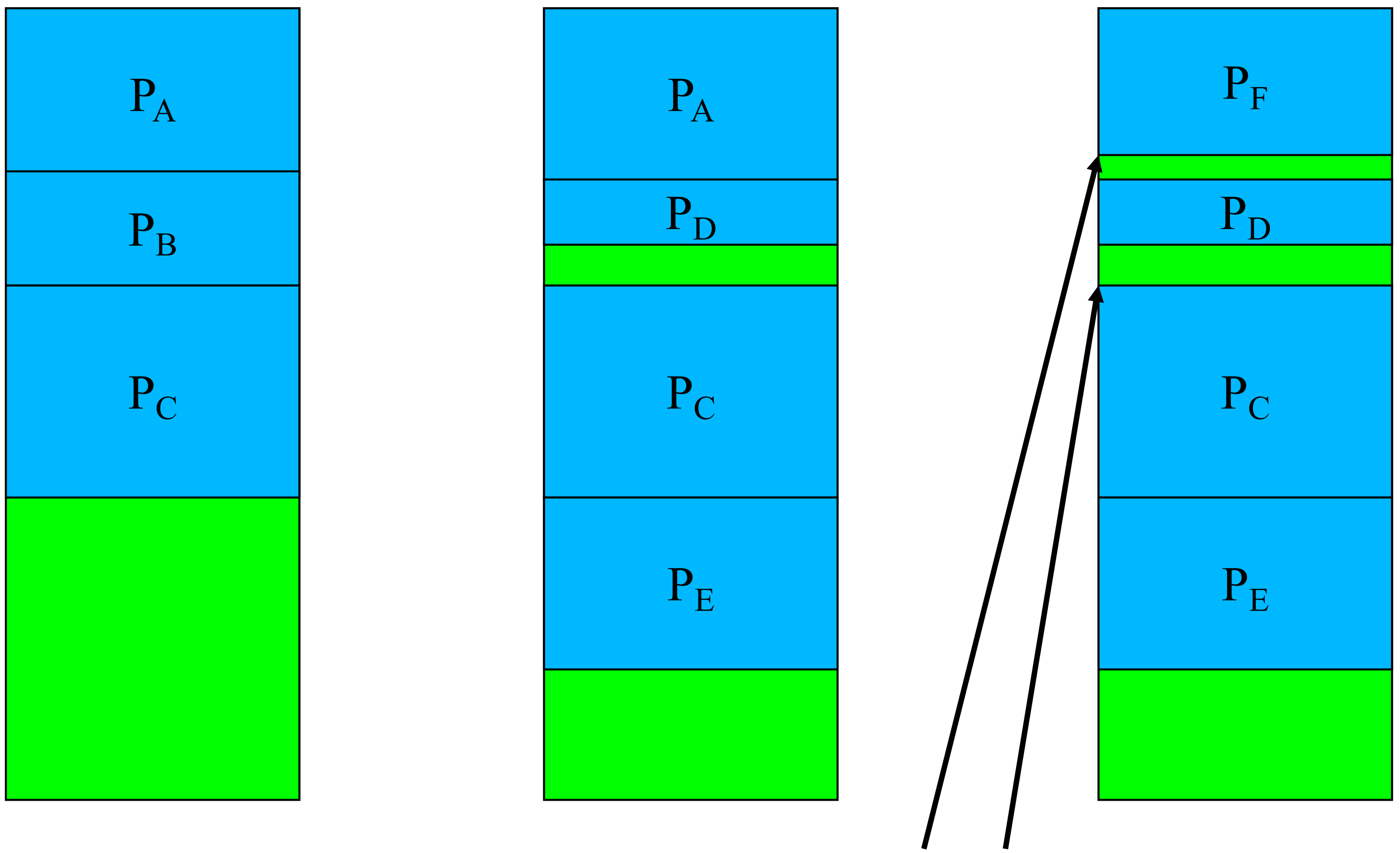
1. Find a large enough free chunk
2. Reduce its len to requested size
3. Create a new header for residual chunk
4. Insert the new chunk into the list
5. Mark the carved piece as in use



Variable Partitions and Fragmentation

- Variable sized partitions not as subject to internal fragmentation
  - Unless requestor asked for more than he will use
  - Which is actually pretty common
  - But at least the memory manager gave him no more than he requested
- Unlike fixed sized partitions, though, subject to another kind of fragmentation
  - *External fragmentation*

External Fragmentation



We gradually build up small, unusable memory chunks scattered through memory

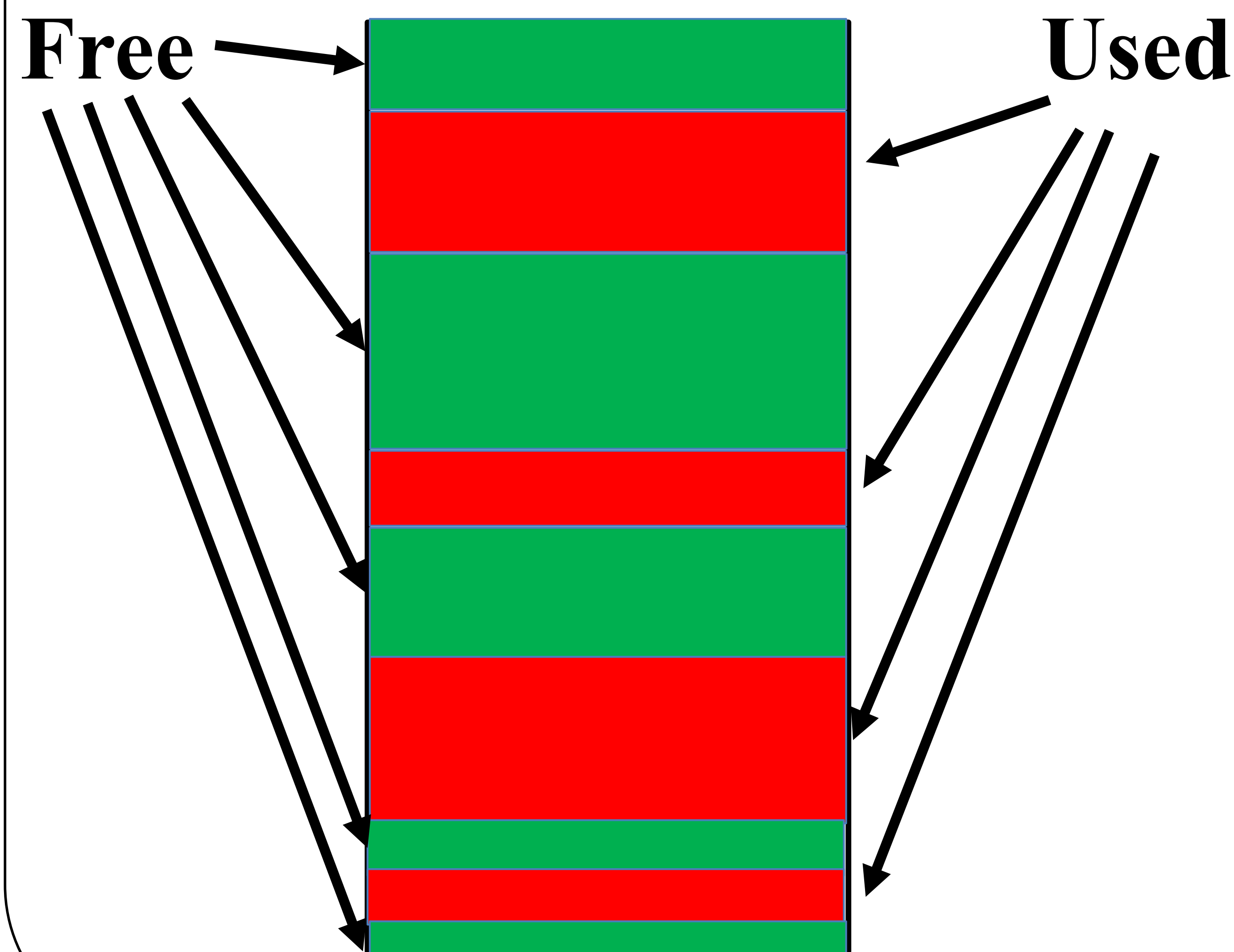
External Fragmentation: Causes and Effects

- Each allocation creates left-over free chunks
  - Over time they become smaller and smaller
- The small left-over fragments are useless
  - They are too small to satisfy any request
  - A second form of fragmentation waste
- Solutions:
  - Try not to create tiny fragments
  - Try to recombine fragments into big chunks

How To Avoid Creating Small Fragments?

- Be smart about which free chunk of memory you use to satisfy a request
- But being smart costs time
- Some algorithm choices:
  - Best fit
  - Worst fit
  - First fit
  - Next fit

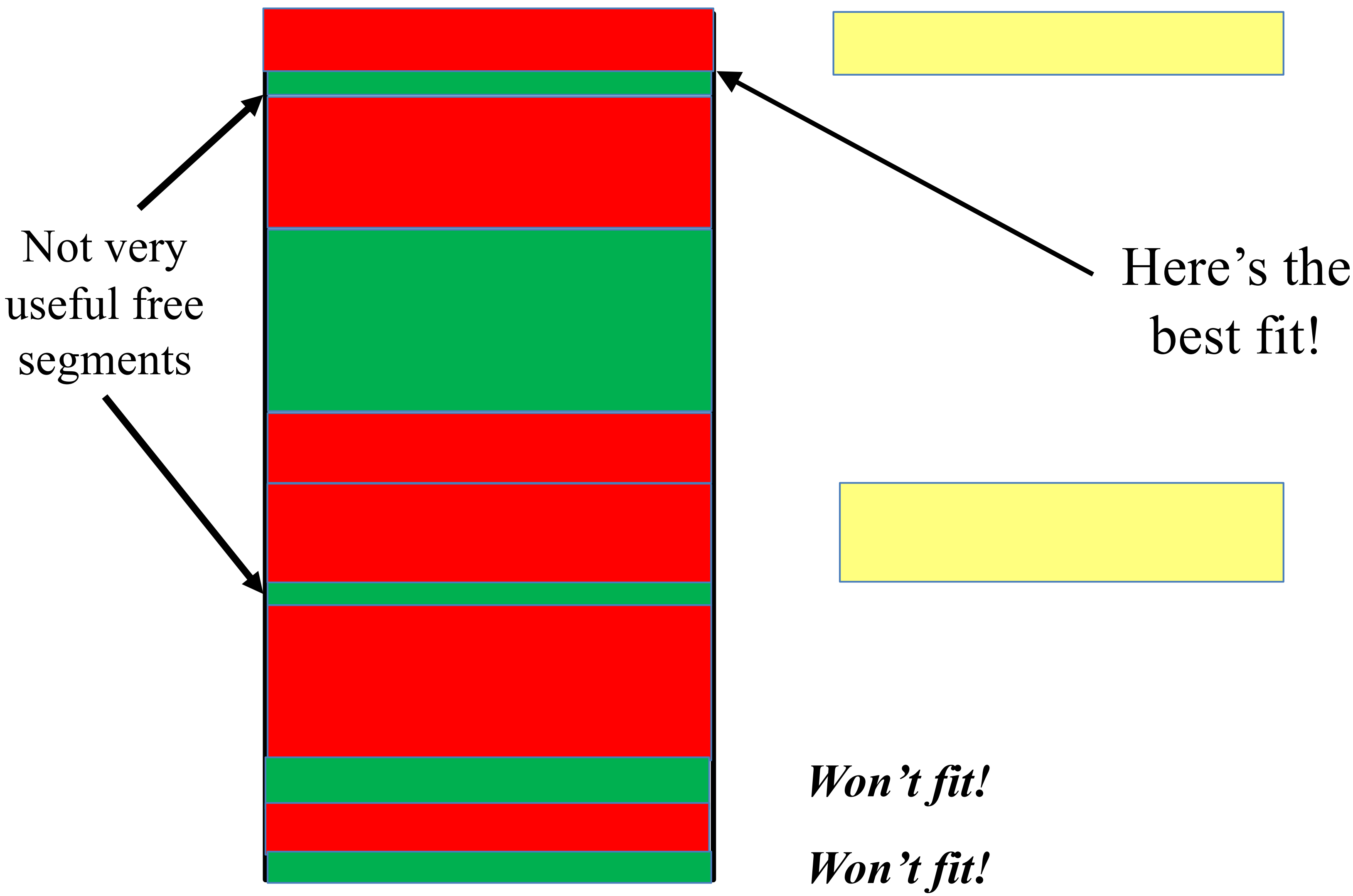
Allocating Partitions in Memory



Best Fit

- Search for the “best fit” chunk
  - Smallest size greater than or equal to requested size
- Advantages:
  - Might find a perfect fit
- Disadvantages:
  - Have to search the entire list every time
  - Quickly creates very small fragments

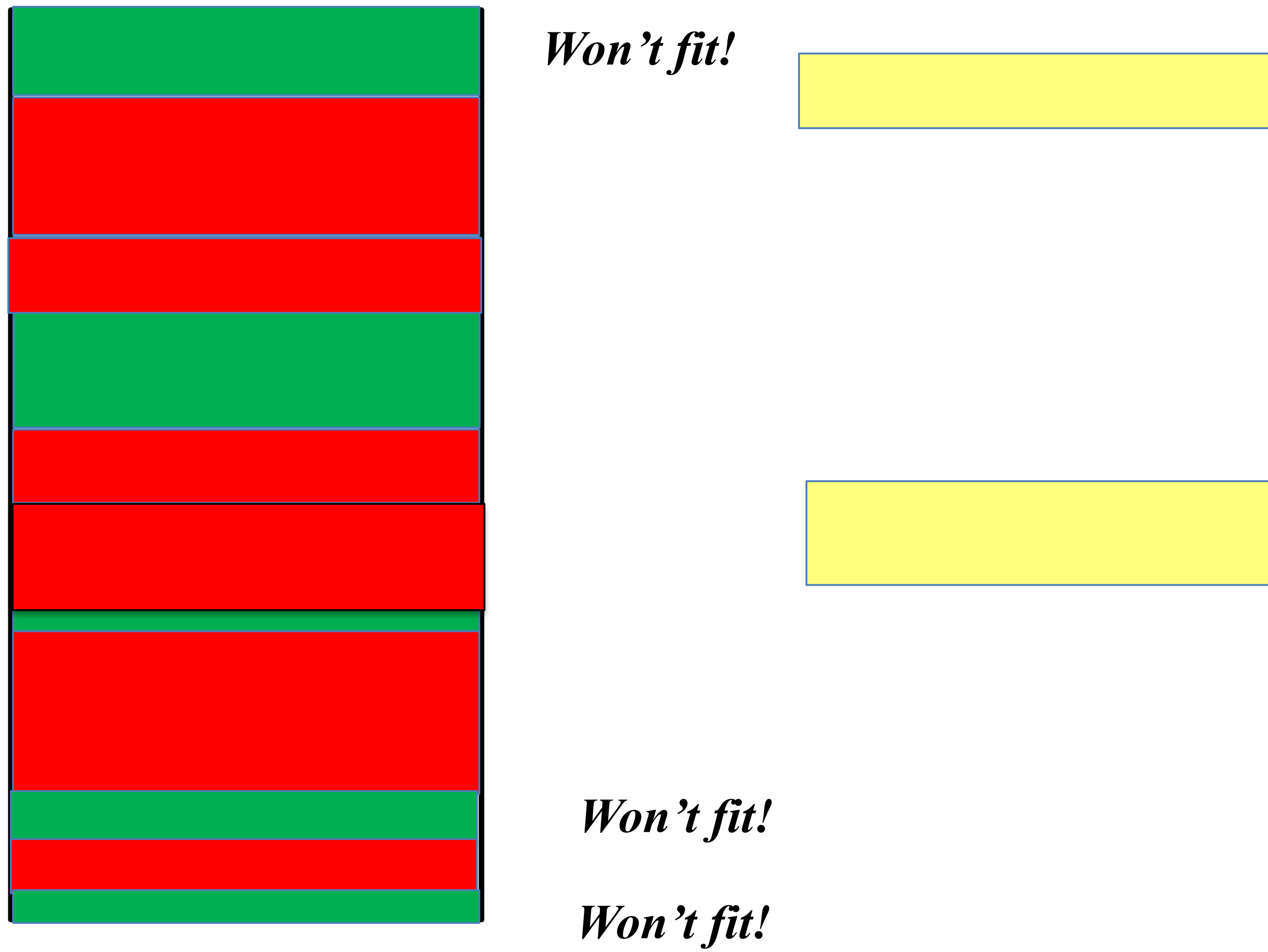
Best Fit in Action



Worst Fit

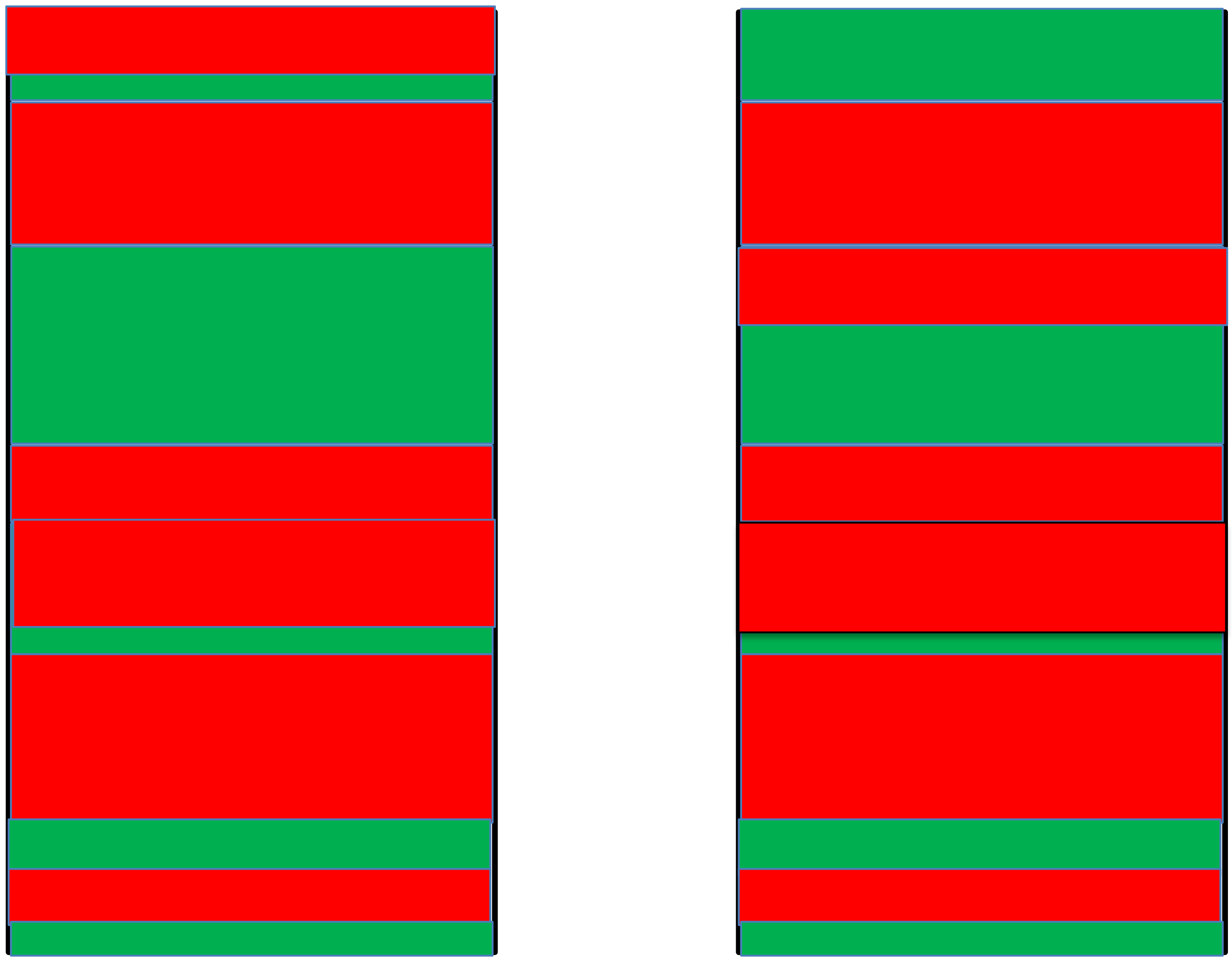
- Search for the “worst fit” chunk
  – Largest size greater than or equal to requested size
- Advantages:
  – Tends to create very large fragments
  … for a while, at least
- Disadvantages:
  – Still have to search the entire list every time

Worst Fit in Action



Comparing Best and Worst Fit

Best fit

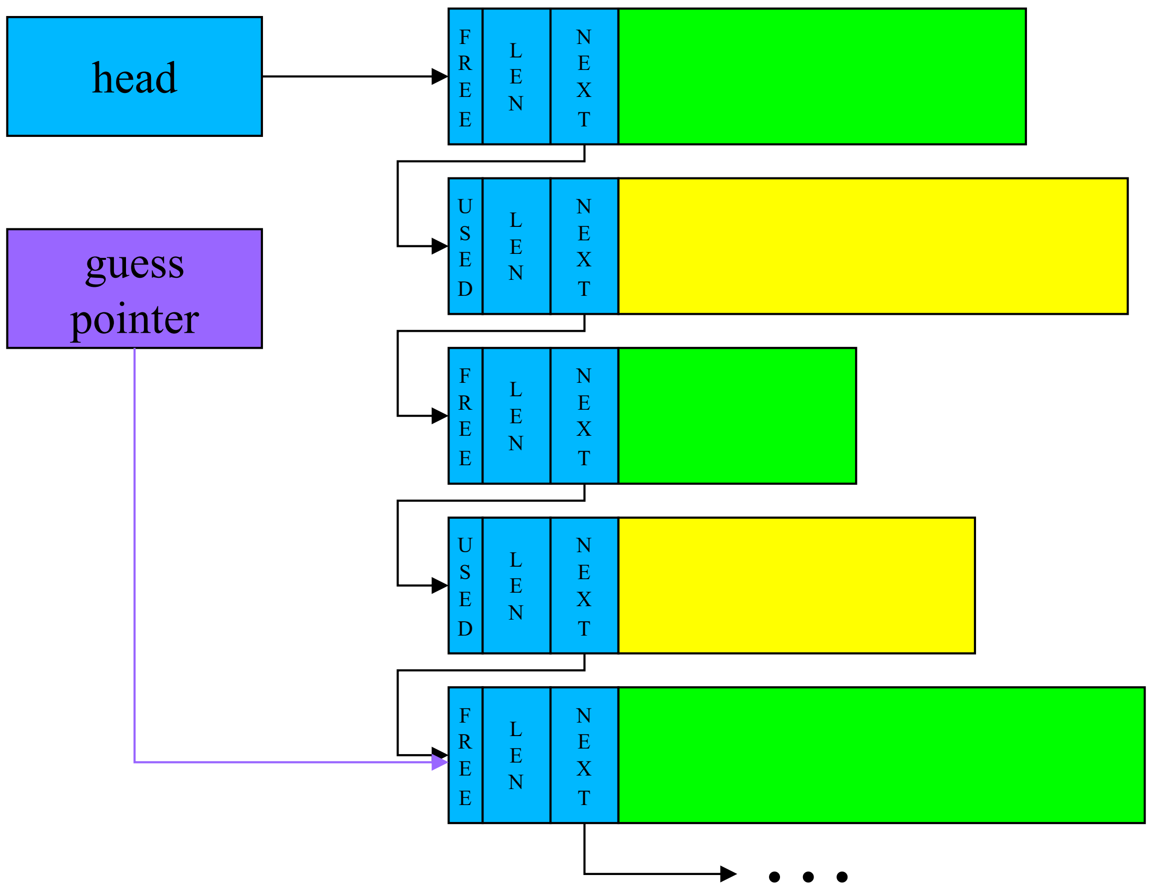


Worst fit

First Fit

- Take the first chunk you find that is big enough
- Advantages:
  - Very short searches
  - Creates random sized fragments
- Disadvantages:
  - The first chunks quickly fragment
  - Searches become longer
  - Ultimately it fragments as badly as best fit

Next Fit



After each search, set guess pointer to chunk after the one we chose.

That is the point at which we will begin our next search.

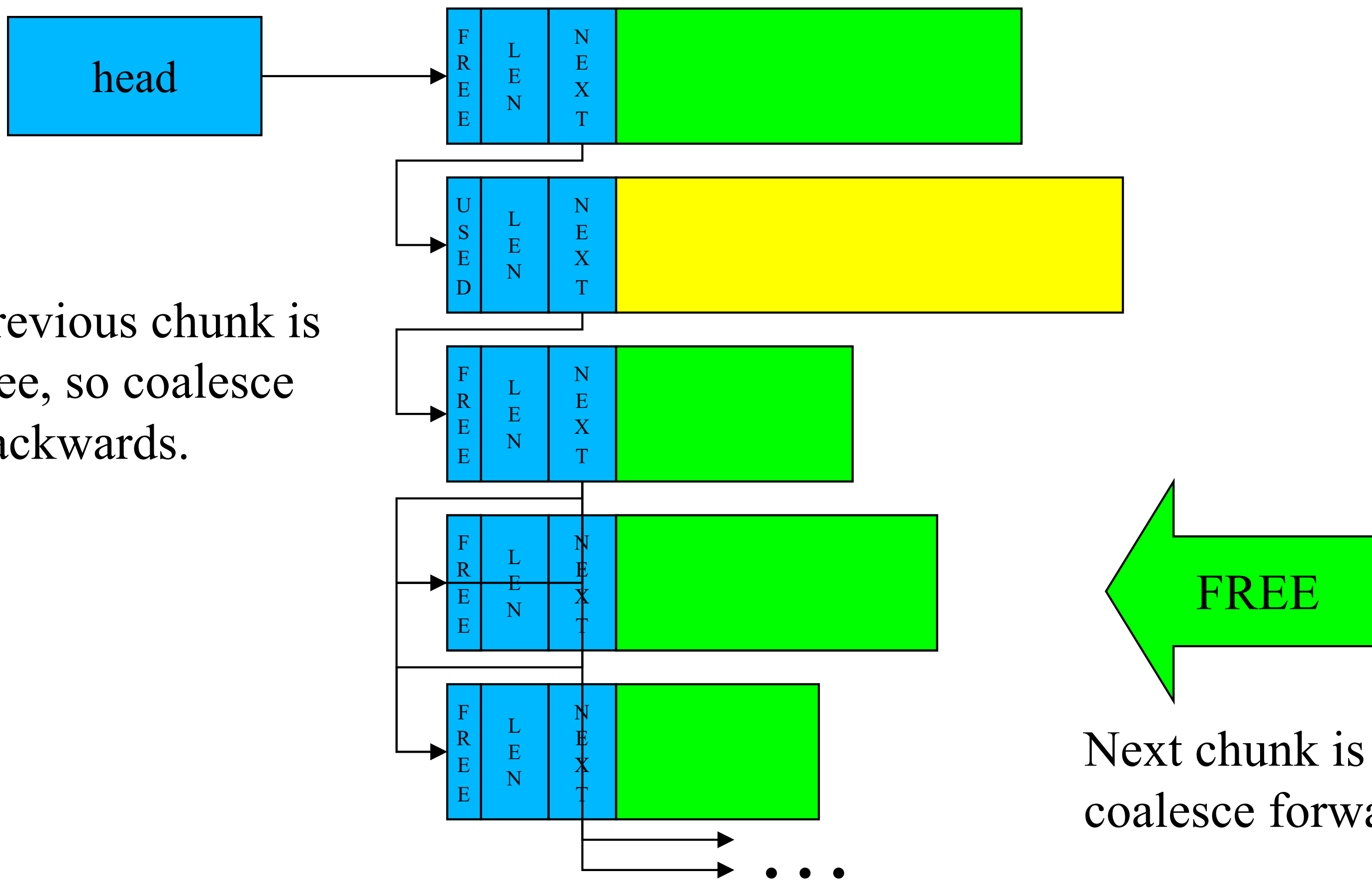
Next Fit Properties

- Tries to get advantages of both first and worst fit
  - Short searches (maybe shorter than first fit)
  - Spreads out fragmentation (like worst fit)
- Guess pointers are a general technique
  - If they are right, they save a lot of time
  - If they are wrong, the algorithm still works
  - They can be used in a wide range of problems

Coalescing Partitions

- All variable sized partition allocation algorithms have external fragmentation
  - Some get it faster, some spread it out
- We need a way to reassemble fragments
  - Check neighbors whenever a chunk is freed
  - Recombine free neighbors whenever possible
  - Free list can be designed to make this easier
    - Order list by chunk address, so neighbors are close
- Counters forces of external fragmentation

Free Chunk Coalescing



Previous chunk is free, so coalesce backwards.

Next chunk is also free, so coalesce forwards.

Fragmentation and Coalescing

- Opposing processes that operate in parallel
  - Which of the two processes will dominate?
- What fraction of space is typically allocated?
  - Coalescing works better with more free space
- How fast is allocated memory turned over?
  - Chunks held for long time cannot be coalesced
- How variable are requested chunk sizes?
  - High variability increases fragmentation rate
- How long will the program execute?
  - Fragmentation, like rust, gets worse with time

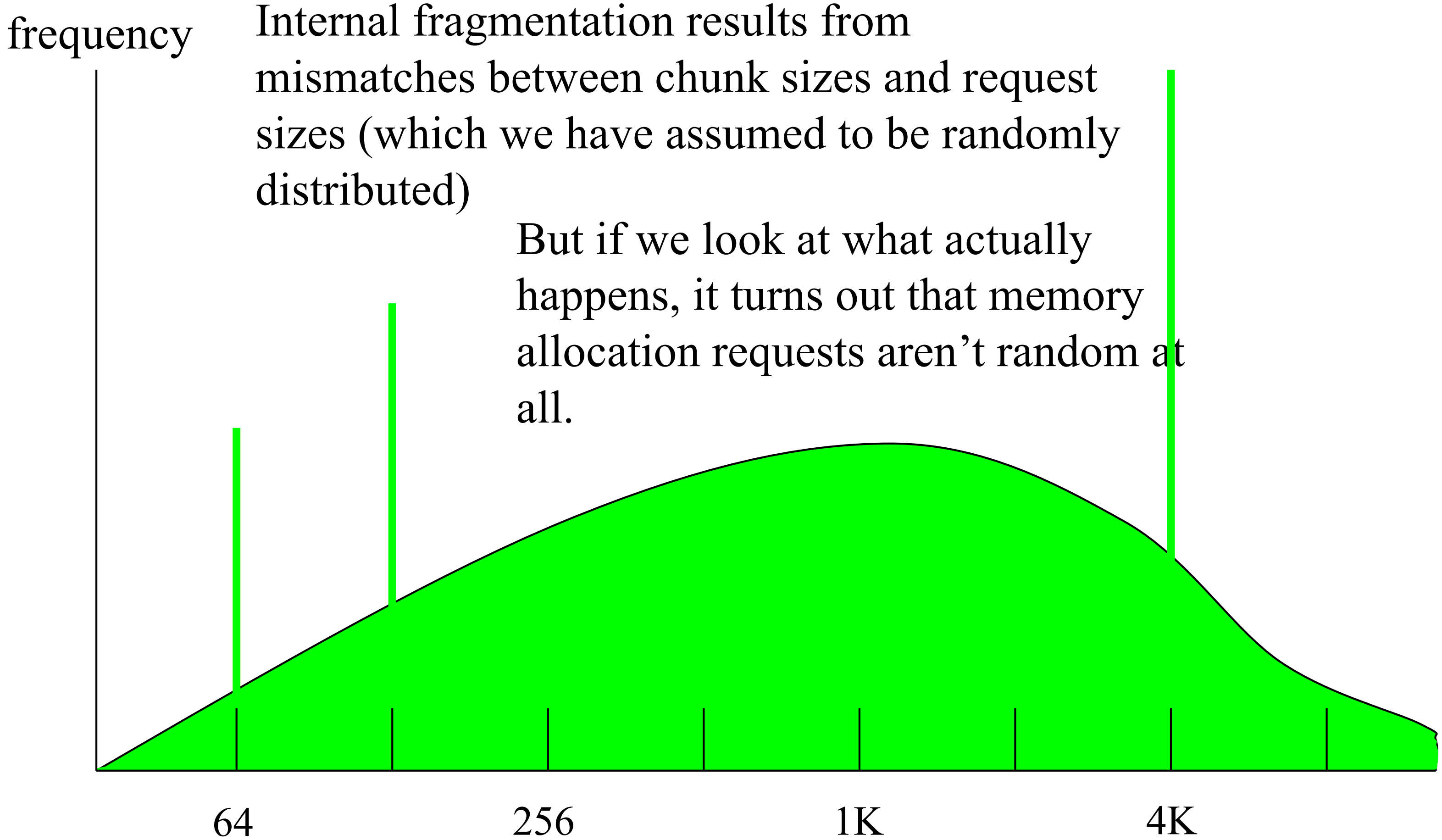
Variable Sized Partition Summary

- Eliminates internal fragmentation
  - Each chunk is custom-made for requestor
- Implementation is more expensive
  - Long searches of complex free lists
  - Carving and coalescing
- External fragmentation is inevitable
  - Coalescing can counteract the fragmentation
- Must we choose the lesser of two evils?

A Special Case for Fixed Allocations

Internal fragmentation results from mismatches between chunk sizes and request sizes (which we have assumed to be randomly distributed)

But if we look at what actually happens, it turns out that memory allocation requests aren't random at all.



Why Aren't Memory Request Sizes Randomly Distributed?

- In real systems, some sizes are requested much more often than others
- Many key services use fixed-size buffers
  - File systems (for disk I/O)
  - Network protocols (for packet assembly)
  - Standard request descriptors
- These account for much transient use
  - They are continuously allocated and freed
- OS might want to handle them specially

Buffer Pools

- If there are popular sizes,
  - Reserve special pools of fixed size buffers
  - Satisfy matching requests from those pools
- Benefit: improved efficiency
  - Much simpler than variable partition allocation
    - Eliminates searching, carving, coalescing
  - Reduces (or eliminates) external fragmentation
- But we must know how much to reserve
  - Too little, and the buffer pool doesn't help much
  - Too much, and we will have a lot of unused buffer space
- <u>Only</u> satisfy perfectly matching requests
  - Otherwise, back to internal fragmentation

How Are Buffer Pools Used?

- Process requests a piece of memory for a special purpose
  - E.g., to send a message
- System supplies one element from buffer pool
- Process uses it, completes, frees memory
  - Maybe explicitly
  - Maybe implicitly, based on how such buffers are used
    - E.g., sending the message will free the buffer “behind the process’ back” once the message is gone

How Big Should the Buffer Pool Be?

- Resize it automatically and dynamically
- If we run low on fixed sized buffers
  - Get more memory from the free list
  - Carve it up into more fixed sized buffers
- If our free buffer list gets too large
  - Return some buffers to the free list
- If the free list gets dangerously low
  - Ask each major service with a buffer pool to return space
- This can be tuned by a few parameters:
  - Low space (need more) threshold
  - High space (have too much) threshold
  - Nominal allocation (what we free down to)
- Resulting system is highly adaptive to changing loads

Lost Memory

- One problem with buffer pools: memory leaks
  - The process is done with the buffer
  - But doesn't free it
- Also a problem when a process manages its own memory space
  - E.g., it allocates a big area and maintains its own free list
- Long running processes with memory leaks can waste huge amounts of memory

Garbage Collection

- One solution to memory leaks
- Don’t count on processes to release memory
- Monitor how much free memory we’ve got
- When we run low, start *garbage collection*
  - Search data space finding every object pointer
  - Note address/size of all accessible objects
  - Compute the complement (what is inaccessible)
  - Add all inaccessible memory to the free list

How Do We Find All Accessible Memory?

- Object oriented languages often enable this
  - All object references are tagged
  - All object descriptors include size information
- It is often possible for system resources
  - Where all possible references are known
    - E.g., we know who has which files open
- How about for the general case?

General Garbage Collection

- Well, what would you need to do?
- Find all the pointers in allocated memory
- Determine "how much" each points to
- Determine what is and is not still pointed to
- Free what isn't pointed to
- Why might that be difficult?

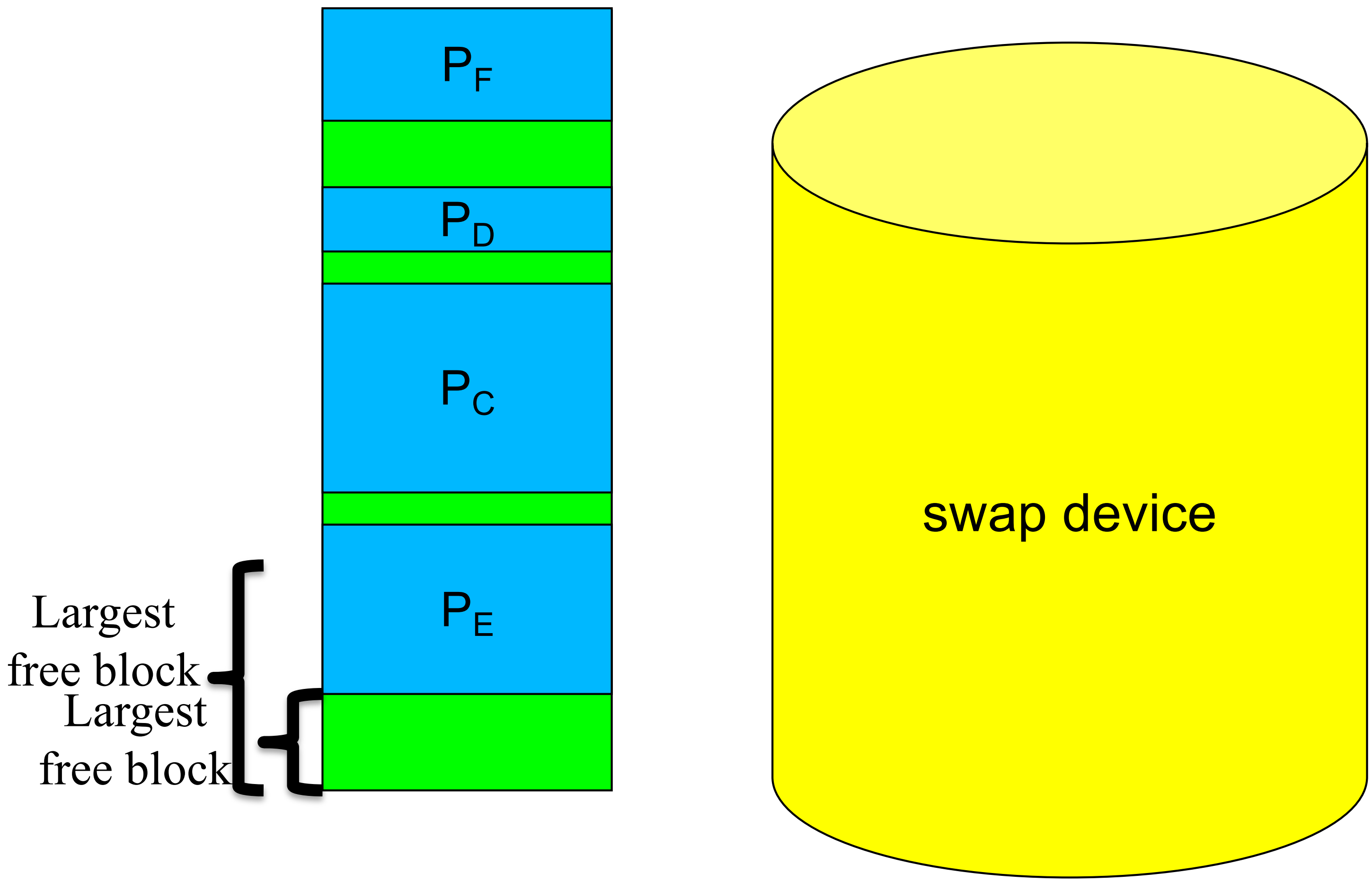
Problems With General Garbage Collection

- A location in the data or stack segments might <u>seem</u> to contain addresses, but ...
  - Are they truly pointers, or might they be other data types whose values happen to resemble addresses?
  - If pointers, are they themselves still accessible?
  - We might be able to infer this (recursively) for pointers in dynamically allocated structures …
  - But what about pointers in statically allocated (potentially global) areas?
- And how much is “pointed to,” one word or a million?

Compaction and Relocation

- Garbage collection is just another way to free memory
  - Doesn’t greatly help or hurt fragmentation
- Ongoing activity can starve coalescing
  - Chunks reallocated before neighbors become free
- We could stop accepting new allocations
  - But processes needing more memory would block until some is freed, slowing the system
- We need a way to rearrange active memory
  - Re-pack all processes in one end of memory
  - Create one big chunk of free space at other end

Memory Compaction



Now let's compact!

An obvious improvement!

All This Requires Is Relocation . . .

- The ability to move a process' data
  - From the region where it was initially loaded
  - Into a new and different region of memory
- What's so hard about that?
- All addresses in the program will be wrong
  - References in the code segment
    - Calls and branches to other parts of the code
    - References to variables in the data segment
  - Plus new pointers created during execution
    - That point into data and stack segments

Why Is Relocation Hard?

`int *foo;`

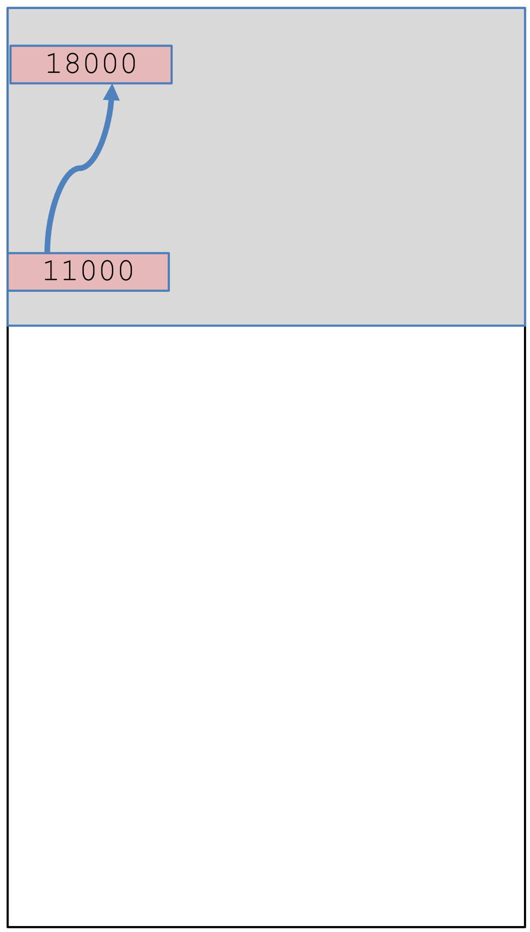
Before

10000

foo

20000

Real physical addresses



Let's move the partition!

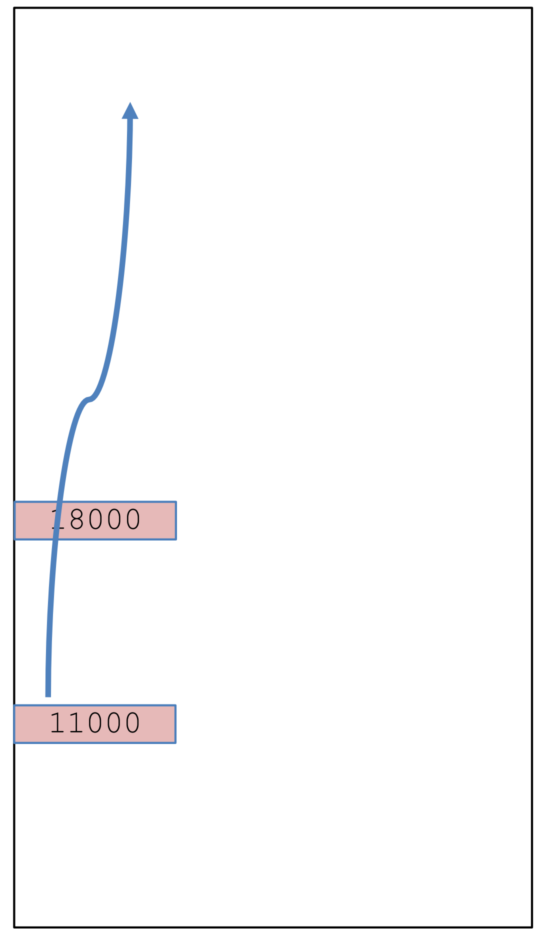
What's going to happen the next time we access foo?

After

23000

foo

33000

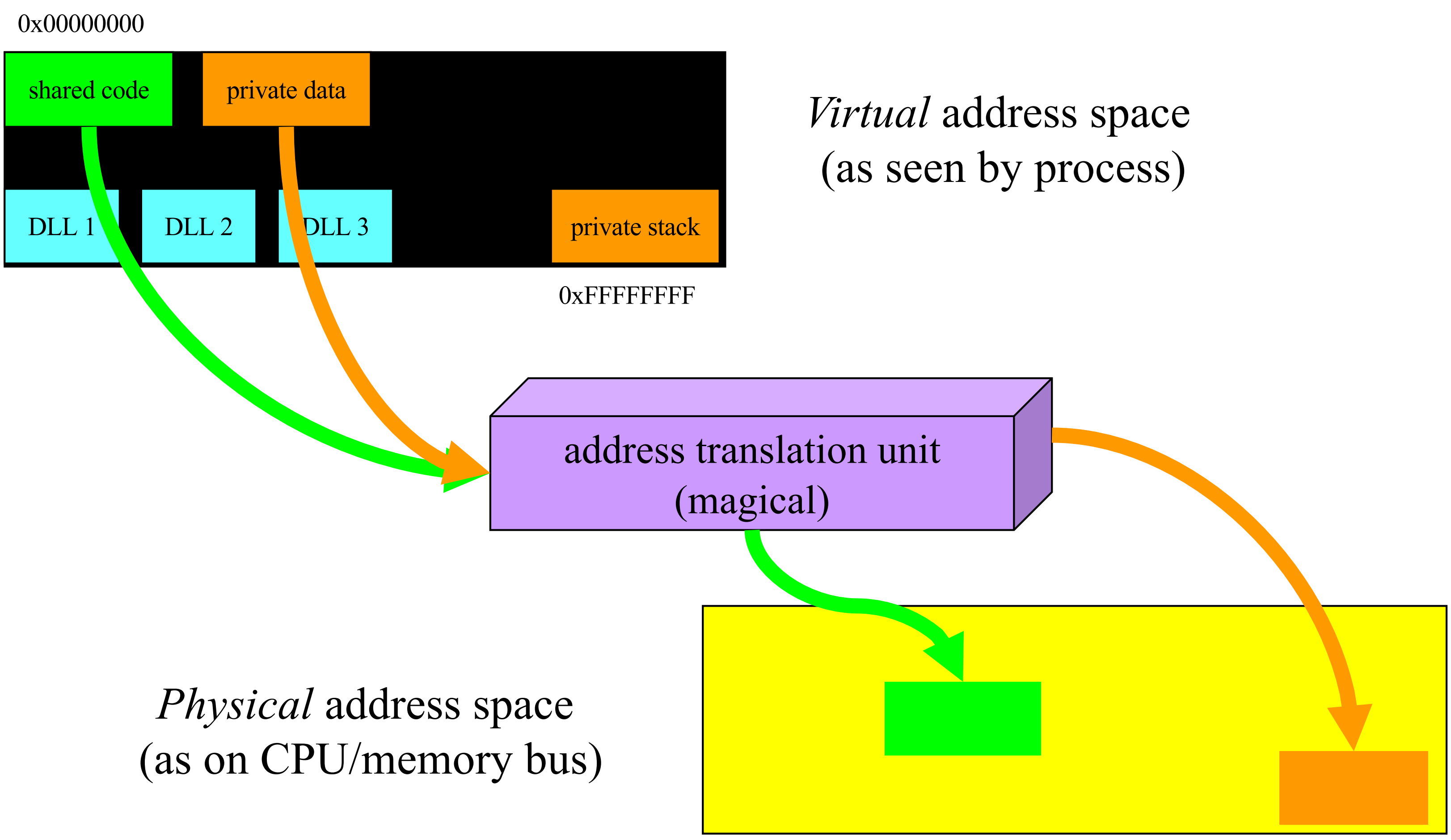


Of course, we copy the partition's contents when we move it

The Relocation Problem

- It is not generally feasible to relocate a process
  - Maybe we could relocate references to code
    - If we kept the relocation information around
  - But how can we relocate references to data?
    - Pointer values may have been changed
    - New pointers may have been created
- We could never find/fix all address references
  - Like the general case of garbage collection
- Can we make processes location independent?

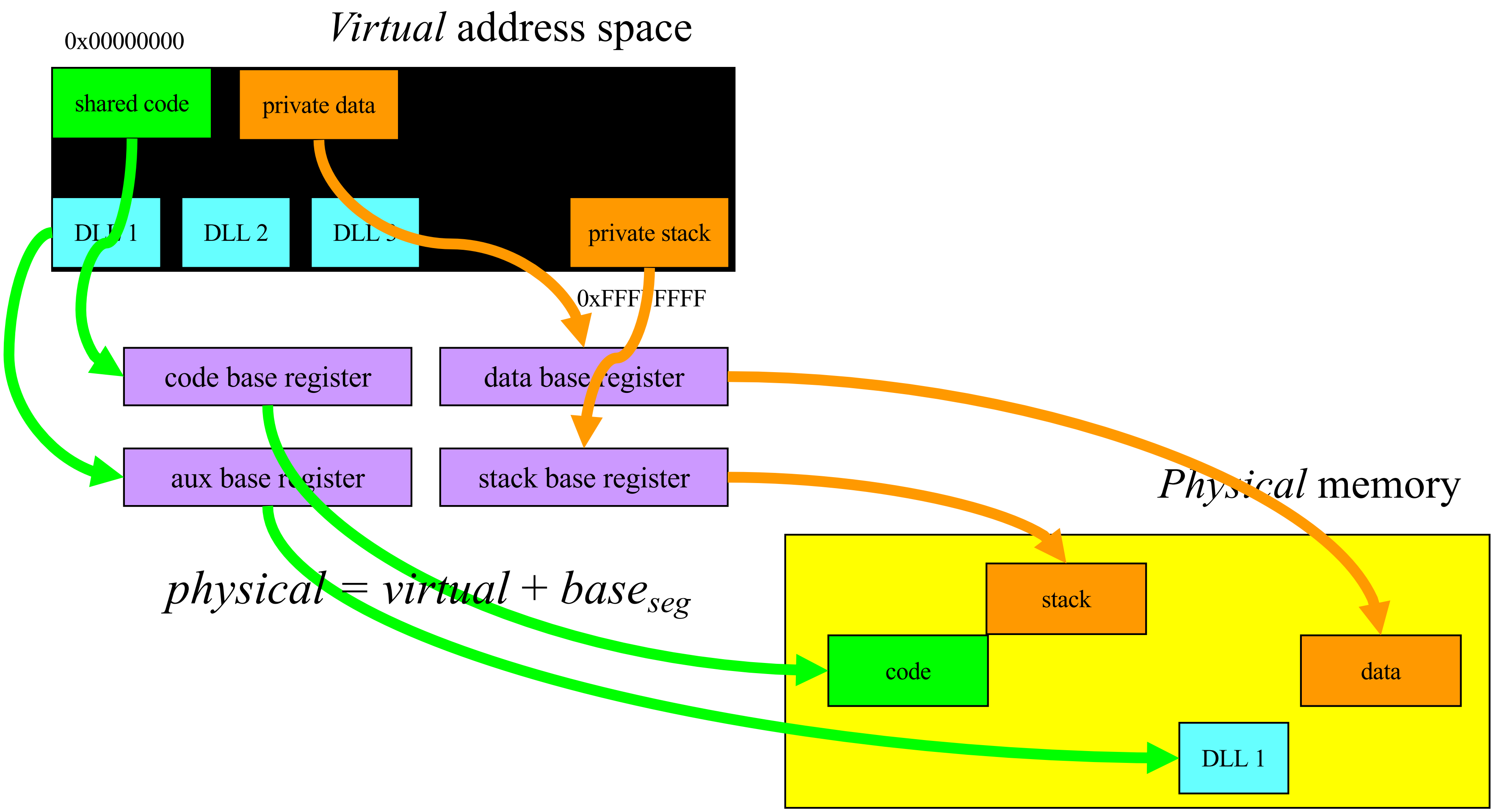
Virtual Address Spaces



Memory Segment Relocation

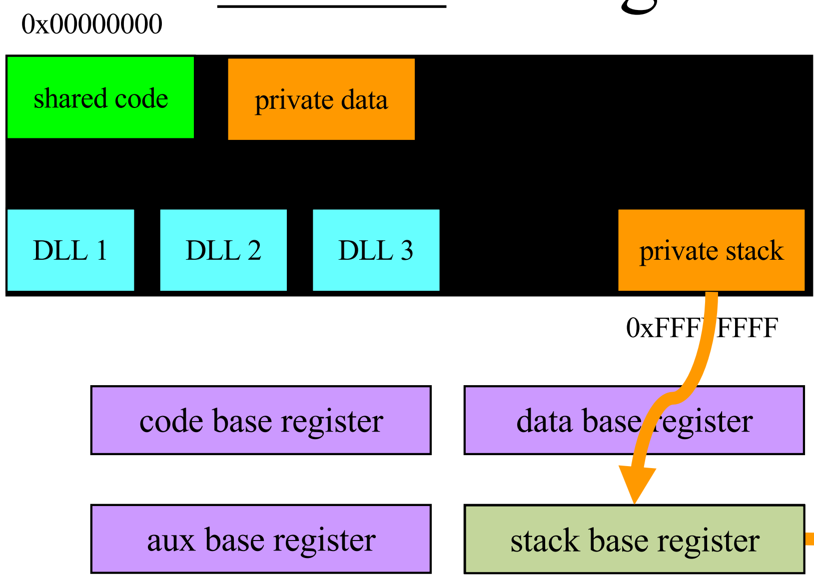
- A natural model
  - Process address space is made up of multiple segments
  - Use the segment as the unit of relocation
  - Long tradition, from the IBM system 360 to Intel x86 architecture
- Computer has special relocation registers
  - Called *segment base registers*
  - Pointing to the start (in physical memory) of each segment
  - CPU automatically adds base register to every address
- OS uses these to perform virtual address translation
  - Set base register to start of region where program is loaded
  - If program is moved, reset base registers to new location
  - Program works no matter where its segments are loaded

How Does Segment Relocation Work?

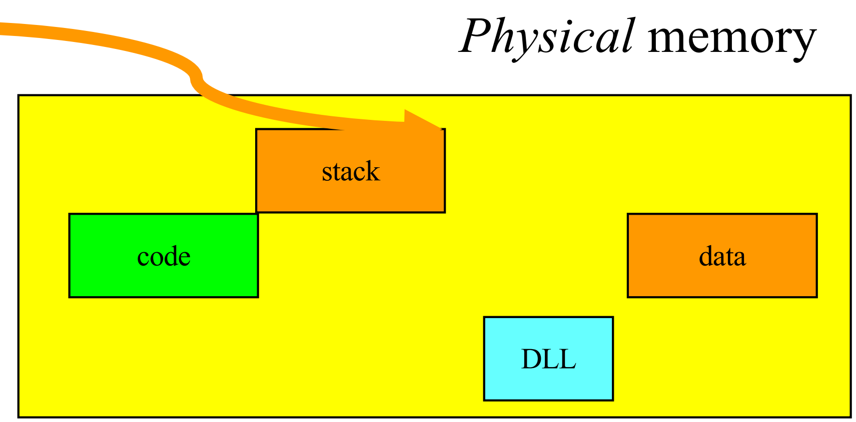


Relocating a Segment

The virtual address of the stack doesn't change



Let's say we need to move the stack in physical memory



$$physical = virtual + base_{seg}$$

We just change the value in the stack base register

Relocation and Safety

- A relocation mechanism (like base registers) is good
  - It solves the relocation problem
  - Enables us to move process segments in physical memory
  - But just relocation is insufficient
- We also need protection
  - Prevent process from reaching outside its allocated memory
    - E.g., by overrunning the end of a mapped segment
- Segments also need a length (or limit) register
  - Specifies maximum legal offset (from start of segment)
  - Any address greater than this is illegal
  - CPU should report it via a <u>segmentation</u> exception (trap)

How Much of Our Problem Does Relocation Solve?

- We can use variable sized partitions
  - Cutting down on internal fragmentation
- We can move partitions around
  - Which helps coalescing be more effective
  - But still requires contiguous chunks of data for segments
  - So external fragmentation is still a problem
- We need to get rid of the requirement of contiguous segments

Conclusion

- RAM memory is a scarce resource that the OS must manage carefully
- Fixed partition management is inflexible and causes internal fragmentation
- Variable partition management is more complex and causes external fragmentation
- Garbage collection and compaction help, but require ability to relocate partitions
  - Which is hard