Memory Management:
Free space and dynamic allocation

M1 MOSIG – Operating System Design

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Acknowledgments

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  - Arnaud Legrand, Noël De Palma, Sacha Krakowiak
  - David Mazières (Stanford)
    - (most slides/figures directly adapted from those of the CS140 class)
  - Randall Bryant, David O'Hallaron, Gregory Kesden, Markus Püschel (Carnegie Mellon University)
    - Textbook: Computer Systems: A Programmer's Perspective (2nd Edition)
    - CS 15-213/18-243 classes (some slides/figures directly adapted from these classes)
  - Remzi and Andrea Arpaci-Dusseau (U. Wisconsin)
  - Textbooks (Silberschatz et al., Tanenbaum)

Outline

- Introduction
  - Motivation
  - Fragmentation
- How to implement a memory allocator?
  - Key design decisions
  - A comparative study of several simple approaches
  - Known patterns of real programs
  - Some other designs
- Implicit memory management (garbage collection)

Dynamic memory allocation – Introduction (1)

- Almost every program uses it
  - Gives very important functionality benefits
    - Avoids statically specifying complex data structures
    - Avoids static overprovisioning of memory
    - Allows having data grow as a function of input size
  - But can have a huge impact on performance

- A general principle, used at several levels of the software stack:
  - In the operating system kernel, to manage physical memory
  - In the C library, to manage the heap, a specific zone within a process' virtual memory
  - (And also possibly) within an application, to manage a big chunk of virtual memory provided by the OS

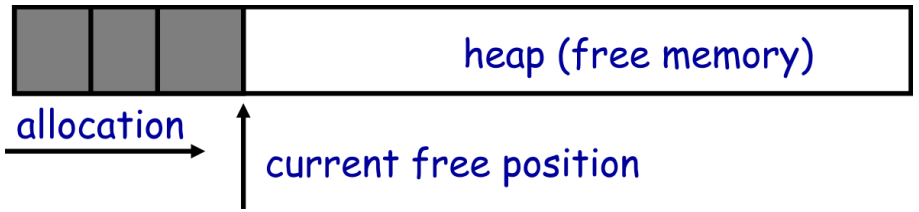
Dynamic memory allocation – Introduction (2)

- Today's focus: how to implement it
  - Lectures draws on [Wilson et al.] (good survey from 1995)

- Some interesting facts (on performance)
  - Changing a few lines of code can have huge, non-obvious impact on how well an allocator works (examples to come)
  - Proven: impossible to construct an "always good" allocator
  - Surprising result: after decades, memory management is still poorly understood

Why is it hard?

- Satisfy arbitrary sequence of alloc/free operations
- Easy without free:
  - Set a pointer to the beginning of some big chunk of memory ("heap") and increment on each allocation



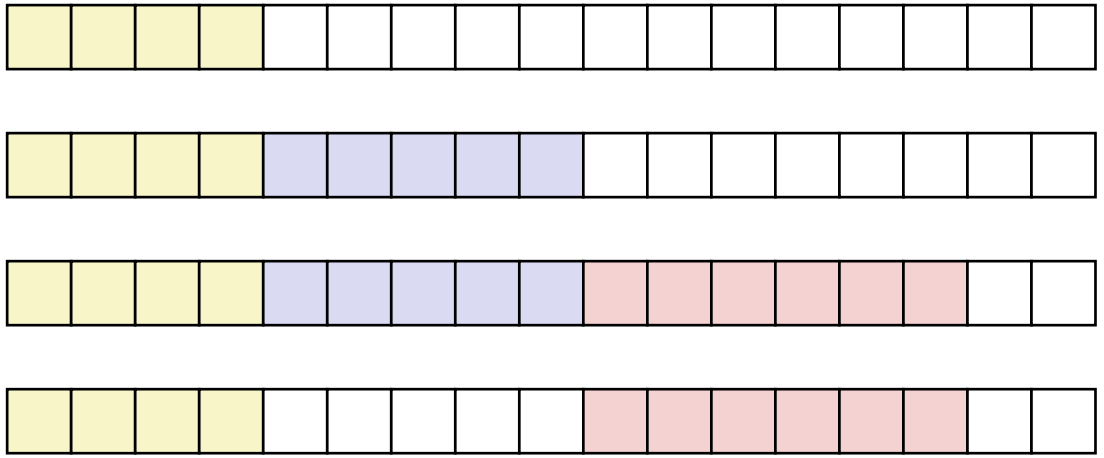
- Problem: free creates holes ("fragmentation"). Result: lots of free space but cannot satisfy request

- Why can't we just move everything to the left when needed?
  - This requires to update memory references (and thus to know about the semantics of data)

External Fragmentation

- Occurs when there is enough aggregate heap memory, but no single free block is large enough

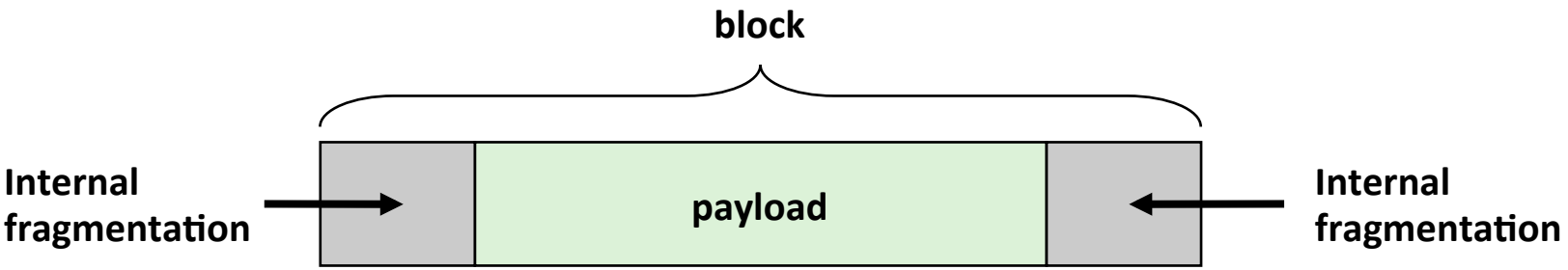
```
p1 = malloc(4)
p2 = malloc(5)
p3 = malloc(6)
free(p2)
p4 = malloc(6)
```



Oops! (what would happen now?)

Internal Fragmentation

- For a given block, ***internal fragmentation*** occurs if payload is smaller than block size

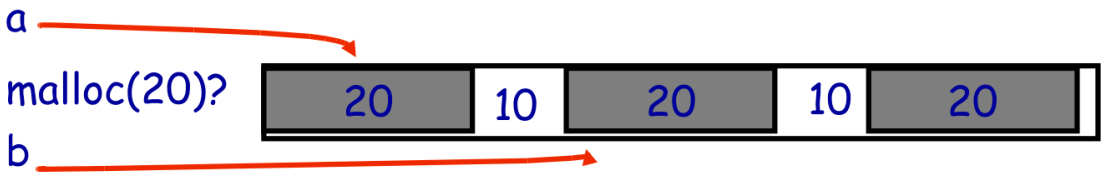


- Caused by
  - overhead of maintaining heap data structures
  - padding for alignment purposes
  - explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

More abstractly

- What an allocator must do:
  - Track which parts of memory are in use, and which parts are free
  - Ideally: no wasted space, no time overhead

- What the allocator cannot do:
  - Control order, number and size of the requested blocks
  - Change user pointers (as a consequence, bad placement decisions are permanent)



- The core fight: minimize fragmentation
  - Application frees blocks in any order, creating holes in "heap"
  - If holes are too small, future requests cannot be satisfied

What is fragmentation?

- Inability to use memory that is free
- Two factors required for fragmentation
  - Different lifetimes:
    - If adjacent objects die at different times, then fragmentation

    - If they die at the same time, then no fragmentation

  - Different sizes:
    - If all requests have the same size, then no fragmentation

    - (As we will see later, in the context of virtual memory, paging relies on this to remove external fragmentation)

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- **How to implement a memory allocator?**
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  - A comparative study of several simple approaches
  - Known patterns of real programs
  - Some other designs
- Implicit memory management (garbage collection)

Important design decisions (1/5)

- **Free block organization**: How do we keep track of free blocks?
- **Placement**: How do we choose an appropriate free block in which to place a newly allocated block?
- **Splitting**: After we place a newly allocated block in some free block, what do we do with the remainder of the free block?
- **Coalescing**: What do we do with a block that has just been freed?

Important design decisions (2/5)

- **Free block organization**: How do we keep track of free blocks?
  - Common approach: "free list" i.e., linked list of descriptors of free blocks
  - Multiple strategies to sort the free list
  - For space efficiency, the free list is stored within the free space!
  - (There are also other approaches/data structures beyond free lists, e.g., balanced trees)

Important design decisions (3/5)

- **Placement**: How do we choose an appropriate free block in which to place a newly allocated block?
  - Placement strategies have a major impact on external fragmentation
  - We will study several examples soon (best fit, first fit, …)
  - Ideal: put block where it will not cause fragmentation later (impossible to guarantee in general: requires future knowledge)

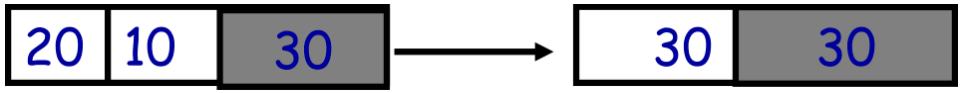
Important design decisions (4/5)

- **Splitting**: After we place a newly allocated block in some free block, what do we do with the remainder of the free block?

  - Two choices:
    - Keep the remainder within the free block
      - Simple, fast
      - but introduces more internal fragmentation
    - Split the free block in two (allocated block and remainder) and insert the remainder block in the free list
      - Better with respect to internal fragmentation (less wasted space)
      - But requires more work (and thus more time), which may be wasted if most remainder blocks are useless (too small)

Important design decisions (5/5)

- **Coalescing**: What do we do with a block that has just been freed?
  - The adjacent blocks may be free
  - Coalescing the newly freed block with the adjacent free block(s) yields a larger free block
  - This helps avoiding “false external fragmentation”



  - Different strategies:
    - Immediate coalescing: systematic attempt whenever a block is freed
      - This may sometimes work “too well”
    - Only on some occasion (e.g., when we are running out of space) or periodically

“Free list”
Typical implementation and space overheads

- Free list bookkeeping + alignment determine minimum allocatable size
  - Store size of block
  - Pointers to next and previous freelist element

- Additional constraints due to the physical machine: memory alignment
  - The allocator does not know the type of the allocated data.
  - Must align memory to conservative boundary.

- Minimum allocation unit? Space overhead when allocated?

Impossible to "solve" fragmentation

- If you read research/technical papers to find the best allocator
  - All discussions revolve around trade-offs
  - Because there cannot be a best allocator

- Theoretical result
  - *For any possible allocation algorithm, there exists streams of allocation and deallocation requests that defeat the allocator and force it into severe fragmentation*

- How much fragmentation should we tolerate?
  - Let M = bytes of live data, n_{min} = smallest allocation size, n_{max} = largest allocation size
  - How much gross memory required?
  - Bad allocator: $M . (n_{max} / n_{min})$
    - (uses maximum size for any size)
  - Good allocator: $\sim M . \log(n_{max} / n_{min})$

Pathological examples

- Example 1: Given allocation of 7 20-byte blocks

  - What is a bad stream of frees and then allocates?
  - Free every one block out of two, then alloc 21 bytes

- Example 2: Given a 128-byte limit on malloc-ed space
  - What is a really bad combination of mallocs and frees?
  - Malloc 128 1-byte blocks, free every chunk but the 1st and the 64th
  - Then, try to malloc 64 bytes

- Next: we will study two allocators (best fit, first fit) that, in practice, work pretty well

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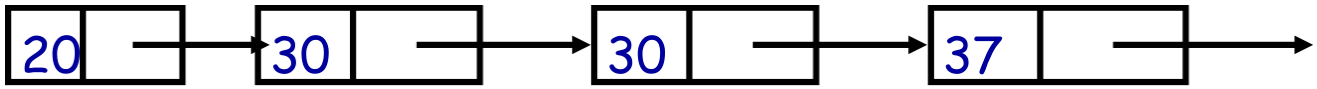
Best fit

- Placement strategy: minimize fragmentation by allocating space from block that leaves smallest fragment
  - Data structure: heap is a list of free blocks, each has a header holding block size and pointer to next



  - Code: Search freelist for block closest in size to the request (exact match is ideal)
  - During free, (usually) coalesce adjacent blocks

- Problem: Sawdust
  - Remainder so small that, over time, we are left with "sawdust" everywhere
  - Fortunately, not often a problem in practice
- Implementation? (go through the whole list? maintain sorted list?)

First fit

- Strategy: pick the first block that fits
  - Data structure: free list
  - Code: scan list, take the first one
  - Multiple strategies for sorting the free list: LIFO, FIFO or by address

- LIFO: put free block on front of list
  - Simple but causes higher fragmentation
  - Potentially good for cache locality

- Address sort: order free blocks by address
  - Makes coalescing easy (just check if next block is free)
  - Also preserves empty/idle space (locality good when paging)

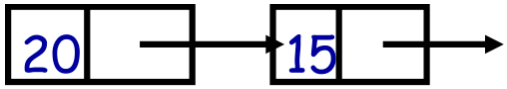
- FIFO: put free block at end of list
  - Gives similar fragmentation as address sort, but unclear why

Subtle pathology: LIFO first fit

- Example of subtle impact of simple decisions
- LIFO first fit seems good:
  - Put object on front of list (cheap), hope same size used again (cheap + good locality)
- But has big problems for simple allocation patterns
  - E.g., repeatedly intermix short-lived allocations of *2n* bytes, with long-lived allocations of *(n+1)* bytes
  - Each time a large object is freed, a small chunk will be quickly taken, leaving useless fragment. Pathological fragmentation

First fit: Nuances

- First fit sorted by address order, in practice:
  - Blocks at front preferentially split, ones at back only split when no larger one found before them
  - Result? Seems to roughly sort free list by size
  - So? Makes first fit operationally similar to best fit: a first fit of a sorted list = best fit!
- Problem: sawdust at beginning of the list
  - Sorting of list forces a large request to skip over many small blocks. Need to use a scalable heap organization.

- Suppose memory has free blocks: 

  - If allocation operations are 10 then 20, best fit wins
  - When is first fit better than best fit?
  - Suppose allocation operations are 8, 12, 12. Then first fit wins

First/best fit: weird parallels

- Both seem to perform roughly equivalently

- In fact, the placement decisions of both are roughly identical under both randomized and real workloads
  - No clear explanation
  - Pretty strange since they seem pretty different

- Possible explanations:
  - Over the time, FF's free list becomes sorted by size: the beginning of the free list accumulates small objects and so FF tends to be close to BF
  - Both have implicit "open space heuristic", try not to cut into large open spaces: large blocks at end only used when have to be (e.g., first fit skips over all smaller blocks)

Some other placement strategies

- Worse fit
  - Strategy: fight against sawdust by splitting block to maximize leftover size
  - In practice, seems to ensure that there are no large blocks

- Next fit
  - Strategy: use first fit, but remember where we found the last thing and start searching from there
  - Seems like a good idea, but tends to break down entire list

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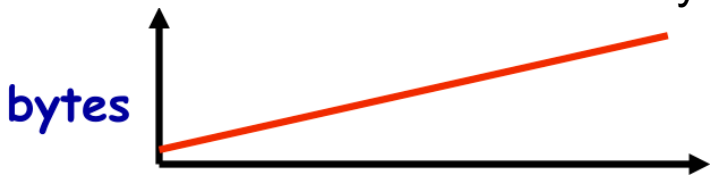
Known patterns of real programs

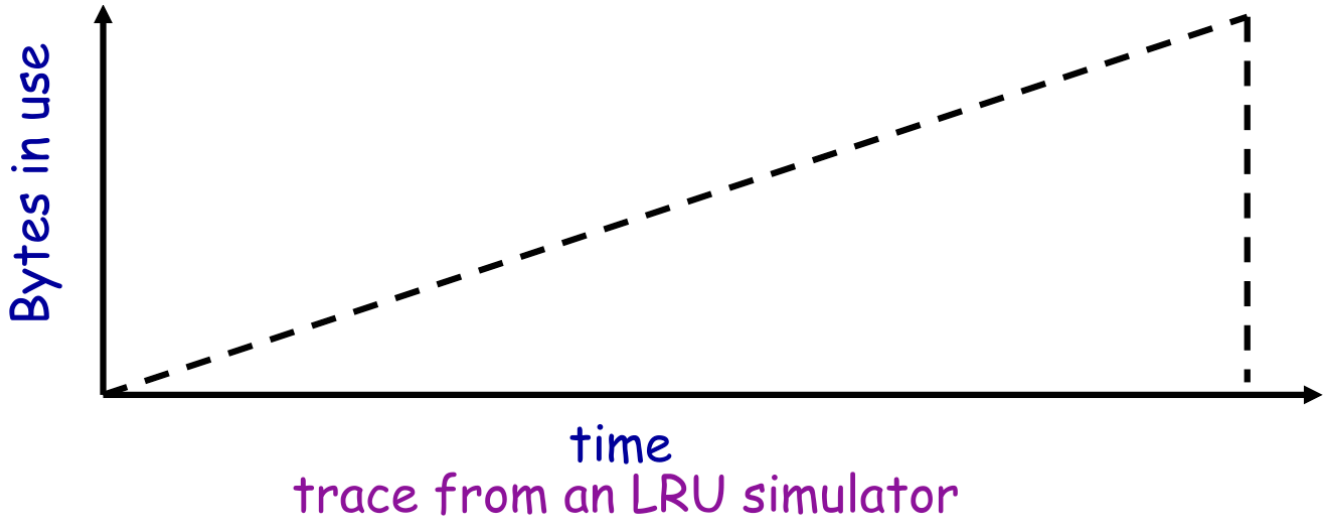
- So far, we have treated programs as black boxes
- Most real programs exhibit 1 or 2 (or all 3) of the following patterns of alloc/dealloc:
  - Ramps: accumulate data monotonically over time



  - Peaks: allocate many objects, use briefly, then free all

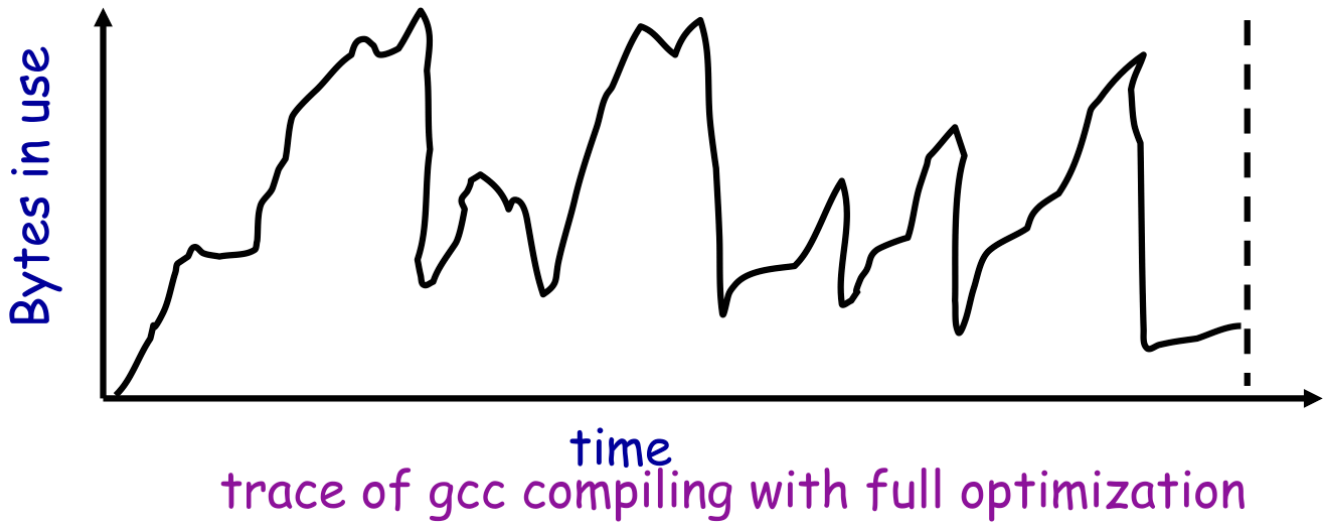
  - Plateaus: allocate many objects, use for a long time

Pattern 1: Ramps



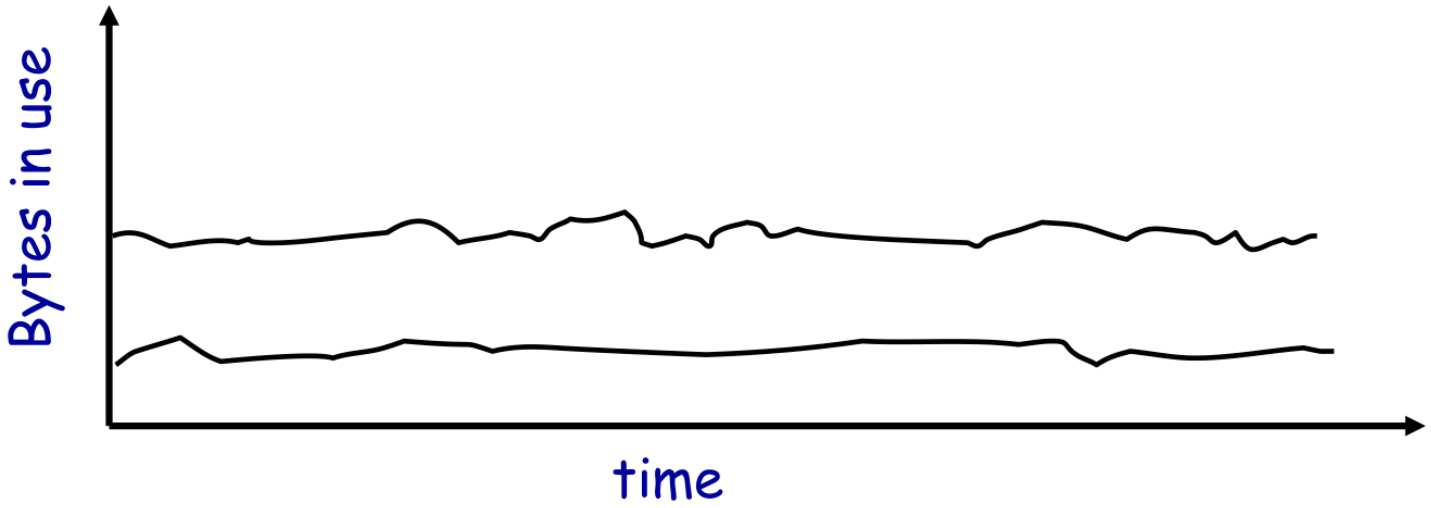
- In practical sense: ramp = no free
  - Implication for fragmentation?
  - What happens if you evaluate allocator with ramp programs only?

Pattern 2: Peaks



- Peaks: allocate many objects, use briefly then free all
  - Surviving data are likely to be of different types
  - Fragmentation a real danger
  - What happens if peak allocated from contiguous memory?
  - Interleave peak and ramp? Interleave two different peaks?

Pattern 3: Plateaus



trace of perl running a string processing script

- Plateaus: allocate many objects, use for a long time
  - What happens if overlap with peak or different plateau?

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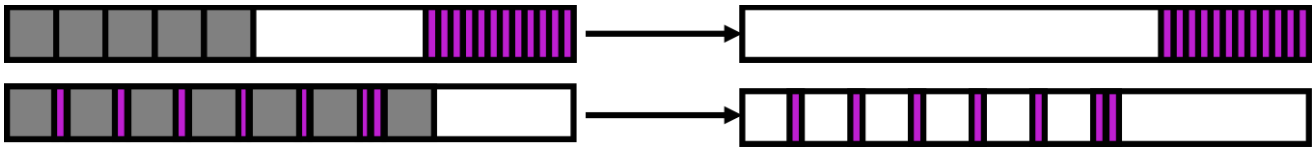
Beyond simple free lists

- We will study a few examples of other approaches:
  - Segregated lists
  - Slab caches
  - Buddy allocation

Fighting fragmentation
Exploiting ordering and size dependencies

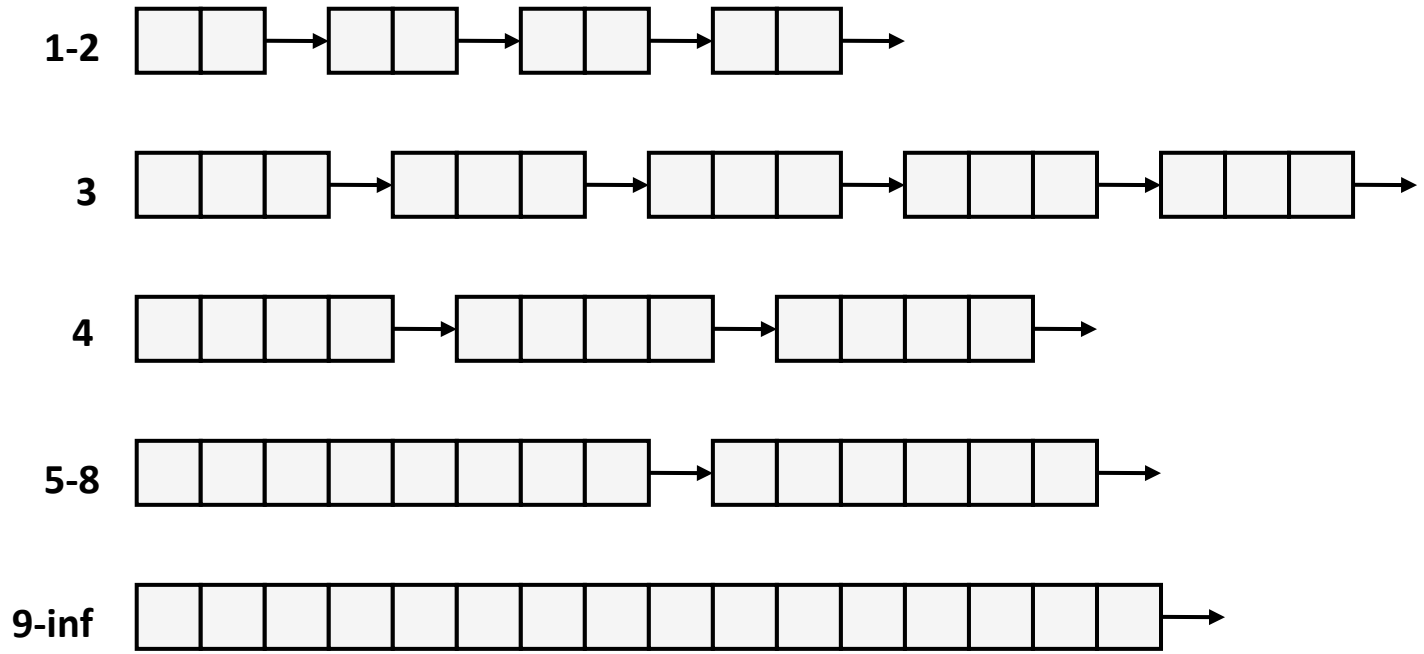
- Segregation = reduced fragmentation
  - Allocated at same time ~ freed at same time
  - Different type ~ freed at different time



- Implementation observations
  - Programs allocate small number of different sizes
  - Fragmentation at peak use is more important than at low
  - Most allocations are small (< 10 words)
  - Work done with allocated memory increases with size
  - Implications?

Segregated List (Seglist) Allocators

- Each ***size class*** of blocks has its own free list



- Often have separate classes for each small size
- For larger sizes: One class for each two-power size

(adapted from the following source: Carnegie Mellon University – 15-213/18-243 class)

Slab allocation

- Remember what we told earlier : if all requests have the same size, then no fragmentation
- The kernel allocates many instances of the same structures
  - E.g., a 1.7 kB **`task_struct`** for every process on the system
  - And often needs contiguous physical memory
- Slab allocation optimizes for this case:
  - A slab is multiple pages of contiguous physical memory
  - A cache contains one or more slabs
  - Each cache stores only one kind of object (fixed size)
- Each slab is full, empty or partial
- Example: need new **`task_struct`**?
  - Look in the **`task_struct`** cache
  - If there is a partial slab, pick free **`task_struct`** in that
  - Else use empty, or may need to allocate new slab for cache
- Advantages: speed and no internal fragmentation [Bonwick]

Buddy allocation

- A special form of segregated allocator
- Here we only discuss the most common type of buddy system: binary buddies

- Relies on specific rules to make management faster:
  - Rounds up all allocation sizes to powers of 2
  - Imposes specific rules/restrictions on splitting/ coalescing procedures
  - Fast but may result in heavy internal fragmentation

Dynamic memory management Recap

- Fragmentation is caused by:
  - Size heterogeneity
  - Isolated deaths
  - Time-varying behavior
- Allocator should try to:
  - Exploit memory patterns
  - Be evaluated under real workloads
  - Have smart and cheap implementation

Summary of Key Allocator Policies

- Placement policy:
  - First-fit, next-fit, best-fit, etc.
  - Trades off lower throughput for less fragmentation
  - ***Interesting observation*****:** segregated free lists approximate a best fit placement policy without having to search entire free list
- Splitting policy:
  - When do we go ahead and split free blocks?
  - How much internal fragmentation are we willing to tolerate?
- Coalescing policy:
  - ***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

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Implicit Memory Management: Garbage Collection

- *Garbage collection:*
  - Automatic reclamation of heap-allocated storage
  - The application never has to free
    - Avoids many memory management bugs
      - Examples: double free bugs, some forms of dangling pointers, some forms of memory leaks
    - … but not all of them
    - Usually yields lower performance than manual memory management

- Common in many languages
  - Functional languages (e.g., Lisp, ML)
  - Scripting languages (e.g., Perl)
  - Modern object oriented languages (e.g., Java)
- Variants (“conservative” garbage collectors) exist for C and C++
  - However, cannot necessarily collect all garbage

Garbage collection

- **Main principle:** How does the memory manager know when a memory block can be freed?

  – In general we cannot know what is going to be used in the future since it depends on conditionals

  – But we can tell that certain blocks cannot be used if there are no pointers to them.
    - **A (dynamically allocated) memory block becomes garbage (i.e., useless) when it cannot be reached anymore by the application**

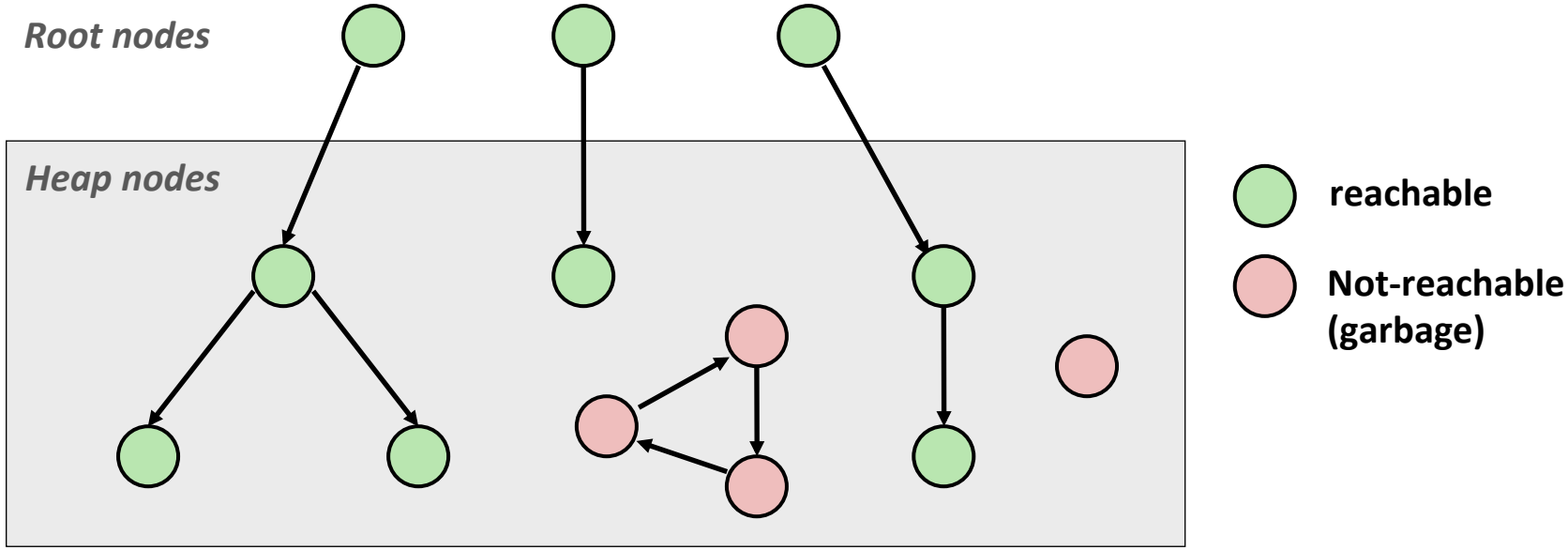
Garbage collection (continued)

- **Assumptions**
  - Pointers (i.e., memory addresses) can be distinguished from other types of variables
  - A pointer can only point to the beginning of a memory block (i.e., not to the middle of a block)
  - A pointer cannot be “hidden” in another data type

- Languages such as C and C++ do not comply with the above assumptions
  - But some restricted forms of garbage collection can nonetheless be implemented with these languages

Tracing garbage collectors
Memory as a Graph

- We view memory as a directed graph
  - Each block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called ***root*** nodes (e.g., registers, locations on the stack, global variables)



A node (block) is *reachable* if there is a path from any root to that node.

Non-reachable nodes are *garbage* (not needed by the application)

Garbage collection algorithms (1/2)

- Tracing collectors (example: Mark-and-sweep)
  - Usually triggered when heap runs out of free space
  - Some important criteria
    - **Moving (a.k.a. "compacting") versus non-moving**
      - Note that, in a safe language (e.g., Java), the runtime system knows about all pointers
      - So an object can be moved if all the related pointers are updated accordingly
      - Good: helpful for fighting fragmentation and improving locality
      - Bad: performance impact of memory copies
    - **Stop-the-world versus incremental versus concurrent**
      - Different trade-offs depending on the requirements of programs (interactivity/reactivity, need to reclaim memory fast, …)
    - **Precise versus conservative**
      - See previous discussions on C/C++

Garbage collection algorithms (2/2)

- Reference counting
  - Another approach (different from tracing collectors)
  - Each object has an internal field (“ref count”), which keeps tracks of the current number of pointers to it
  - The ref count is incremented when a pointer is set to this object
  - The ref count is decremented when a pointer is set to another object or destroyed
  - The object can be reclaimed when the ref count reaches zero

  - Pros
    - No need to halt program when running collector
    - Immediate reclamation of available memory
  - Cons
    - Need to update the ref counts (negative performance effects)
    - Problems with circular data structures (leaks)
    - Problems with deep data structures (long recursive destruction)

References

- Andrea & Remzi Arpaci-Dusseau. **OSTEP textbook** (http://www.ostep.org). Chapters:
  - *"Memory API"*
  - *"Free space management"*

- [CSAPP (book)] Randall Bryant, David O'Hallaron. ***Computer Systems: A Programmer's Perspective***. Pearson.
  - See chapter on "Virtual memory", section on "Dynamic memory allocation" (Also covers garbage collection)

- [Wilson et al.] P. R. Wilson, M. R. Johnstone, M. Neely, D. Boles. ***Dynamic Storage Allocation: A Survey and Critical Review***. University of Texas at Austin, 1995.

- [Bonwick] J. Bonwick. ***The Slab Allocator: An Object-Caching Kernel Memory Allocator***. Usenix Summer 1994 Technical Conference.