Dynamic Memory Allocation (cont.) and Exceptions

CSCI 237: Computer Organization
34th Lecture, Wednesday, December 4, 2024

Kelly Shaw

Administrative Details

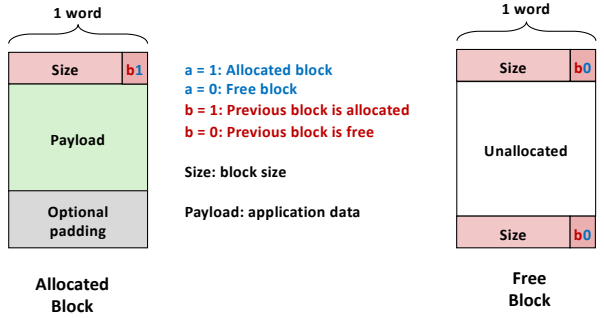
- Read CSAPP 9.9, 8.1-8.2
- Quiz open today at 2:30 until Friday at 2:30pm
- Lab #6 due Friday at 5pm
- Review session on Sun or Tues?
  - https://www.when2meet.com/?27868617-GeNrF
- Final exam
  - Wednesday, December 11, 9:30am – 11:30am (2 hours)
  - Clark Hall 105
- Colloquium talk on Friday at 2:35pm in Wege
  - "Systems research to address societal problems"
  - Aruna Balasubramanian, Stony Brook University

Today

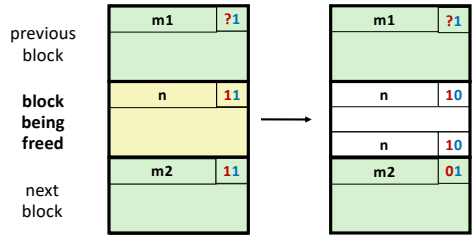
- Dynamic Memory Allocation (Ch 9.9)
  - Tracking Free Blocks
    - Implicit Lists
    - Explicit Lists
    - Segregated Lists
- Exceptional Control Flow
- Exceptions

Optimization: No Boundary Tag for Allocated Blocks

- Boundary tag is only needed for free blocks
- Insight: when sizes are multiples of 4 or more, have 2+ spare bits



No Boundary Tag for Allocated Blocks (Case 1)



Header: Use 2 bits (always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

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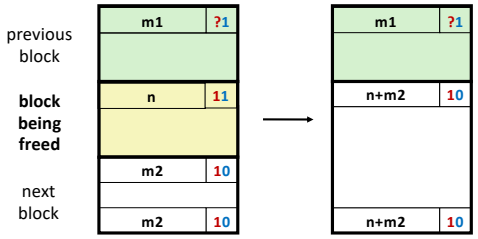
No Boundary Tag for Allocated Blocks (Case 2)



Header: Use 2 bits (always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

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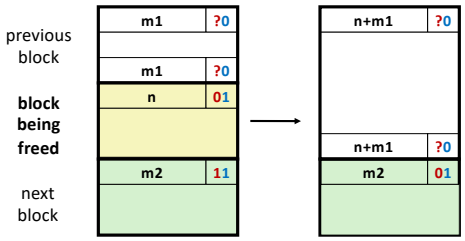
No Boundary Tag for Allocated Blocks (Case 3)



Header: Use 2 bits (always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

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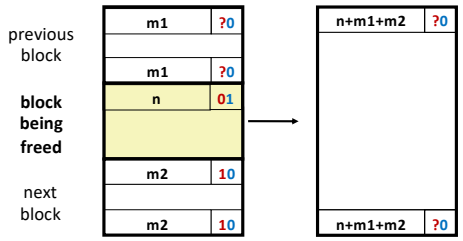
No Boundary Tag for Allocated Blocks (Case 4)



Header: Use 2 bits (always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

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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 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 placement policy
  - First-fit, next-fit or best-fit
- Not used in practice for `malloc/free` because of linear-time allocation
  - used in many special purpose applications
- However, the concepts of splitting and boundary tag coalescing are general to *all* allocators

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Practice on Your Own

Consider a system where

- The memory is byte addressable.
- Memory accesses are to 1-byte words
- Virtual addresses are 16 bits wide.
- Physical addresses are 14 bits wide.
- The page size is 1024 bytes = 2^{10}
- The TLB is 4-way set associative with 16 total entries

Parameter	Value
VPN	0x
TLB Index	0x
TLB Tag	0x
TLB Hit? (Y/N)	
Page Fault? (Y/N)	
PPN	0x
PA	

For the following virtual addresses, fill out the table above

- 0x76BD
- 0x57EB

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TLB			
Index	Tag	PPN	Valid
0	A	C	0
	4	9	1
	3	D	0
	9	3	0
1	2	0	1
	F	2	0
	7	4	0
	5	6	1
2	7	7	0
	2	9	0
	0	B	1
	6	F	1
3	6	A	0
	7	4	1
	C	1	0
	1	8	0

Page Table					
VPN	PPN	Valid	VPN	PPN	Valid
00	7	0	10	9	1
01	5	0	11	0	0
02	B	1	12	0	0
03	D	1	13	5	0
04	9	0	14	3	0
05	8	0	15	6	1
06	5	1	16	E	0
07	2	0	17	A	0
08	E	1	18	1	0
09	0	1	19	0	0
0A	F	0	1A	F	1
0B	D	0	1B	9	0
0C	C	0	1C	7	0
0D	4	0	1D	2	1
0E	3	0	1E	8	0
0F	1	0	1F	4	1

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Practice on Your Own

- Assuming double-word alignment is used and the implicit free list format discussed in slides is used (i.e., 4 byte header). Block sizes are rounded up to nearest multiple of 8 bytes to maintain alignment.
- What would the block size be in bytes (including payload, header, and padding)? What would be stored in the block header (in hex)?
  - malloc(2)
  - malloc(9)
  - malloc(16)

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Practice on Your Own

- When using implicit lists that only have a header, what is the smallest size of an allocated block (assuming double word alignment)?
- When using implicit lists that use headers and footers in all blocks, what is the smallest size of an allocated block (assuming double word alignment)?
- When using implicit lists that use headers in all blocks but footers only in free blocks, what is the smallest size of an allocated block (assuming double word alignment)?

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  - Tracking Free Blocks
    - Implicit Lists
    - Explicit Lists
    - Segregated Lists
- Exceptional Control Flow
- Exceptions

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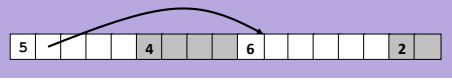
Keeping Track of Free Blocks

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

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



- Method 3: *Segregated free list*
  - Different free lists for different size classes
- Method 4: *Blocks sorted by size*
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

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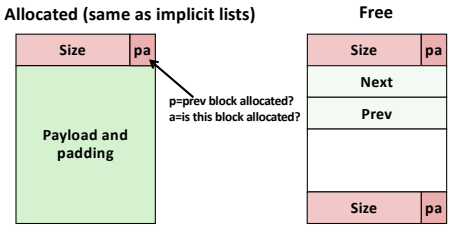
Explicit Free Lists



- Maintain list(s) of *free* blocks, not *all* blocks
  - The "next" free block could be physically anywhere (not necessarily adjacent block)
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags (but only in free blocks!) for coalescing
  - Luckily we track only free blocks, so we can use payload area for pointers

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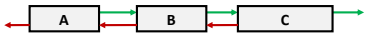
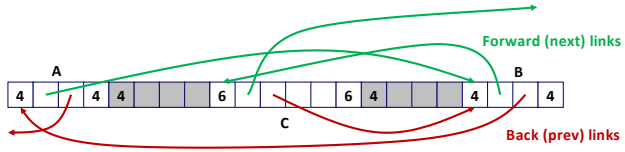
Explicit Free Lists

- Logically:



- Physically: blocks can be in any order



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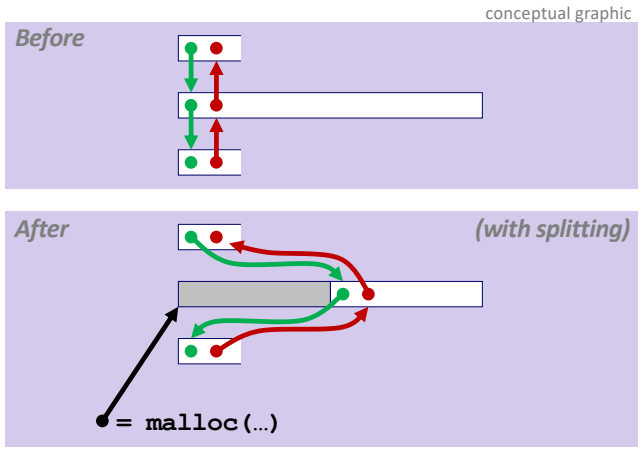
Allocating From Explicit Free Lists



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Splitting Tasks

- Suppose we split a free block B into two: block A, and block F:
  - Allocated block A needs to be updated and removed from the list
  - Free block B needs to be updated so F is kept in the list
- `sizeAndTags` for both A and F needs to be adjusted
  - Shrink A to its allocation size
  - Create a `sizeAndTags` field in F to reflect new block's size (B – A)
- The next/previous pointers from A need to be added to F
- The next/previous blocks need their previous/next pointers to be updated to point to F
- Useful macros:
  - #define UNSCALED_POINTER_ADD(p,x) ((void*)((char*)(p) + (x)))
  - #define UNSCALED_POINTER_SUB(p,x) ((void*)((char*)(p) - (x)))

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Freeing With Explicit Free Lists

- *Insertion policy:* Where in the free list do you put a newly freed block?

- **LIFO (last-in-first-out) policy**
  - Insert freed block at the beginning of the free list
  - ***Pro:*** simple and constant time
  - ***Con:*** studies suggest fragmentation is worse than address ordered

- **Address-ordered policy**
  - Insert freed blocks so that free list blocks are always in address order:
    addr(prev) < addr(curr) < addr(next)
  - ***Con:*** requires search
  - ***Pro:*** studies suggest fragmentation is lower than LIFO

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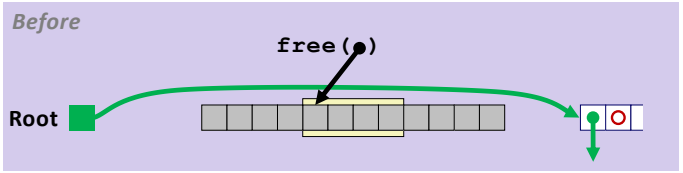
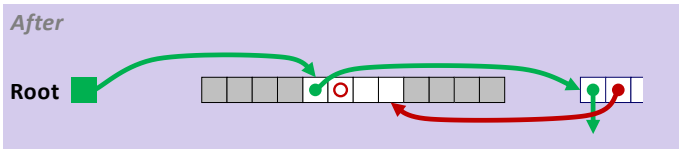
Freeing With a LIFO Policy (Case 1)

conceptual graphic



- Insert the freed block at the root of the list



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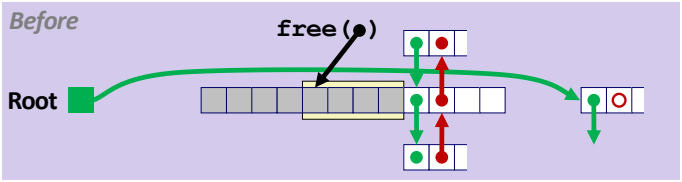
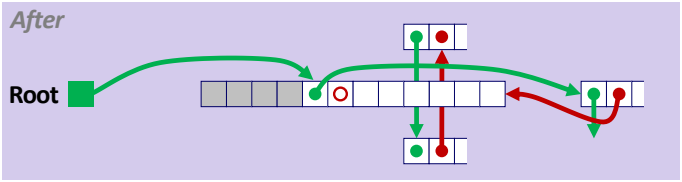
Freeing With a LIFO Policy (Case 2)

conceptual graphic



- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list



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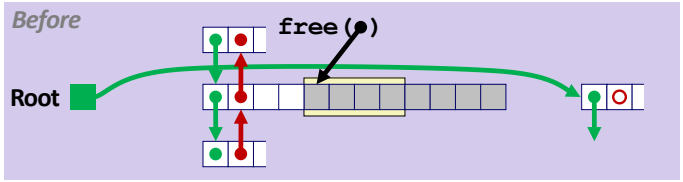
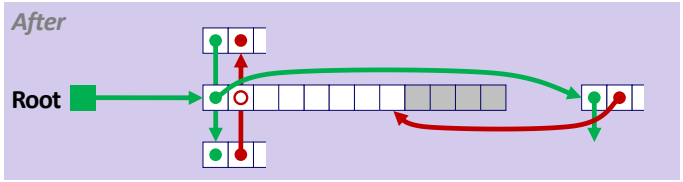
Freeing With a LIFO Policy (Case 3)

conceptual graphic



- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



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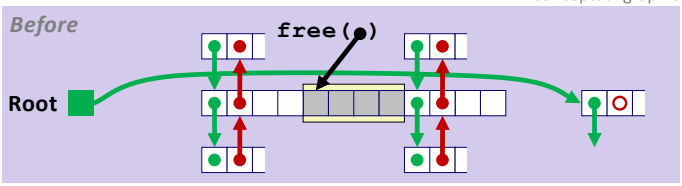
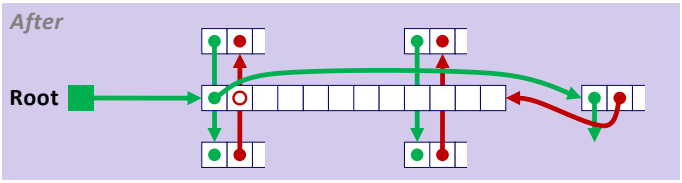
Freeing With a LIFO Policy (Case 4)

conceptual graphic



- Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list



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Explicit List Summary

- Comparison to implicit list:
  - Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free procedures since we need to splice blocks in and out of the list
  - Need some extra space for the links (2 extra words needed for each block)
    - Does this increase internal fragmentation? (maybe!)
- One of most common uses of linked lists is in conjunction with segregated free lists (up next)
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

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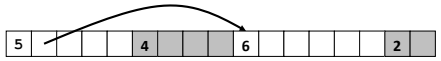

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  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

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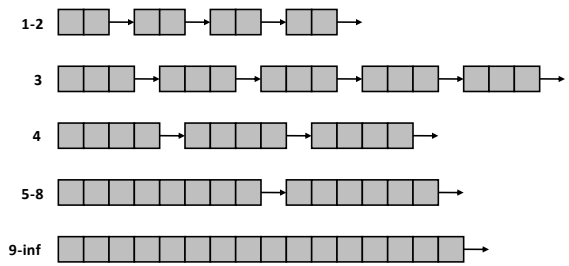
Segregated List (Seglist) Allocators

- 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 power-of-two size

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Seglist Allocator

- Given an array of free lists, each one for some size class
- To allocate a block of size *n*:
  - Search appropriate free list for block of size *m* >= *n*
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list (optional)
  - If no block is found, try next larger class
  - Repeat until block is found
- If no block is found:
  - Request additional heap memory from OS (using **`sbrk()`**)
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in largest size class.

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Seglist Allocator (cont.)

- To free a block:
  - Coalesce and place on appropriate list
- Advantages of seglist allocators
  - Higher throughput
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap.
    - Extreme case: Giving each block its own size class is equivalent to best-fit.
- Seglist is used by GNU malloc provided in C std library

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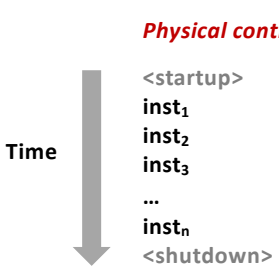
Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)



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Altering the Control Flow

- Two mechanisms for changing control flow:
  - Jumps and branches
  - Call and return

  React to changes in ***program state***
- Insufficient for a useful system:

  Difficult to react to changes in *system state*
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - User hits Ctrl-C at the keyboard
  - System timer expires
- System needs mechanisms for "exceptional control flow"

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Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

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