Dynamic Memory Allocation

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Harsh Reality

- *Memory Matters*
- Memory is not unbounded
  - It must be allocated and managed
  - Many applications are memory dominated
    - Especially those based on complex, graph algorithms
- Memory referencing bugs especially pernicious
  - Effects are distant in both time and space
- Memory performance is not uniform
  - Cache and virtual memory effects can greatly affect program performance
  - Adapting program to characteristics of memory system can lead to major speed improvements

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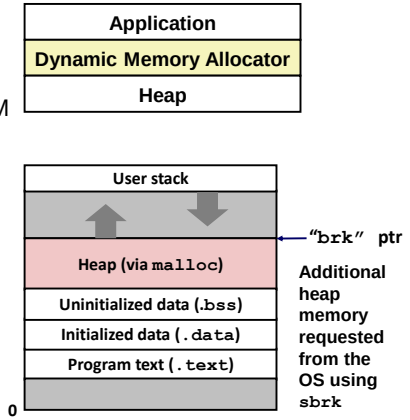
Dynamic Memory Allocation

- Programmers use *dynamic memory allocators* (such as `malloc`) to acquire VM at run time
  - For data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process virtual memory known as the *heap*



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Dynamic Memory Allocation

- Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free*
- Types of allocators
  - ***Explicit allocator***: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - ***Implicit allocator:*** application allocates, but does not free space
    - E.g. garbage collection in Java, ML, and Lisp
- Will discuss explicit memory management today

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The `malloc` Package

```
#include <stdlib.h>
void *malloc(size_t size)
```

- Successful:
  - Returns a pointer to a memory block of at least **`size`** bytes aligned to an 8-byte (x86) or 16-byte (x86-64) boundary
  - If **`size == 0`**, returns NULL
- Unsuccessful: returns NULL (0) and sets **`errno`**

```
void free(void *p)
```

- Returns the block pointed at by **`p`** to pool of available memory
- **`p`** must come from a previous call to **`malloc`** or **`realloc`**

Other functions

- **`calloc`**: Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`**: Changes the size of a previously allocated block.
- **`sbrk`**: Used internally by allocators to grow or shrink the heap

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`malloc` Example

```
#include <stdio.h>
#include <stdlib.h>

void foo(int n) {
  int i, *p;

  /* Allocate a block of n ints */
  p = (int *) malloc(n * sizeof(int));
  if (p == NULL) {
    perror("malloc");
    exit(0);
  }

  /* Initialize allocated block */
  for (i=0; i<n; i++)
        p[i] = i;


  /* Return allocated block to the heap */
  free(p);
}
```

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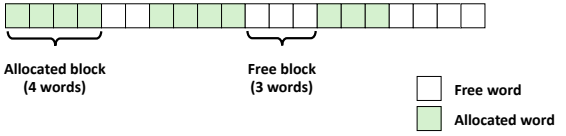
Assumptions Made in This Lecture

- Memory is word addressed.
- Words are int-sized.



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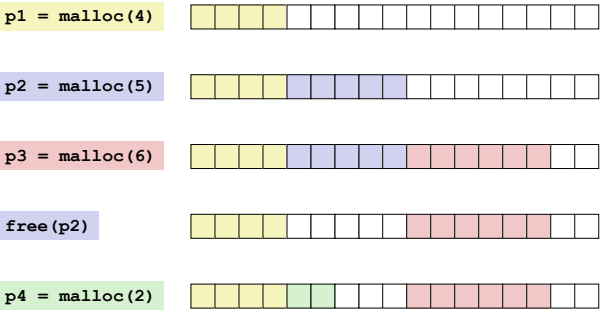
Allocation Example



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Constraints

- Applications
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request must be to a **`malloc`**'d block
- Allocators
  - Can't control number or size of allocated blocks
  - Must respond immediately to **`malloc`** requests
    - *i.e.*, can't reorder or buffer requests
  - Must allocate blocks from free memory
    - *i.e.*, can only place allocated blocks in free memory
  - Must align blocks so they satisfy all alignment requirements
    - 8-byte (x86) or 16-byte (x86-64) alignment on Linux boxes
  - Can manipulate and modify only free memory
  - Can't move the allocated blocks once they are **`malloc`**'d
    - *i.e.*, compaction is not allowed

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Performance Goal: Throughput

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, ..., R_k, ... , R_{n-1}$
- Goals: maximize throughput and peak memory utilization
  - These goals are often conflicting
- Throughput:
  - Number of completed requests per unit time
  - Example:
    - 5,000 **`malloc`** calls and 5,000 **`free`** calls in 10 seconds
    - Throughput is 1,000 operations/second

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Performance Goal: Peak Memory Utilization

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, ..., R_k, ... , R_{n-1}$
- *Def: Aggregate payload* P_k
  - **`malloc(p)`** results in a block with a ***payload*** of **`p`** bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
- *Def: Current heap size* H_k
  - Assume H_k is monotonically nondecreasing
    - i.e., heap only grows when allocator uses **`sbrk`**
- *Def: Peak memory utilization after k+1 requests*
  - $U_k = (max_{i<=k} P_i) \ / \ H_k$

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Fragmentation

- Poor memory utilization caused by *fragmentation*
  - ***internal*** fragmentation
  - ***external*** fragmentation

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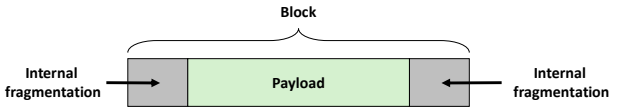
Internal Fragmentation

- 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)
- Depends only on the pattern of *previous* requests
  - Thus, easy to measure

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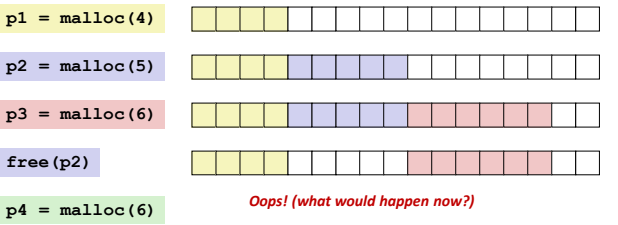
External Fragmentation

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



- Depends on the pattern of future requests
  - Thus, difficult to measure

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Implementation Issues

- 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 structure 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?

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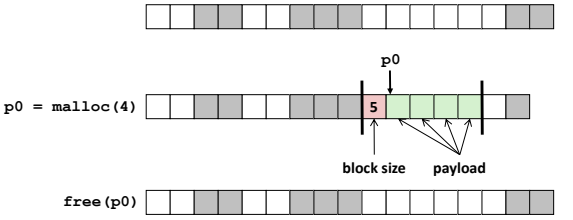
Knowing How Much to Free

- Standard method
  - Keep the length of a block in the word preceding the block.
    - This word is often called the ***header field*** or ***header***
  - Requires an extra word for every allocated block



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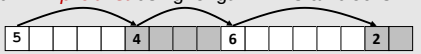
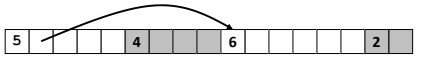
Keeping Track of Free Blocks

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



- Method 2: *Explicit 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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Today

- Simple virtual memory system example
- Linux and the virtual memory system
- Dynamic memory allocation
  - Explicit memory management
    - Implicit free lists

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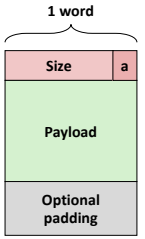
Method 1: Implicit List

- For each block we need both size and allocation status
  - Could store this information in two words: wasteful!
- Standard trick
  - If blocks are aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - When reading size word, must mask out this bit

Format of allocated and free blocks



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

Size: block size

Payload: application data (allocated blocks only)

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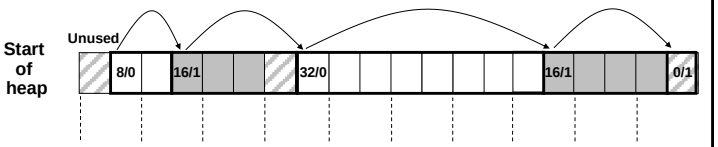
Detailed Implicit Free List Example



Double-word aligned

Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

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Implicit List: Finding a Free Block

- *First fit:*
  - Search list from beginning, choose ***first*** free block that fits:

```
p = start;
while ((p < end) &&      \\ not passed end
       ((*p & 1) ||      \\ already allocated
       (*p  <= len)))    \\ too small
  p = p + (*p & -2);     \\ goto next block (word addressed)
```

  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- *Next fit:*
  - Like first fit, but search list starting where previous search finished
  - Should often be faster than first fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- *Best fit:*
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

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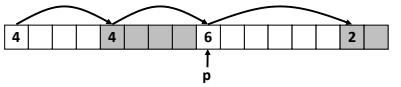
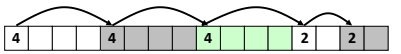
Implicit List: Allocating in Free Block

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



addblock(p, 4)




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

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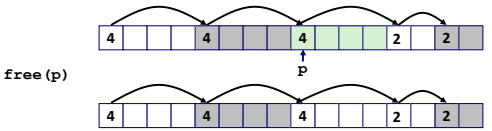
Implicit List: Freeing a Block

- Simplest implementation:
  - Need only clear the "allocated" flag

```
void free_block(ptr p) { *p = *p & -2 }
```

  - But can lead to "false fragmentation"



There is enough free space, but the allocator won't be able to find it

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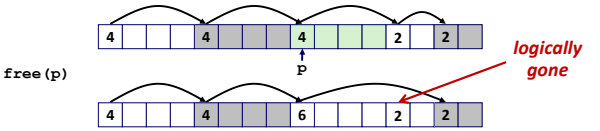
Implicit List: Coalescing

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




```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

  - But how do we coalesce with *previous* block?

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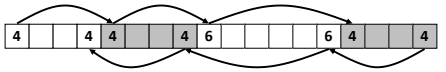
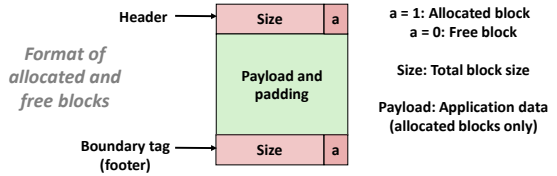
Implicit List: Bidirectional Coalescing

- *Boundary tags* [Knuth73]
  - Replicate size/allocated word at "bottom" (end) of free blocks
  - Allows us to traverse the "list" backwards, but requires extra space
  - Important and general technique!





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Constant Time Coalescing

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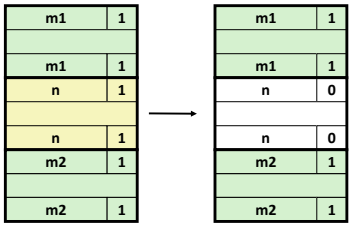
Constant Time Coalescing (Case 1)



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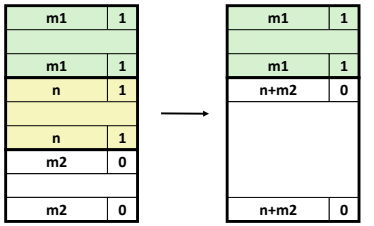
Constant Time Coalescing (Case 2)



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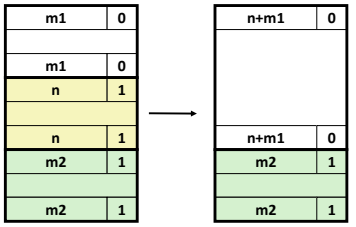
Constant Time Coalescing (Case 3)



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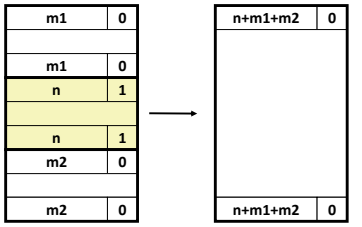
Constant Time Coalescing (Case 4)



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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 (next lecture) 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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Today

- Simple virtual memory system example
- Linux and the virtual memory system
- Dynamic memory allocation
  - Explicit memory management
    - Implicit free lists
    - Explicit free lists

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Keeping Track of Free Blocks

- Method 1: *Implicit free 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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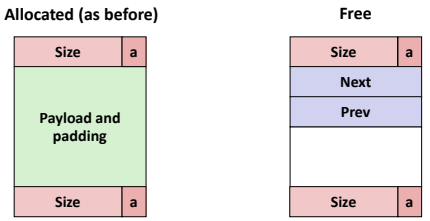
Explicit Free Lists



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

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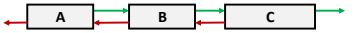
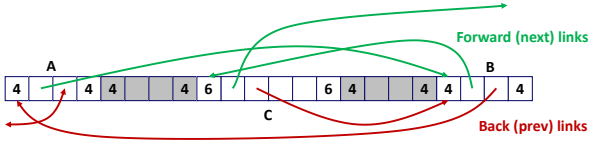
Explicit Free Lists

- Logically:



- Physically: blocks can be in any order



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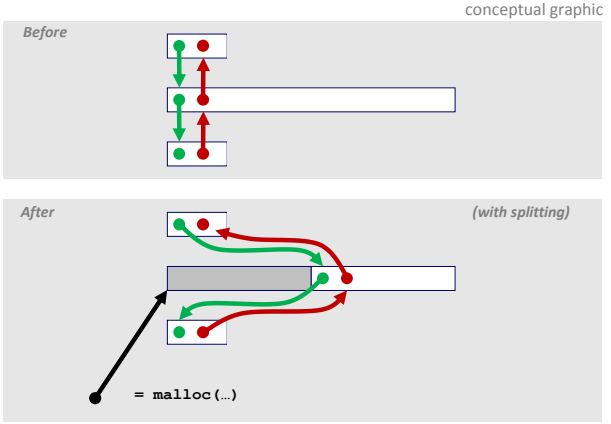
Allocating From Explicit Free Lists

conceptual graphic



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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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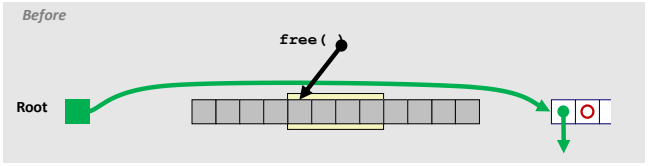
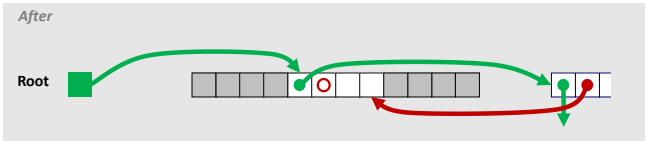
Freeing With a LIFO Policy (Case 1)

conceptual graphic



- Insert the freed block at the root of the list



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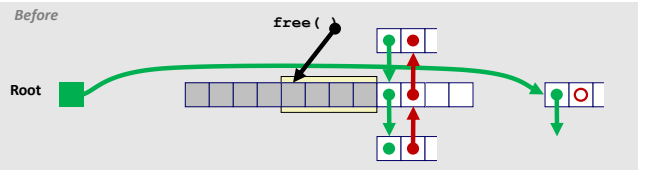
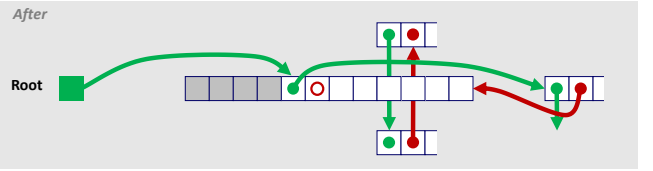
Freeing With a LIFO Policy (Case 2)

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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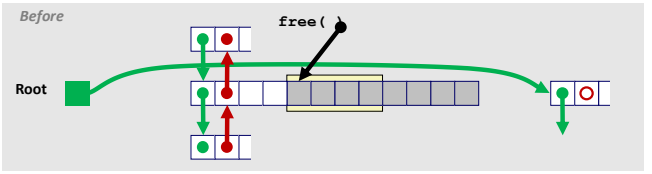
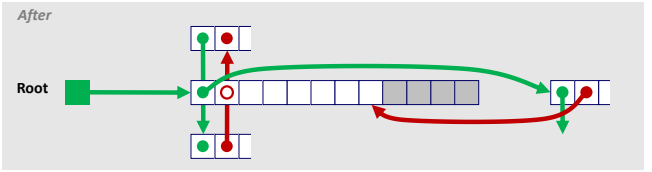
Freeing With a LIFO Policy (Case 3)

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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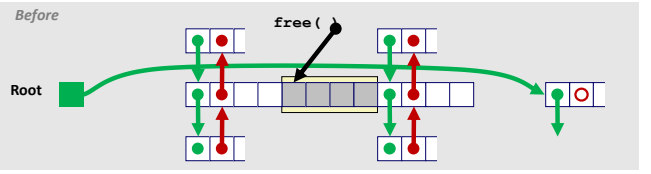
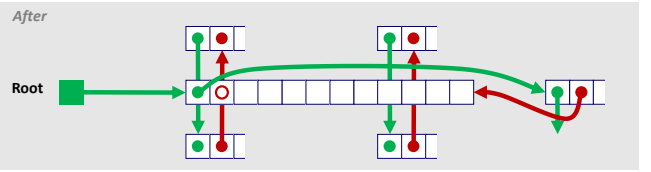
Freeing With a LIFO Policy (Case 4)

conceptual graphic



- Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new



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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 since needs to splice blocks in and out of the list
  - Some extra space for the links (2 extra words needed for each block)
    - Does this increase internal fragmentation?
- Most common use of linked lists is in conjunction with segregated free lists
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

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Today

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- Linux and the virtual memory system
- Dynamic memory allocation
  - Explicit memory management
    - Implicit free lists
    - Explicit free lists
    - Segregated free lists

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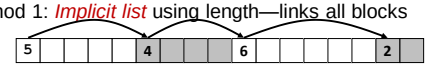
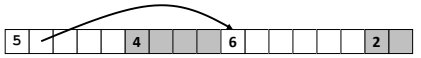
Keeping Track of Free Blocks

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



- Method 2: *Explicit 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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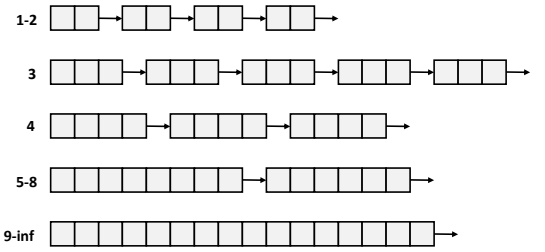
Segregated List (Seglist) Allocators

- 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

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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
    - log time for power-of-two size classes
  - 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

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More Info on Allocators

- D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973
  - The classic reference on dynamic storage allocation
- Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.
  - Comprehensive survey
  - Available from CS:APP student site (csapp.cs.cmu.edu)

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Communication and Interaction: I/O and Networking

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Unix I/O Overview

- A Linux *file* is a sequence of *m* bytes:
  - B_0 , B_1 , ... , B_k , ... , B_{m-1}
- Cool fact: All I/O devices are represented as files:
  - **`/dev/sda2`** (**`/usr`** disk partition)
  - **`/dev/tty2`** (terminal)
- Even the kernel is represented as a file:
  - **`/boot/vmlinuz-3.13.0-55-generic`** (kernel image)
  - **`/proc`** (kernel data structures)

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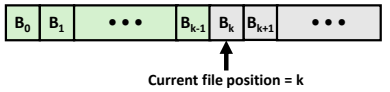
Unix I/O Overview

- Elegant mapping of files to devices allows kernel to export simple interface called *Unix I/O:*
  - Opening and closing files
    - **`open()`** and **`close()`**
  - Reading and writing a file
    - **`read()`** and **`write()`**
  - Changing the ***current file position*** (seek)
    - indicates next offset into file to read or write
    - **`lseek()`**



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File Types

- Each file has a *type* indicating its role in the system
  - *Regular file:* Contains arbitrary data
  - *Directory:* Index for a related group of files
  - *Socket:* For communicating with a process on another machine
- Other file types beyond our scope
  - *Named pipes (FIFOs)*
  - *Symbolic links*
  - *Character and block devices*

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Regular Files

- A regular file contains arbitrary data
- Applications often distinguish between *text files* and *binary files*
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel doesn't know the difference!
- Text file is sequence of *text lines*
  - Text line is sequence of chars terminated by *newline char* (`'\n'`)
    - Newline is `0xa`, same as ASCII line feed character (LF)
- End of line (EOL) indicators in other systems
  - Linux and Mac OS: `'\n'` (`0xa`)
    - line feed (LF)
  - Windows and Internet protocols: `'\r\n'` (`0xd 0xa`)
    - Carriage return (CR) followed by line feed (LF)

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Directories

- Directory consists of an array of *links*
  - Each link maps a *filename* to a file
- Each directory contains at least two entries
  - `.` (dot) is a link to itself
  - `..` (dot dot) is a link to *the parent directory* in the *directory hierarchy* (next slide)
- Commands for manipulating directories
  - `mkdir`: create empty directory
  - `ls`: view directory contents
  - `rmdir`: delete empty directory

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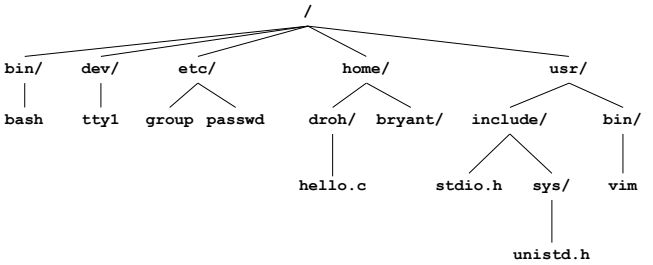
Directory Hierarchy

- All files are organized as a hierarchy anchored by root directory named / (slash)



- Kernel maintains *current working directory (cwd)* for each process
  - Modified using the `cd` command

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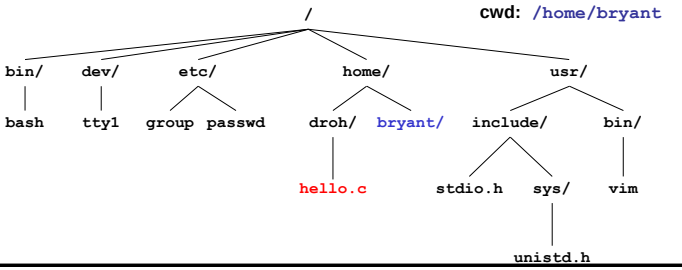
Pathnames

- Locations of files in the hierarchy denoted by *pathnames*
  - *Absolute pathname* starts with '/' and denotes path from root
    - `/home/droh/hello.c`
  - *Relative pathname* denotes path from current working directory
    - `../home/droh/hello.c`



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Opening Files

- Opening a file informs the kernel that you are getting ready to access that file

```
int fd;   /* file descriptor */

if ((fd = open("/etc/hosts", O_RDONLY)) < 0) {
   perror("open");
   exit(1);
}
```

- Returns a small identifying integer *file descriptor*
  - **`fd == -1`** indicates that an error occurred
- Each process created by a Linux shell begins life with three open files associated with a terminal:
  - 0: standard input (stdin)
  - 1: standard output (stdout)
  - 2: standard error (stderr)

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Closing Files

- Closing a file informs the kernel that you are finished accessing that file

```
int fd;     /* file descriptor */
int retval; /* return value */

if ((retval = close(fd)) < 0) {
   perror("close");
   exit(1);
}
```

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Reading Files

- Reading a file copies bytes from the current file position to memory, and then updates file position

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* Open file fd ...  */
/* Then read up to 512 bytes from file fd */
if ((nbytes = read(fd, buf, sizeof(buf))) < 0) {
   perror("read");
   exit(1);
}
```

- Returns number of bytes read from file `fd` into `buf`
  - Return type **`ssize_t`** is signed integer
  - **`nbytes < 0`** indicates that an error occurred
  - ***Short counts*** (**`nbytes < sizeof(buf)`**) are possible and are not errors!

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Writing Files

- Writing a file copies bytes from memory to the current file position, and then updates current file position

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* Open the file fd ... */
/* Then write up to 512 bytes from buf to file fd */
if ((nbytes = write(fd, buf, sizeof(buf)) < 0) {
   perror("write");
   exit(1);
}
```

- Returns number of bytes written from `buf` to file `fd`
  - **`nbytes < 0`** indicates that an error occurred
  - As with reads, short counts are possible and are not errors!

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File Metadata

- *Metadata* is data about data, in this case file data
- Per-file metadata maintained by kernel

```
/* Metadata returned by the stat and fstat functions */
struct stat {
    dev_t         st_dev;      /* Device */
    ino_t         st_ino;      /* inode */
    mode_t        st_mode;     /* Protection and file type */
    nlink_t       st_nlink;    /* Number of hard links */
    uid_t         st_uid;      /* User ID of owner */
    gid_t         st_gid;      /* Group ID of owner */
    dev_t         st_rdev;     /* Device type (if inode device) */
    off_t         st_size;     /* Total size, in bytes */
    unsigned long st_blksize;  /* Blocksize for filesystem I/O */
    unsigned long st_blocks;   /* Number of blocks allocated */
    time_t        st_atime;    /* Time of last access */
    time_t        st_mtime;    /* Time of last modification */
    time_t        st_ctime;    /* Time of last change */
};
```

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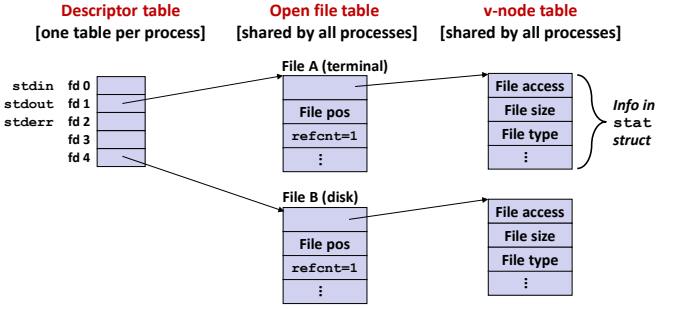
How the Unix Kernel Represents Open Files

- Two descriptors referencing two distinct open files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file



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