Recap of Last Week

- Programmer's view of virtual memory
  - Each process has its own private linear address space
  - Cannot be corrupted by other processes
- System view of virtual memory
  - Uses memory efficiently by caching virtual memory pages
    - Efficient only because of locality
  - Simplifies memory management and programming
  - Simplifies protection by providing a convenient interpositioning point to check permissions
- Challenges addressed:
  - Double (or more) the number of memory accesses
    - Solution: translation lookaside buffer (TLB)
  - Size of translation information (page table)
    - Solution: multi-level page tables

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Today

- Simple virtual memory system example
- Linux and the virtual memory system
- Dynamic memory allocation

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Review of Symbols

- Basic Parameters
  - **N = 2^n** : Number of addresses in virtual address space
  - **M = 2^m** : Number of addresses in physical address space
  - **P = 2^p** : Page size (bytes)
- Components of the virtual address (VA)
  - **TLBI**: TLB index
  - **TLBT**: TLB tag
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number
- Components of the physical address (PA)
  - **PPO**: Physical page offset (same as VPO)
  - **PPN:** Physical page number
  - **CO**: Byte offset within cache line
  - **CI:** Cache index
  - **CT**: Cache tag

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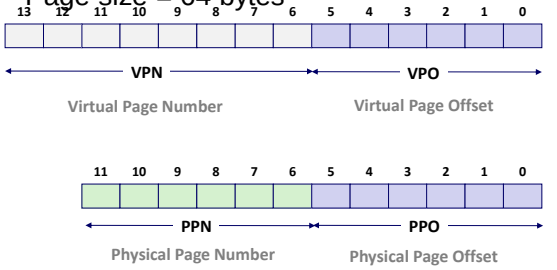
Simple Memory System Example

- Addressing
  - 14-bit virtual addresses
  - 12-bit physical address
  - Page size = 64 bytes



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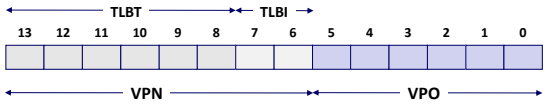
1. Simple Memory System TLB

- 16 entries
- 4-way associative



Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
0	03	–	0	09	0D	1	00	–	0	07	02	1
1	03	2D	1	02	–	0	04	–	0	0A	–	0
2	02	–	0	08	–	0	06	–	0	03	–	0
3	07	–	0	03	0D	1	0A	34	1	02	–	0

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2. Simple Memory System Page Table

Only show first 16 entries (out of 256)

VPN	PPN	Valid
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

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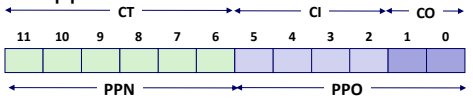
3. Simple Memory System Cache

- 16 lines, 4-byte block size
- Physically addressed
- Direct mapped



Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

Idx	Tag	Valid	B0	B1	B2	B3
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

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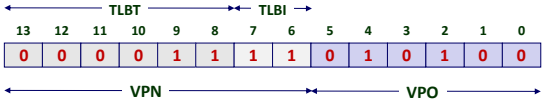
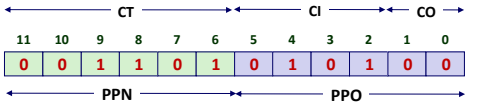
Address Translation Example #1

Virtual Address: `0x03D4`



VPN 0x0F TLBI 0x3 TLBT 0x03 TLB Hit? Y Page Fault? N PPN: 0x0D

Physical Address



CO 0 CI 0x5 CT 0x0D Hit? Y Byte: 0x36

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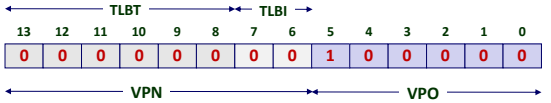
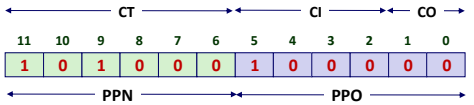
Address Translation Example #2

Virtual Address: 0x0020



VPN 0x00 TLBI 0 TLBT 0x00 TLB Hit? N Page Fault? N PPN: 0x28

Physical Address



CO 0 CI 0x8 CT 0x28 Hit? N Byte: Mem

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Today

- Simple virtual memory system example
- Linux and the virtual memory system
- Dynamic memory allocation

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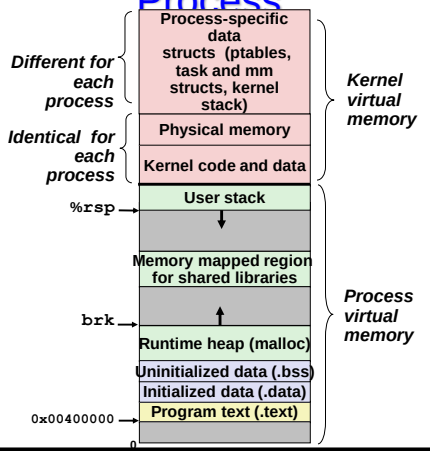
Virtual Address Space of a Linux Process



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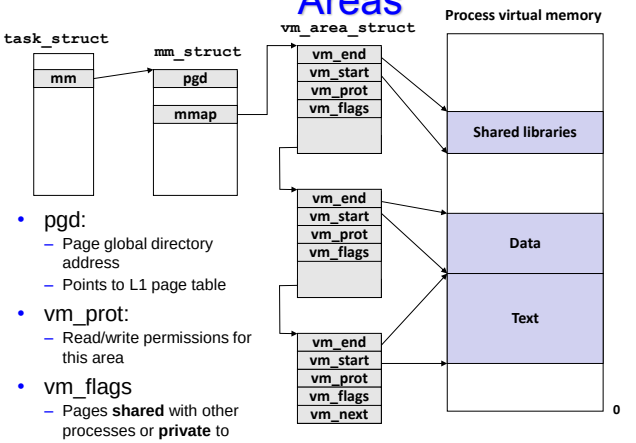
Linux Organizes VM as Collection of "Areas"



- pgd:
  - Page global directory address
  - Points to L1 page table
- vm_prot:
  - Read/write permissions for this area
- vm_flags
  - Pages **shared** with other processes or **private** to this process

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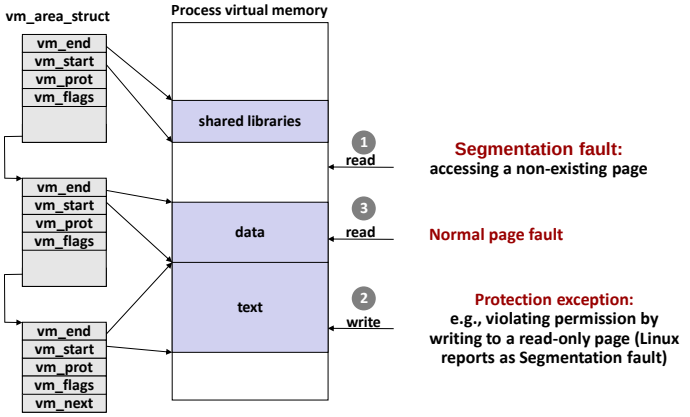
Linux Page Fault Handling



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Memory Mapping

- VM areas initialized by associating them with disk objects.
  - Process is known as ***memory mapping***.
- Area can be *backed by* (i.e., get its initial values from) :
  - ***Regular file*** on disk (e.g., an executable object file)
    - Initial page bytes come from a section of a file
  - ***Anonymous file*** (e.g., nothing)
    - First fault will allocate a physical page full of 0's (***demand-zero page***)
    - Once the page is written to (***dirtied***), it is like any other page
- Dirty pages are copied back and forth between memory and a special *swap file*

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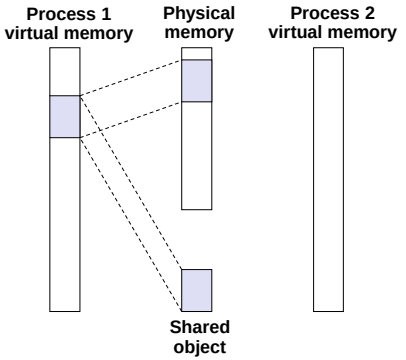
Sharing Revisited: Shared Objects



- Process 1 maps the shared object

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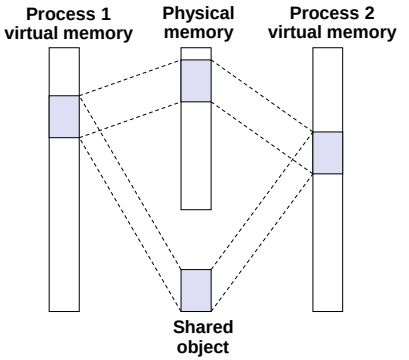
Sharing Revisited: Shared Objects



- **Process 2 maps the shared object.**
- **Notice how the virtual addresses can be different**

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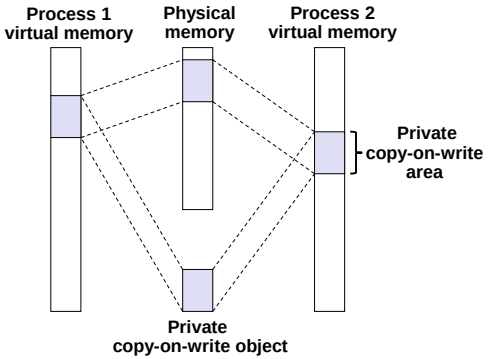
Sharing Revisited: Private Copy-on-write (COW) Objects



- Two processes mapping a *private copy-on-write (COW)* object
- Area flagged as private copy-on-write
- PTEs in private areas are flagged as read-only

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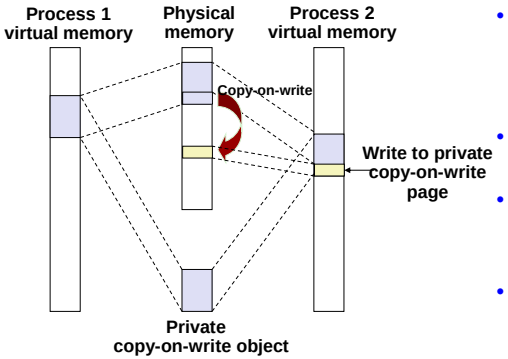
Sharing Revisited: Private Copy-on-write (COW) Objects



- Instruction writing to private page triggers protection fault.
- Handler creates new R/W page.
- Instruction restarts upon handler return.
- Copying deferred as long as possible!

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The `fork` Function Revisited

- VM and memory mapping explain how `fork` provides private address space for each process.
- To create virtual address for new new process
  - Create exact copies of current `mm_struct`, `vm_area_struct`, and page tables.
  - Flag each page in both processes as read-only
  - Flag each `vm_area_struct` in both processes as private COW
- On return, each process has exact copy of virtual memory
- Subsequent writes create new pages using COW mechanism.

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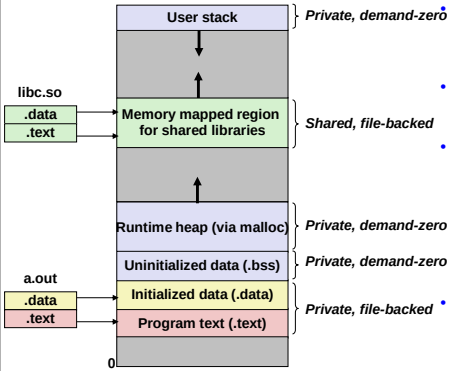
The `execve` Function Revisited



To load and run a new program `a.out` in the current process using `execve`:

- Free `vm_area_struct`'s and page tables for old areas
- Create `vm_area_struct`'s and page tables for new areas
  - Programs and initialized data backed by object files
  - `.bss` and stack backed by anonymous files
- Set PC to entry point in `.text`
  - Linux will fault in code and data pages as needed

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User-Level Memory Mapping

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```

- Map **`len`** bytes starting at offset **`offset`** of the file specified by file description **`fd`**, preferably at address **`start`**
  - **`start`**: may be 0 for "pick an address"
  - **`prot`**: PROT_READ, PROT_WRITE, ...
  - **`flags`**: MAP_ANON, MAP_PRIVATE, MAP_SHARED, ...
- Return a pointer to start of mapped area (may not be **`start`**)

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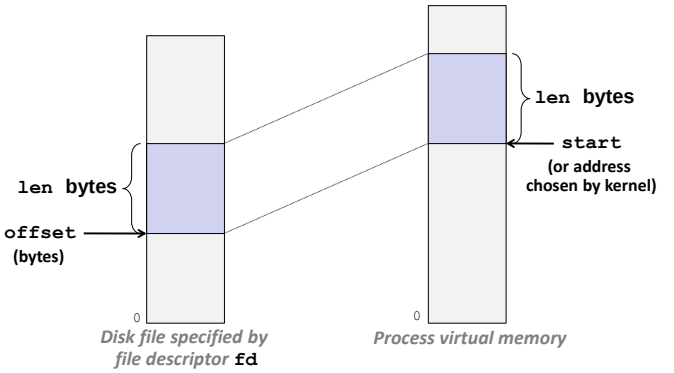
User-Level Memory Mapping

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```



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Example: Using `mmap` to Copy Files

- Copying a file to `stdout` without transferring data to user space

```c
#include "csapp.h"

void mmapcopy(int fd, int size)
{
    /* Ptr to memory mapped area */
    char *bufp;

    bufp = mmap(NULL, size,
                PROT_READ,
                MAP_PRIVATE,
                fd, 0);
    Write(1, bufp, size);
    return;
}
```

mmapcopy.c

```c
/* mmapcopy driver */
int main(int argc, char **argv)
{
    struct stat stat;
    int fd;

    /* Check for required cmd line arg */
    if (argc != 2) {
        printf("usage: %s <filename>\n",
               argv[0]);
        exit(0);
    }

    /* Copy input file to stdout */
    fd = open(argv[1], O_RDONLY, 0);
    fstat(fd, &stat);
    mmapcopy(fd, stat.st_size);
    exit(0);
}
```

mmapcopy.c

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Memory System Summary

- Cache Memory
  - Purely a speed-up technique
  - Behavior invisible to application programmer and OS
  - Implemented totally in hardware
- Virtual Memory
  - Supports many OS-related functions
    - Process creation
      - Initial
      - Forking children
    - Task switching
    - Protection
  - Combination of hardware & software implementation
    - Software management of tables, allocations
    - Hardware access of tables
    - Hardware caching of table entries (TLB)

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Today

- Simple virtual memory system example
- Linux and the virtual memory system
- Dynamic memory allocation

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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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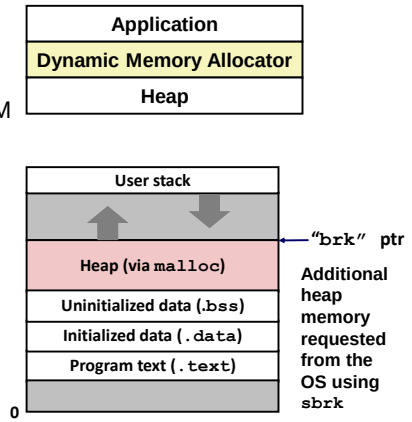
Dynamic Memory Allocation

- 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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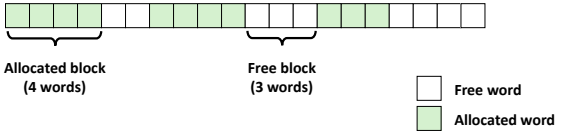
Assumptions Made in This Lecture

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



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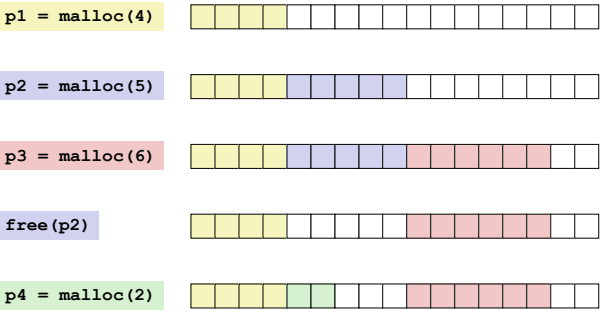
Allocation Example



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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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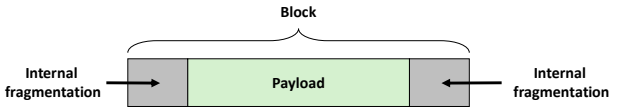
Internal Fragmentation

- 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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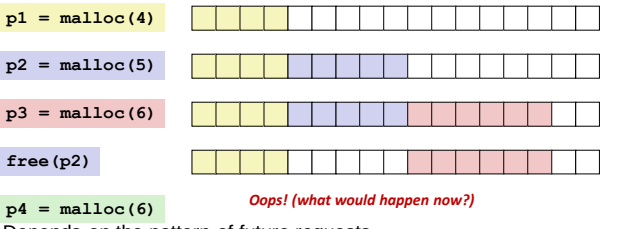
External Fragmentation

- 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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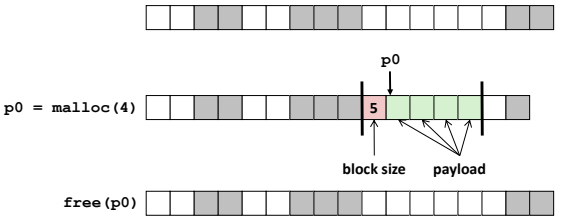
Knowing How Much to Free

- 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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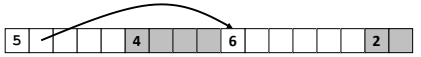
Keeping Track of Free Blocks

- 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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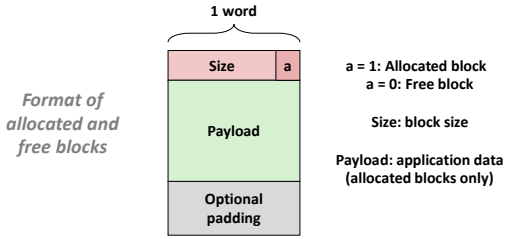
Method 1: Implicit List

- 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



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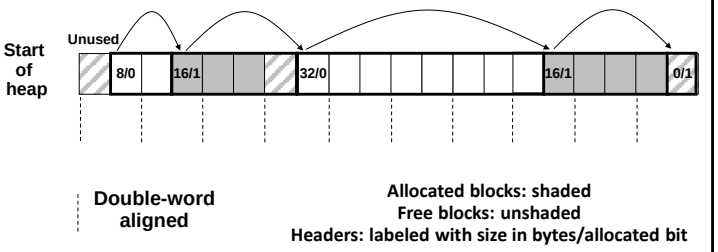
Detailed Implicit Free List Example



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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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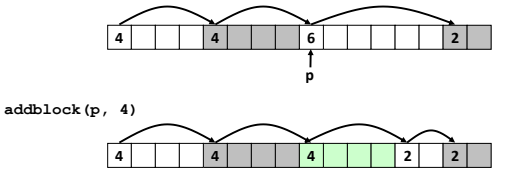
Implicit List: Allocating in Free Block

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




```
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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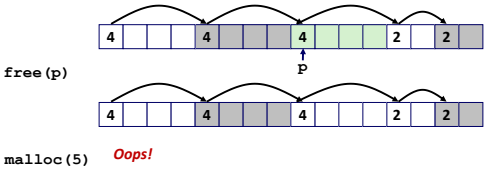
Implicit List: Freeing a Block

- 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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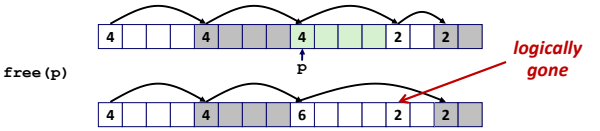
Implicit List: Coalescing

- 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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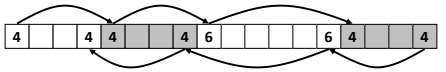
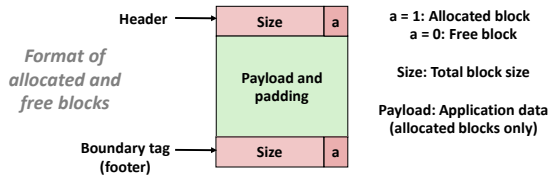
Implicit List: Bidirectional Coalescing

- *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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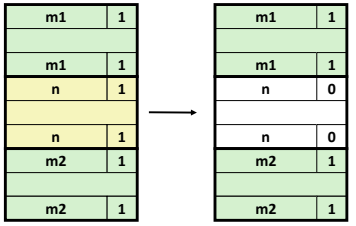
Constant Time Coalescing (Case 1)



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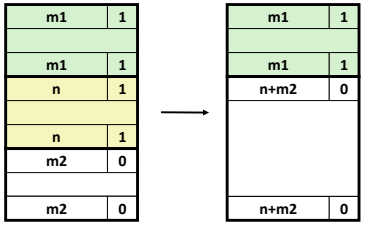
Constant Time Coalescing (Case 2)



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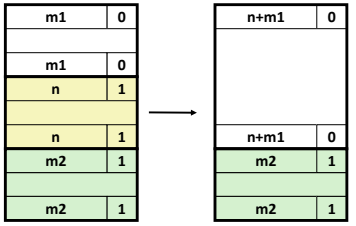
Constant Time Coalescing (Case 3)



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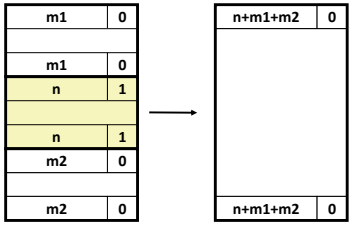
Constant Time Coalescing (Case 4)



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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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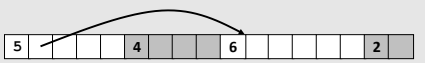
Keeping Track of Free Blocks

- 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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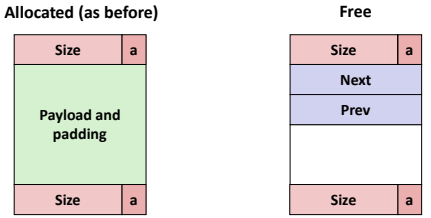
Explicit Free Lists



- 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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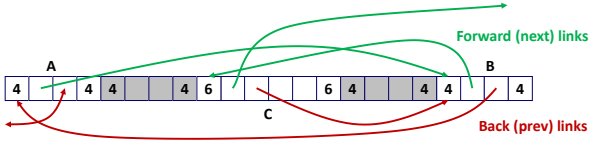
Explicit Free Lists

- Logically:

- Physically: blocks can be in any order



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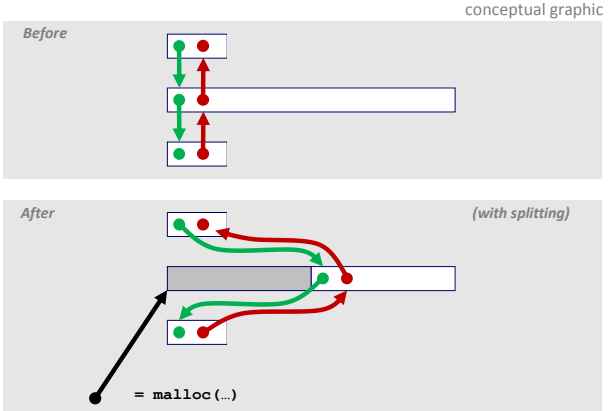
Allocating From Explicit Free Lists

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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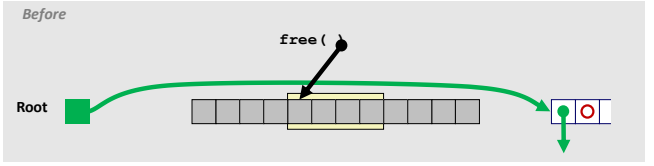
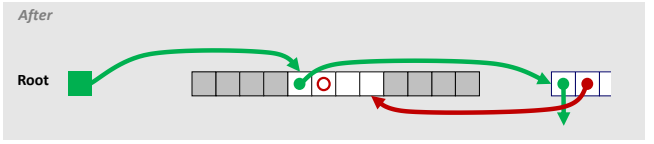
Freeing With a LIFO Policy (Case 1)

conceptual graphic



- Insert the freed block at the root of the list



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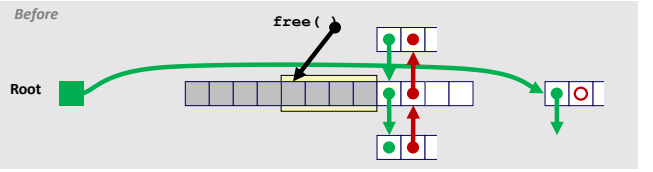
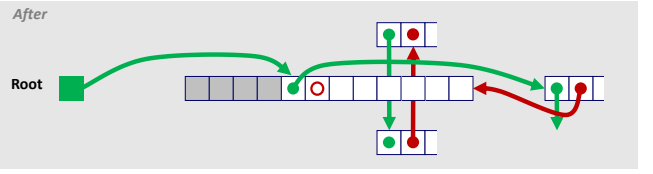
Freeing With a LIFO Policy (Case 2)

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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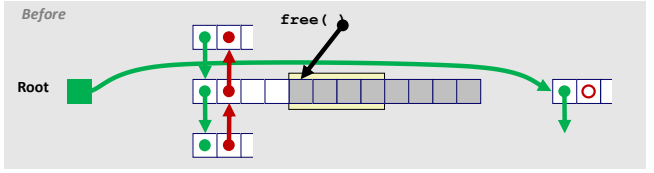
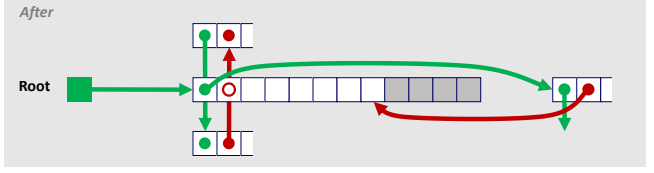
Freeing With a LIFO Policy (Case 3)

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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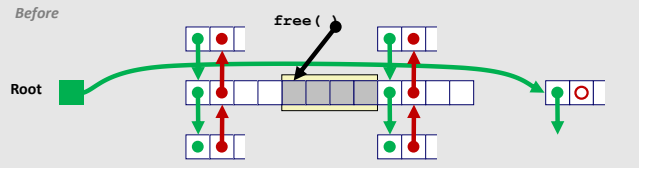
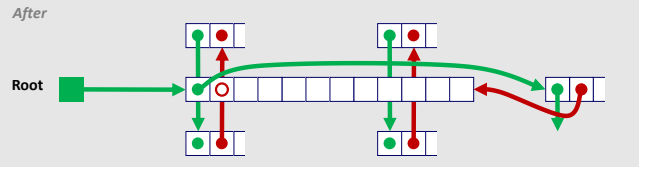
Freeing With a LIFO Policy (Case 4)

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

- Simple virtual memory system example
- 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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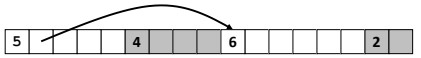
Keeping Track of Free Blocks

- 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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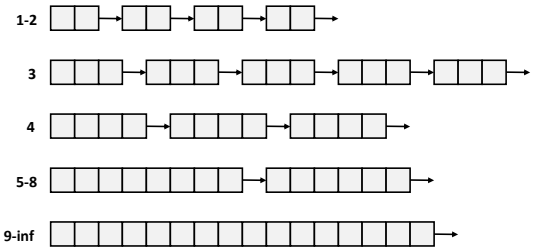
Segregated List (Seglist) Allocators

- 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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