CS 318 Principles of Operating Systems

Fall 2019

Lecture 12: Dynamic Memory Allocation

Prof. Ryan Huang

Johns Hopkins
Whiting School of Engineering

Administrivia

- **Lab 2 due next Saturday**
  - If you haven't started yet, please do now.
  - Otherwise you won't be able to complete the lab.
- Next Tuesday's class is cancelled, working on lab 2
- **Next next Tuesday (October 22nd) is Midterm**

Memory Allocation

- **Static Allocation (fixed in size)**
  - want to create data structures that are fixed and don’t need to grow or shrink
  - global variables, e.g., char name[16];
  - done at compile time
- **Dynamic Allocation (change in size)**
  - want to increase or decrease the size of a data structure according to different demands
  - done at run time

Dynamic Memory Allocation

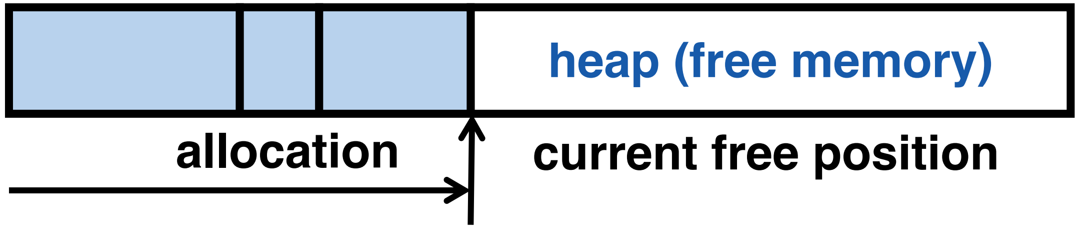
- **Almost every useful program uses it**
  - Gives wonderful functionality benefits
  - Don’t have to statically specify complex data structures
  - Can have data grow as a function of input size
  - Allows recursive procedures (stack growth)
  - But, can have a huge impact on performance
- **Two types of dynamic memory allocation**
  - Stack allocation: restricted, but simple and efficient
  - Heap allocation (focus today): general, but difficult to implement.

Dynamic Memory Allocation

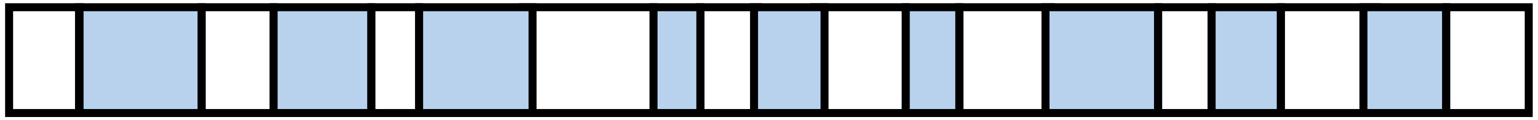
- **Today: how to implement dynamic heap allocation**
  - Lecture based on [Wilson]
- **Some interesting facts:**
  - Two or three line code change can have huge, non-obvious impact on how well allocator works (examples to come)
  - Proven: impossible to construct an "always good" allocator
  - Surprising result: after 35 years, memory management still poorly understood
    - *Mallacc: Accelerating Memory Allocation:* ASPLOS 2017 Highlights
  - Big companies may write their own “malloc”
    - Google: TCMalloc
    - Facebook: jemalloc

Why Is It Hard?

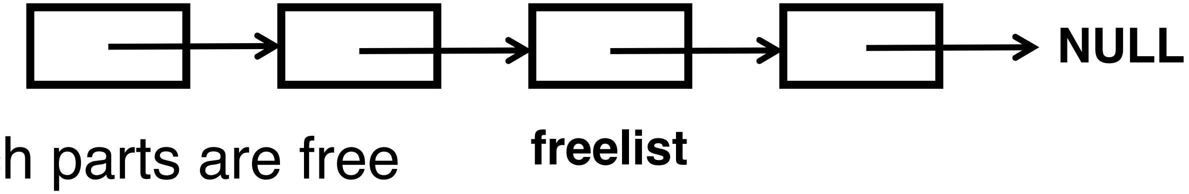
- Satisfy arbitrary set of allocation and frees.
- Easy without free: set a pointer to the beginning of some big chunk of memory (“heap”) and increment on each allocation:



- Problem: free creates holes (“fragmentation”) Result? Lots of free space but cannot satisfy request!

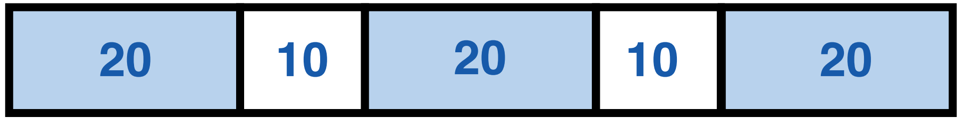


More Abstractly



- **What an allocator must do?**
  - Track which parts of memory in use, which parts are free
  - Ideal: no wasted space, no time overhead
- **What the allocator cannot do?**
  - Control order of the number and size of requested blocks
  - Know the number, size, & lifetime of future allocations
  - Move allocated regions (bad placement decisions permanent), unlike Java allocator

`malloc(20)?`

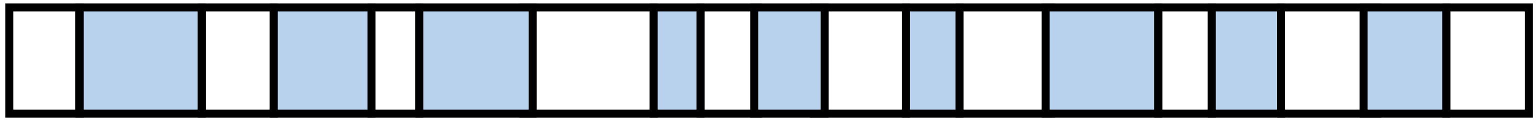


- **The core fight: minimize fragmentation**
  - App frees blocks in any order, creating holes in “heap”
  - Holes too small? cannot satisfy future requests

What Is Fragmentation Really?

- **Inability to use memory that is free**

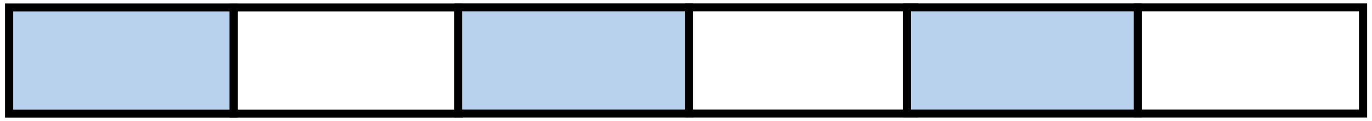
- **Two factors required for fragmentation**
  1. Different lifetimes—if adjacent objects die at different times, then fragmentation:

     - If all objects die at the same time, then no fragmentation:

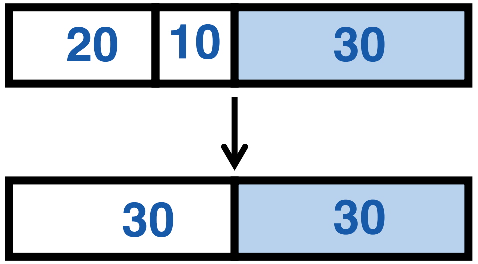
     

  2. Different sizes: If all requests the same size, then no fragmentation (that's why no external fragmentation with paging):

Important Decisions

- **Placement choice: where in free memory to put a requested block?**
  - Freedom: can select any memory in the heap
  - Ideal: put block where it won't cause fragmentation later (impossible in general: requires future knowledge)
- **Split free blocks to satisfy smaller requests?**
  - Fights internal fragmentation
  - Freedom: can choose any larger block to split
  - One way: choose block with smallest remainder (best fit)
- **Coalescing free blocks to yield larger blocks**
  - Freedom: when to coalesce (deferring can save work)
  - Fights external fragmentation



Impossible to "Solve" Fragmentation

- **If you read allocation papers to find the best allocator**
  - All discussions revolve around tradeoffs
  - The reason? There cannot be a best allocator
- **Theoretical result:**
  - For any allocation algorithm, there exist 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, $\mathrm{n_{min}}$ = smallest allocation, $\mathrm{n_{max}}$ = largest allocation
  - Bad allocator: $\mathrm{M} \cdot (\mathrm{n_{max}}/\mathrm{n_{min}})$
    - E.g., make all allocations of size $\mathrm{n_{max}}$ regardless of requested size
  - Good allocator: $\sim \mathrm{M} \cdot \log(\mathrm{n_{max}}/\mathrm{n_{min}})$

Pathological Examples

- **Suppose heap currently has 7 20-byte chunks**

20	20	20	20	20	20	20

  - What's a bad stream of frees and then allocates?

- **Next: two allocators (best fit, first fit) that, in practice, work pretty well**
  - "pretty well" = ~20% fragmentation under many workloads

Pathological Examples

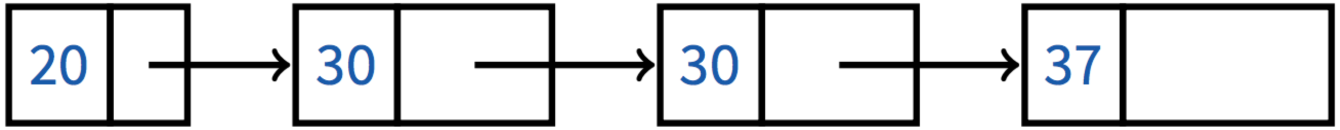
- **Suppose heap currently has 7 20-byte chunks**

20	20	20	20	20	20	20

  - What's a bad stream of frees and then allocates?
  - Free every other chunk, then alloc 21 bytes
- **Next: two allocators (best fit, first fit) that, in practice, work pretty well**
  - "pretty well" = ~20% fragmentation under many workloads

Best Fit

- **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 a pointer to the next block



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

- **Potential problem: Sawdust**
  - Remainder so small that over time left with “sawdust” everywhere
  - Fortunately not a problem in practice

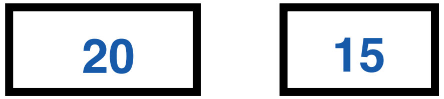
Best Fit Gone Wrong

- **Simple bad case: allocate** n, m $(n < m)$ **in alternating orders, free all the** n**s, then try to allocate an** $n + 1$
- **Example: start with 99 bytes of memory**
  - alloc 19, 21, 19, 21, 19

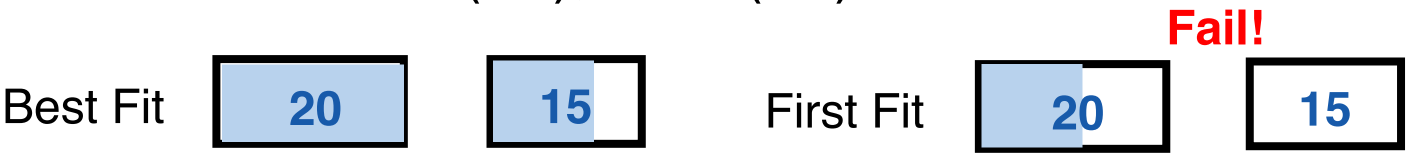
  - free 19, 19, 19:

  - alloc 20? Fails! (wasted space = 57 bytes)
- **However, doesn't seem to happen in practice**

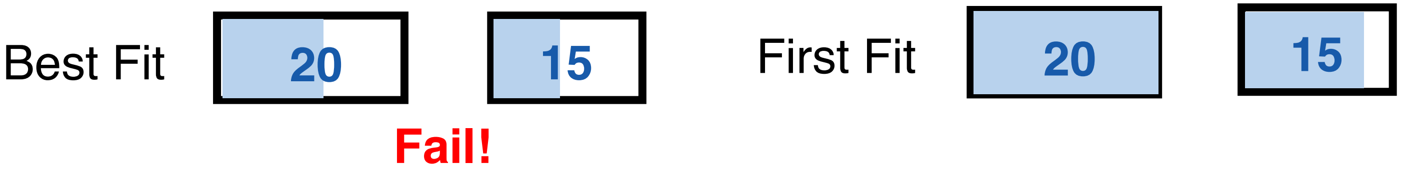
First Fit

- **Strategy: pick the first block that fits**
  - Data structure: free list, sorted LIFO, FIFO, or by address
  - Code: scan list, take the first one
- **Suppose memory has free blocks:** 

  - Workload 1: alloc(10), alloc(20)



  - Workload 2: alloc(8), alloc(12), alloc(12)



First Fit

- **LIFO: put free object 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 object at end of list**
  - Gives similar fragmentation as address sort, but unclear why

Subtle Pathology: LIFO FF

- **Storage management 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 $2n$-byte allocations, with long-lived $(n + 1)$-byte allocations

    `alloc`(8), `free`(8), `alloc`(5), `alloc`(8), `free`(8), `alloc`(5), `alloc`(8), `free`(8), …

  - Each time large object 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 requests to skip over many small blocks. Need to use a scalable heap organization

Some Other Ideas

- **Worst-fit:**
  - Strategy: fight against sawdust by splitting blocks to maximize leftover size
  - In real life seems to ensure that no large blocks around
- **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
- **Buddy systems:**
  - Round up allocations to power of 2 to make management faster

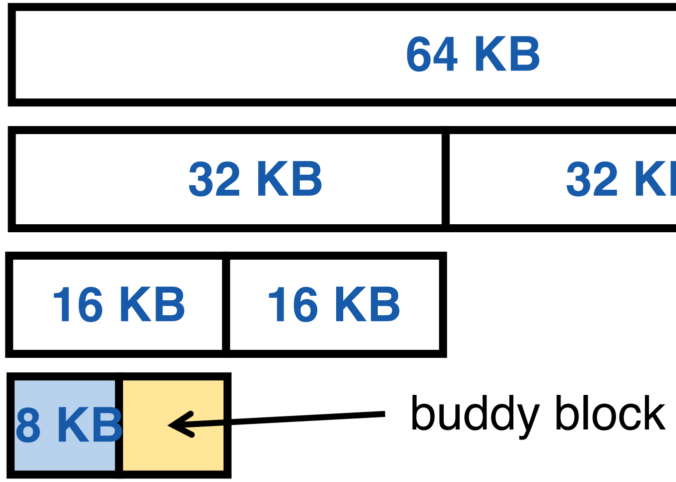
Buddy Allocator Motivation

- **Allocation requests: frequently 2^n**
  - E.g., allocation physical pages in Linux
  - Generic allocation strategies: overly generic
- **Fast search (allocate) and merge (free)**
  - Avoid iterating through free list
- **Avoid external fragmentation for req of 2^n**
- **Keep physical pages contiguous**
- **Used by Linux, FreeBSD**

Buddy Allocator Implementation

- **Data structure**
  - *N* free lists of blocks of size 2^0, 2^1, …, 2^N
- **Allocation restrictions: 2^k, 0<= k <= N**
- **Allocation of 2^k:**
  - Search free lists (k, k+1, k+2, …) for appropriate size
  - Recursively divide larger blocks until reach block of correct size
  - Insert “buddy” blocks into free lists
- **Free**
  - recursively coalesce block with “buddy” if buddy free

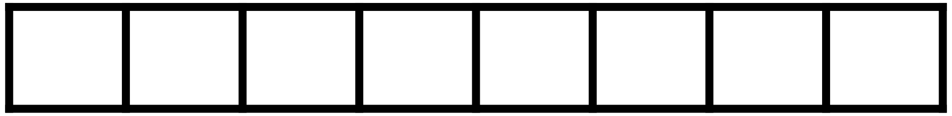
Buddy Allocation



- **Recursively divide larger blocks until reach suitable block**
  - Big enough to fit but if further splitting would be too small
- **Insert “buddy” blocks into free lists**
  - The addresses of the buddy pair only differ by one bit!
- **Upon free, recursively coalesce block with buddy if buddy free**

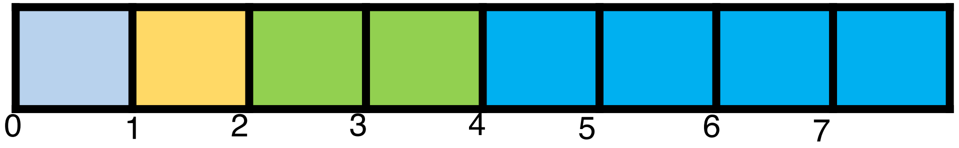
Buddy Allocation Example

Note: 2^3



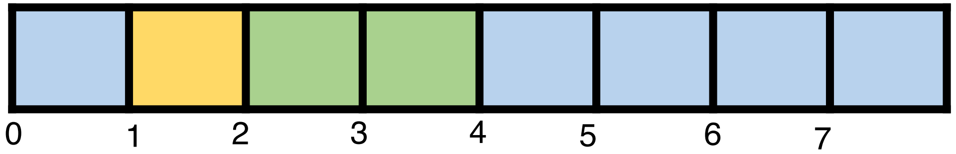
freelist[3] = {0}

`p1 = alloc(2^0)`



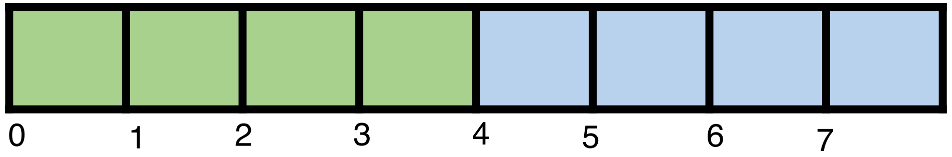
freelist[0] = {1}, freelist[1] = {2}, freelist[2] = {4}

`p2 = alloc(2^2)`



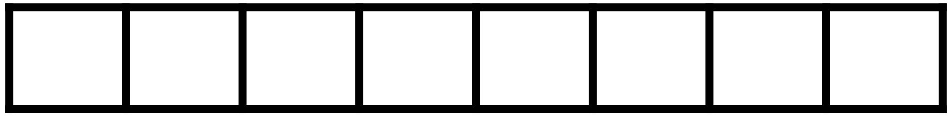
freelist[0] = {1}, freelist[1] = {2}

`free(p1)`



freelist[2] = {0}

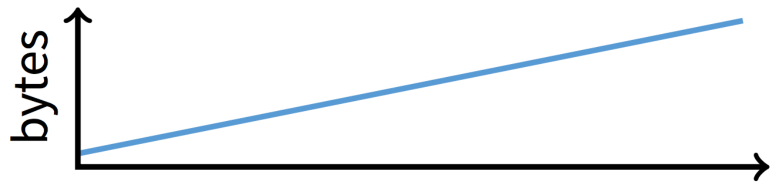
`free(p2)`



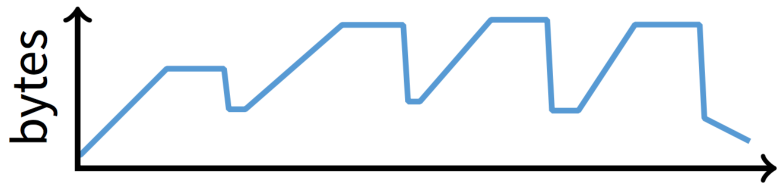
freelist[3] = {0}

Known Patterns of Real Programs

- **So far we've 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

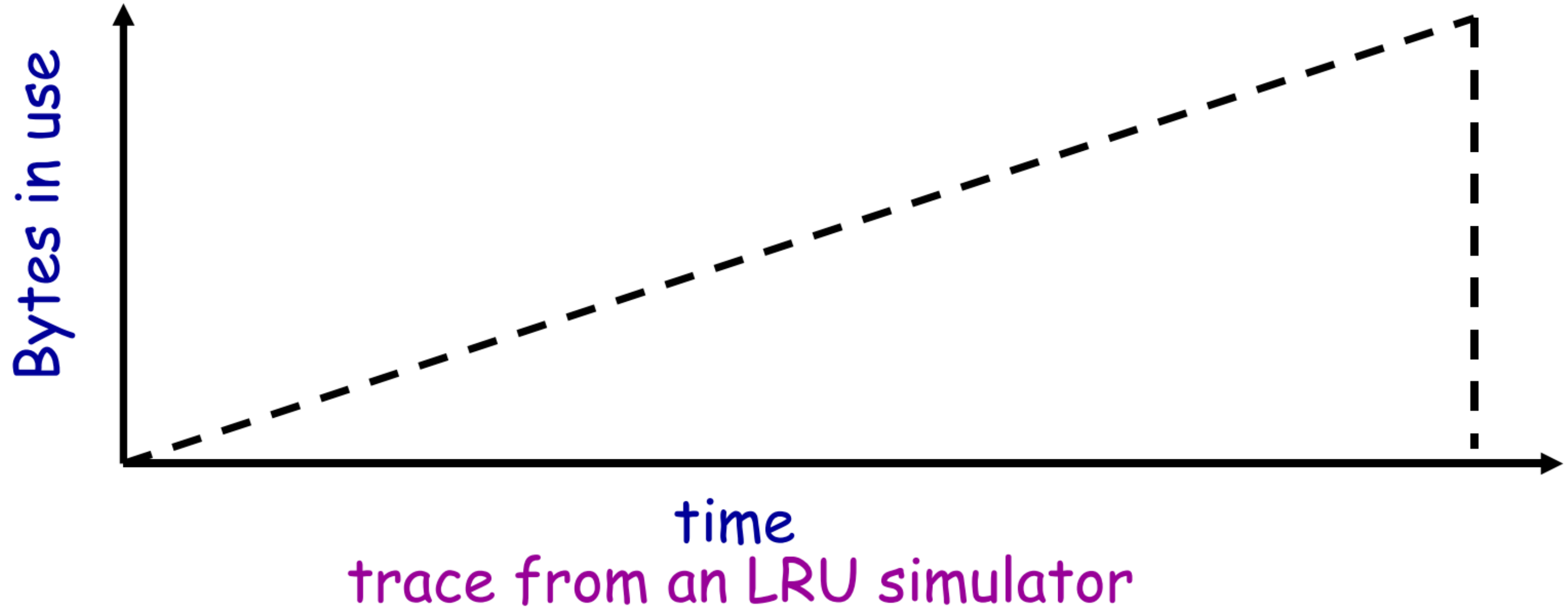


  - *Peaks*: allocate many objects, use briefly, then free all



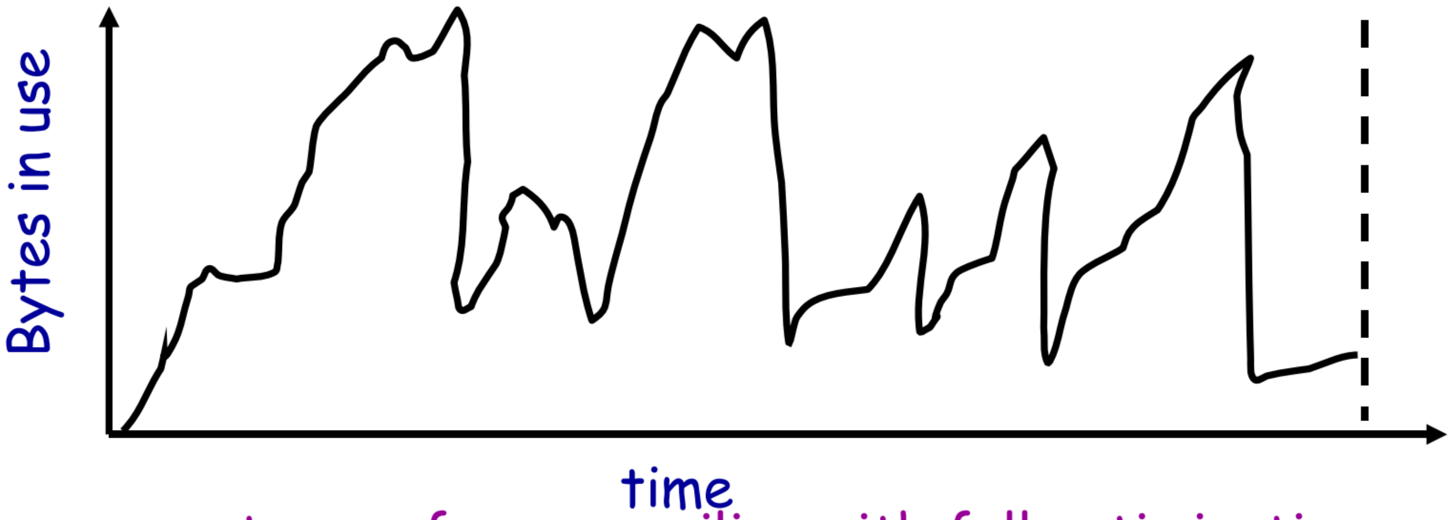
  - *Plateaus*: allocate many objects, use for a long time

Pattern 1: ramps



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

Pattern 2: Peaks



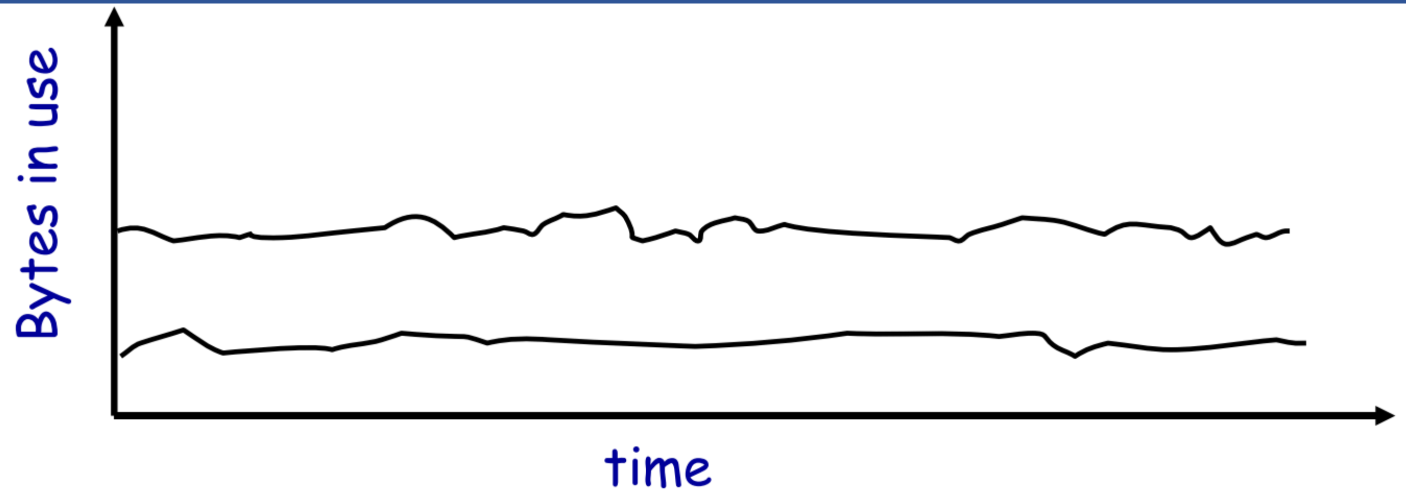
trace of gcc compiling with full optimization

- **Peaks: allocate many objects, use briefly, then free all**
  - Fragmentation a real danger
  - What happens if peak allocated from contiguous memory?
  - Interleave peak & ramp? Interleave two different peaks?

Exploiting Peaks

- **Peak phases: allocate a lot, then free everything**
  - Change allocation interface: allocate as before, but only support free of everything all at once
  - Called "arena allocation", "obstack" (object stack), or alloca/procedure call (by compiler people)
- **Arena = a linked list of large chunks of memory**
  - Advantages: alloc is a pointer increment, free is "free"
  - No wasted space for tags or list pointers
  - See Pintos threads/malloc.c

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?

Slab Allocation

- **Kernel allocates many instances of same structures**
  - E.g., a 1.7 KB `task_struct` for every process on system
- **Often want contiguous physical memory (for DMA)**
- **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**

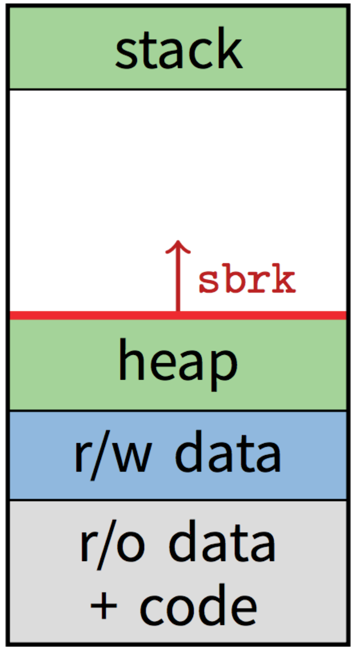
Slab Allocation

- **E.g., 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
- **Free memory management: bitmap**
  - Allocate: set bit and return slot, Free: clear bit
- **Advantages: speed, and no internal fragmentation**
- **Used in FreeBSD and Linux, implemented on top of buddy page allocator**

Getting More Space from OS

- `malloc` **is a library call, how does** `malloc` **gets free space?**
  - Note in Pintos, malloc is provided as a kernel function (see threads/malloc.c)

- **On Unix, can use** `sbrk` **and** `brk`
  - `int brk(void *p)`
    - Move the program break to address p
    - Return 0 if successful and -1 otherwise
  - `void *sbrk(intptr_t n)`
    - Increment the program break by *n* bytes
    - If n is 0, then return the current location of the program break
    - Return 0 if successful and (void*)-1 otherwise



Implement `malloc()`

```
void *malloc(size_t n)
{
  char *p = sbrk(0);
  if (brk(p + n) == -1)
    return NULL;
  return p;
}

void free(void * p)
{
}
```

get current "program break"

set "program break" to be current plus n

Problem?

- Two system calls for every malloc!
- Freed blocks are not reused

Solutions

- Allocators request memory pool
- Keep track of free list
- If can't find free chunk, request from OS

Returning Heap Memory

- **Allocator can mark blocks as free when `free()` is called**
  - But these blocks can be reused later by the process
  - i.e., they are not returned to the system!
  - Can cause memory pressure
- **Allocator can return heap memory with `brk(pBrk–n)`, but…**
  - `p` in `free(p)` is not always at the end of the heap!
  - So can't reduce the heap size with `brk(pBrk–n)`
- **Therefore, for large allocations, `sbrk()` is a bad idea**
  - Can't return memory to the system

Solution: VM Mapping

- `void *mmap(void *p, size_t n, int prot, int flags, int fd, off_t offset);`
  - Creates a new mapping in the virtual address space of the calling process
  - `p`: the starting address for the new mapping
  - `n`: the length of the mapping
  - If `p` is NULL, the kernel chooses the address at which to create the mapping
  - On success, returns address of the mapped area
- `int munmap(void *p, size_t n);`
  - Deletes the mappings for the specified address range

Implement `malloc()` with mmap

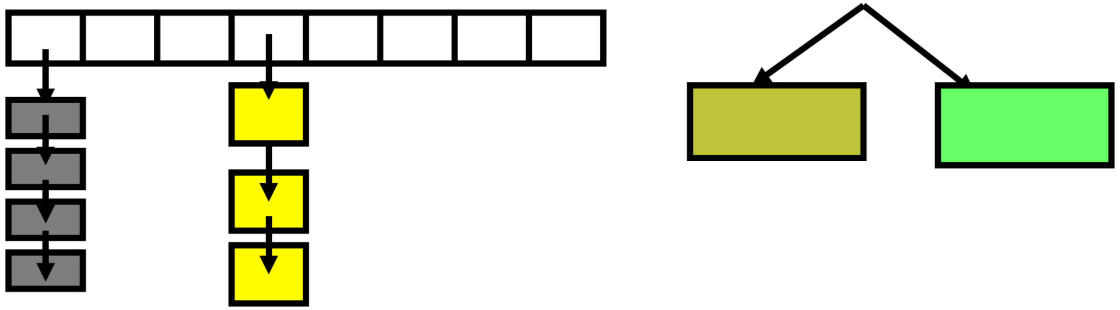
```
void *malloc(size_t n)
{
  size_t *p;
  if (n == 0) return NULL;
  p = mmap(NULL, n + sizeof(size_t),
        PROT_READ|PROT_WRITE,
        MAP_PRIVATE|MAP_ANONYMOUS, 0, 0);
  if (p == (void*)-1) return NULL;
  *p = n + sizeof(size_t); // Store size in header
  p++; // Move forward from header to payload
  return p;
}
```

```
void free(void *p)
{
  if (p == NULL) return;
  p--; // Move backward from
       // payload to header
  munmap(p, *p);
}
```

Next Time…

- **Midterm Review**

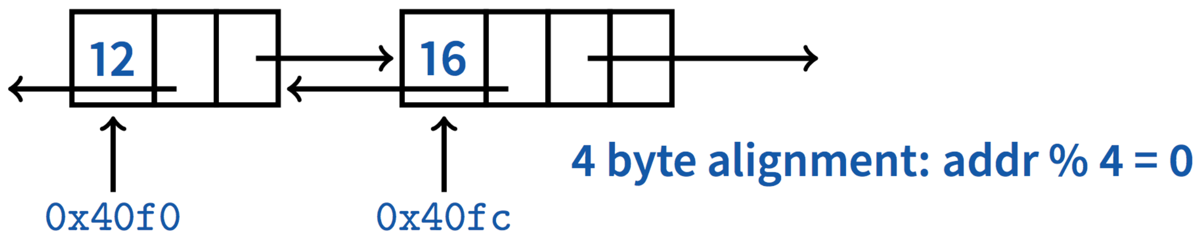
Simple, Fast Segregated Free Lists



- **Array of free lists for small sizes, tree for larger**
  - Place blocks of same size on same page
  - Have count of allocated blocks: if goes to zero, can return page
- **Pro: segregate sizes, no size tag, fast small alloc**
- **Con: worst case waste: 1 page per size even w/o free, After pessimal free: waste 1 page per object**
- **TCMalloc [Ghemawat] is a well-documented malloc like this**

Typical Space Overheads

- **Free list bookkeeping and alignment determine minimum allocatable size:**
- **If not implicit in page, must store size of block**
- **Must store pointers to next and previous freelist element**



- **Allocator doesn't know types**
  - Must align memory to conservative boundary