Administrivia

- **New office hour policy**
  - First hour of previous CAs' OH does not use queuestatus
  - Round-robin format will benefit students with similar questions
- **But Kevin will add 4 extra (queuestatus) OH per week**

Outline

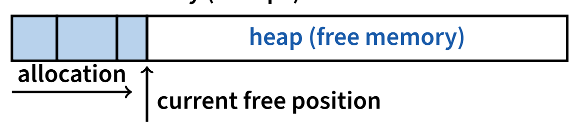
1. Malloc and fragmentation
2. Exploiting program behavior
3. Allocator designs
4. User-level MMU tricks
5. Garbage collection

Dynamic memory allocation

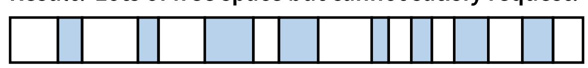
- **Almost every useful program uses it**
  - Gives wonderful functionality benefits
    - Don't have to statically specify complex data structures
    - Can have data grow as a function of input size
    - Allows recursive procedures (stack growth)
  - But, can have a huge impact on performance
- **Today: how to implement it**
  - 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: memory management still poorly understood

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:**

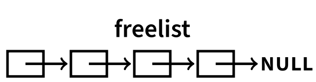


- **Problem: free creates holes ("fragmentation")**
  Result? Lots of free space but cannot satisfy request!



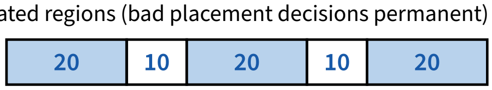
More abstractly

- **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, or lifetime of future allocations
  - Move allocated regions (bad placement decisions permanent)

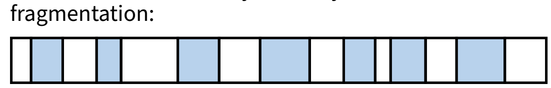
`malloc(20)`?



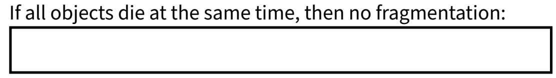
- **The core fight: minimize fragmentation**
  - App frees blocks in any order, creating holes in "heap"
  - Holes too small? cannot satisfy future requests

What is fragmentation really?

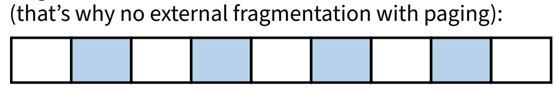
- **Inability to use memory that is free**
- **Two factors required for fragmentation**
  1. Different lifetimes—if adjacent objects die at different times, then fragmentation:



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

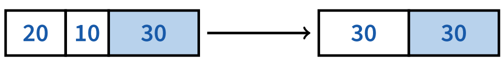


  2. Different sizes: If all requests the same size, then no fragmentation (that's why no external fragmentation with paging):



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 possible 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, n_{min} = smallest allocation, n_{max} = largest – How much gross memory required?
  - Bad allocator: $M \cdot (n_{max}/n_{min})$
    - E.g., only ever use a memory location for a single size
    - E.g., make all allocations of size n_{max} regardless of requested size
  - Good allocator: $\sim M \cdot \log(n_{max}/n_{min})$

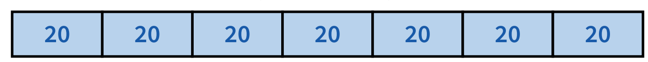
Pathological examples

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

  - What's a bad stream of frees and then allocates?
- **Given a 128-byte limit on malloced space**
  - What's a really bad combination of mallocs & frees?
- **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**



  - What's a bad stream of frees and then allocates?
  - Free every other chunk, then alloc 21 bytes
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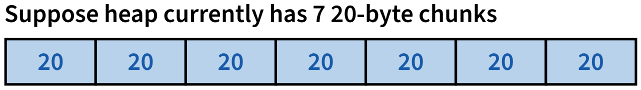
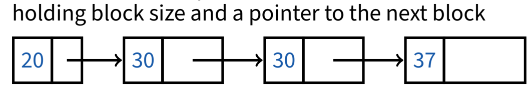


  - What's a bad stream of frees and then allocates?
  - Free every other chunk, then alloc 21 bytes
- **Given a 128-byte limit on malloced space**
  - What's a really bad combination of mallocs & frees?
  - Malloc 128 1-byte chunks, free every other
  - Malloc 32 2-byte chunks, free every other (1- & 2-byte) chunk
  - Malloc 16 4-byte chunks, free every other chunk…
- **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 (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 ns, then try to allocate an $n+1$**
- **Example: start with 99 bytes of memory**
  - alloc 19, 21, 19, 21, 19

19	21	19	21	19

  - free 19, 19, 19:

19	21	19	21	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
- **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
  - 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
- **Suppose memory has free blocks:** [20] → [15]
  - If allocation ops are 10 then 20, best fit wins
  - When is FF better than best fit?

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  - If allocation ops are 10 then 20, best fit wins
  - When is FF better than best fit?
  - Suppose allocation ops are 8, 12, then 12 $\Longrightarrow$ first fit wins

Some worse 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
  - Result? Heavy internal fragmentation

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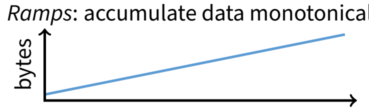
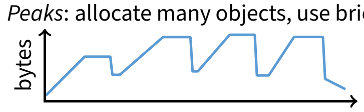
Known patterns of real programs

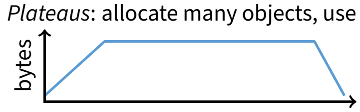
- **So far we've treated programs as black boxes.**
- **Most real programs exhibit 1 or 2 (or all 3) of the following patterns of alloc/dealloc:**
  - *Ramps*: accumulate data monotonically over time



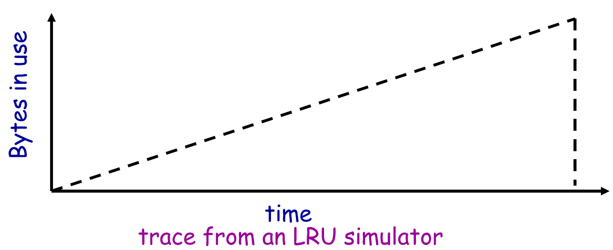
  - *Peaks*: allocate many objects, use briefly, then free all



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

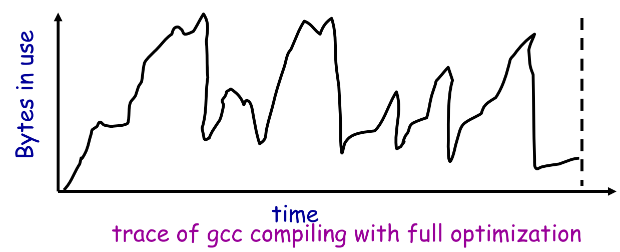


Pattern 1: ramps



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

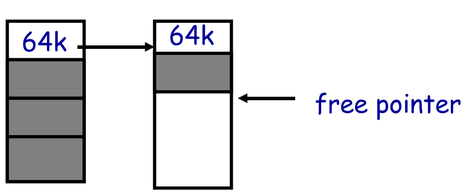
Pattern 2: peaks



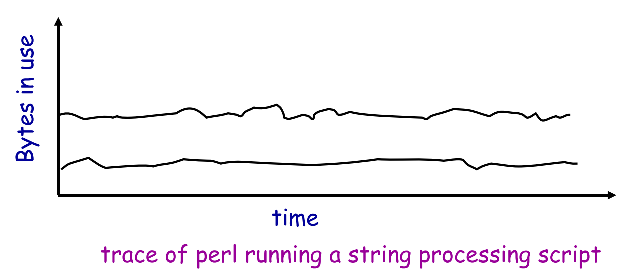
- **Peaks: allocate many objects, use briefly, then free all**
  - Fragmentation a real danger
  - What happens if peak allocated from contiguous memory?
  - Interleave peak & ramp? Interleave two different peaks?

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



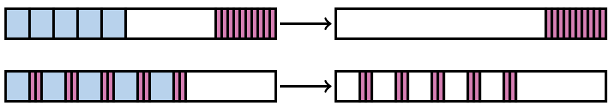
Pattern 3: Plateaus



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

Fighting fragmentation

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



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

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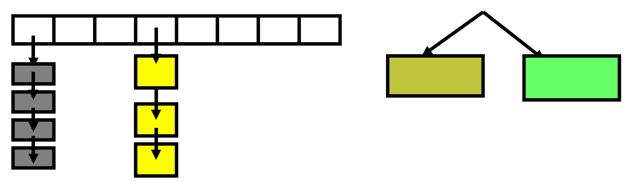
Slab allocation [Bonwick]

- **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**
- **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
- **Advantages: speed, and no internal fragmentation**

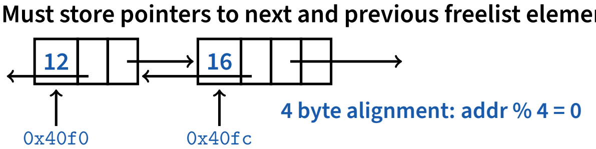
Simple, fast segregated free lists



- **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**
  - Also uses "thread caching" to reduce coherence misses

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**

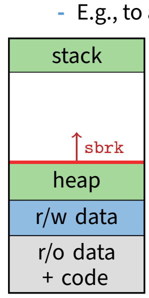


- **Allocator doesn't know types**
  - Must align memory to conservative boundary
- **Minimum allocation unit? Space overhead when allocated?**

[demo mtest]

Getting more space from OS

- **On Unix, can use `sbrk`**
  - E.g., to activate a new zero-filled page:




```
/* add nbytes of valid virtual address space */
void *get_free_space(size_t nbytes) {
  void *p = sbrk(nbytes);
  if (p == (void *) -1)
    error("virtual memory exhausted");
  return p;
}
```

- **For large allocations, `sbrk` a bad idea**
  - May want to give memory back to OS
  - Can't with `sbrk` unless big chunk last thing allocated
  - So allocate large chunk using `mmap`'s `MAP_ANON`

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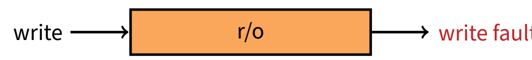
Faults + resumption = power

- **Resuming after fault lets us emulate many things**
  - "All problems in CS can be solved by another layer of indirection"
- **Example: sub-page protection**
- **To protect sub-page region in paging system:**

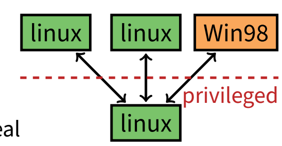
  - Set entire page to most restrictive permission; record in PT



  - Any access that violates permission will cause a fault
  - Fault handler checks if page special, and if so, if access allowed
  - Allowed? Emulate write ("tracing"), otherwise raise error

More fault resumption examples

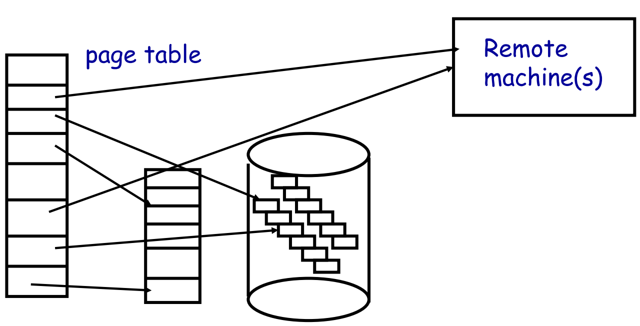
- **Emulate accessed bits:**
  - Set page permissions to "invalid".
  - On any access will get a fault: Mark as accessed
- **Avoid save/restore of floating point registers**
  - Make first FP operation cause fault so as to detect usage
- **Emulate non-existent instructions:**
  - Give inst an illegal opcode; OS fault handler detects and emulates fake instruction
- **Run OS on top of another OS!**
  - Slam OS into normal process
  - When does something "privileged," real OS gets woken up with a fault.
  - If operation is allowed, do it or emulate it; otherwise kill guest
  - IBM's VM/370. Vmware (sort of)



Not just for kernels

- **User-level code can resume after faults, too. Recall:**
  - `mprotect` – protects memory
  - `sigaction` – catches signal after page fault
  - Return from signal handler restarts faulting instruction
- **Many applications detailed by [Appel & Li]**
- **Example: concurrent snapshotting of process**
  - Mark all of process's memory read-only with `mprotect`
  - One thread starts writing all of memory to disk
  - Other thread keeps executing
  - On fault – write that page to disk, make writable, resume

Distributed shared memory



- **Virtual memory allows us to go to memory or disk**
  - But, can use the same idea to go anywhere! Even to another computer. Page across network rather than to disk. Faster, and allows network of workstations (NOW)

Persistent stores

- **Idea: Objects that persist across program invocations**
  - E.g., object-oriented database; useful for CAD/CAM type apps
- **Achieve by memory-mapping a file**
  - Write your own "malloc" for memory in a file
- **But only write changes to file at end if commit**
  - Use dirty bits to detect which pages must be written out
  - Or emulate dirty bits with *mprotect/sigaction* (using write faults)
- **On 32-bit machine, store can be larger than memory**
  - But single run of program won't access $>$ 4GB of objects
  - Keep mapping of 32-bit memory pointers $\leftrightarrow$ 64-bit disk offsets
  - Use faults to bring in pages from disk as necessary
  - After reading page, translate pointers—known as *swizzling*

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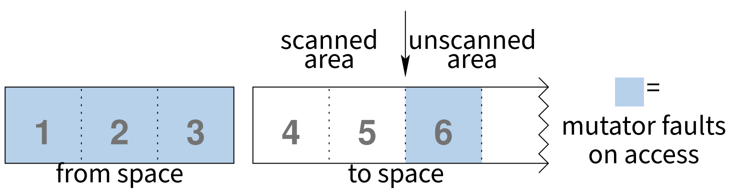
Garbage collection

- **In safe languages, runtime knows about all pointers**
  - So can move an object if you change all the pointers
- **What memory locations might a program access?**
  - Any globals or objects whose pointers are currently in registers
  - Recursively, any pointers in objects it might access
  - Anything else is *unreachable*, or *garbage*; memory can be re-used
- **Example: stop-and-copy garbage collection**
  - Memory full? Temporarily pause program, allocate new heap
  - Copy all objects pointed to by registers into new heap
    - ▷ Mark old copied objects as copied, record new location
  - Start scanning through new heap. For each pointer:
    - ▷ Copied already? Adjust pointer to new location
    - ▷ Not copied? Then copy it and adjust pointer
  - Free old heap—program will never access it—and continue

Concurrent garbage collection

- **Idea: Stop & copy, but without the stop**
  - *Mutator* thread runs program, *collector* concurrently does GC
- **When collector invoked:**
  - Protect from space & unscanned to space from mutator
  - Copy objects in registers into *to space*, resume mutator
  - All pointers in scanned *to space* point to *to space*
  - If mutator accesses unscanned area, fault, scan page, resume



(See [Appel & Li].)

Heap overflow detection

- **Many GCed languages need fast allocation**
  - E.g., in lisp, constantly allocating cons cells
  - Allocation can be as often as every 50 instructions
- **Fast allocation is just to bump a pointer**

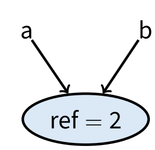
```
char *next_free;
char *heap_limit;

void *alloc (unsigned size) {
  if (next_free + size > heap_limit) /* 1 */
    invoke_garbage_collector ();     /* 2 */
  char *ret = next_free;
  next_free += size;
  return ret;
}
```

- **But would be even faster to eliminate lines 1 & 2!**

Heap overflow detection 2

- **Mark page at end of heap inaccessible**
  - `mprotect (heap_limit, PAGE_SIZE, PROT_NONE);`
- **Program will allocate memory beyond end of heap**
- **Program will use memory and fault**
  - Note: Depends on specifics of language
  - But many languages will touch allocated memory immediately
- **Invoke garbage collector**
  - Must now put just allocated object into new heap
- **Note: requires more than just resumption**
  - Faulting instruction must be resumed
  - But must resume with different target virtual address
  - Doable on most architectures since GC updates registers

Reference counting



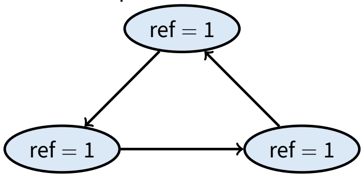
- **Seemingly simpler GC scheme:**
  - Each object has "ref count" of pointers to it
  - Increment when pointer set to it
  - Decremented when pointer killed
    (C++ destructors handy—c.f. `shared_ptr`)

```
void foo(bar c) {
  bar a b;
  a = c;     // c.refcnt++
  b = a;     // a.refcnt++
  a = 0;     // c.refcnt--
  return;    // b.refcnt--
}
```

  - ref count == 0? Free object
- **Works well for hierarchical data structures**
  - E.g., pages of physical memory

Reference counting pros/cons

- **Circular data structures always have ref count > 0**
  - No external pointers means lost memory



- **Can do manually w/o PL support, but error-prone**
- **Potentially more efficient than real GC**
  - No need to halt program to run collector
  - Avoids weird unpredictable latencies
- **Potentially less efficient than real GC**
  - With real GC, copying a pointer is cheap
  - With refcounts, must update count each time & possibly take lock (but C++11 std::move can avoid overhead)

Ownership types

- **Another approach: avoid GC by exploiting type system**
  - Use ownership types, which prohibit copies
- **You can move a value into a new variable (e.g., copy pointer)**
  - But then the original variable is no longer usable
- **You can *borrow* a value by creating a pointer to it**
  - But must prove pointer will not outlive borrowed value
  - And can't use original unless both are read-only (to avoid races)
- **Ownership types available now in Rust language**
  - First serious competitor to C/C++ for OSes, browser engines
- **C++11 does something similar but weaker with unique types**
  - `std::unique_ptr`, `std::unique_lock`,...
  - Can std::move but not copy these

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

int
main()
{
  char *p1 = malloc(1);
  char *p2 = malloc(1);
  printf("%p - %p = %ld\n", p2, p1, p2 - p1);
}
```