INF333 - Operating Systems

Lecture XII

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Course website

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Based On

cs212.stanford.edu

OSC-10 Slides

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

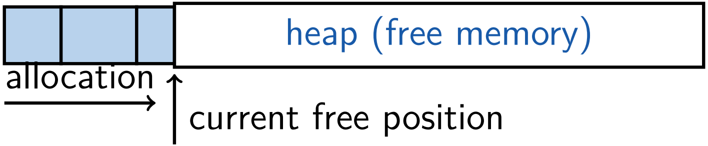
Dynamic memory allocation

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?

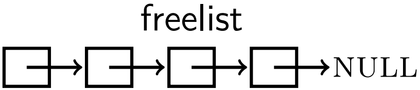
- Satisfy arbitrary set of allocation and frees.
- Easy without free: set a pointer to the beginning of some big chunk of memory ("heap") and increment on each allocation:



- 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:

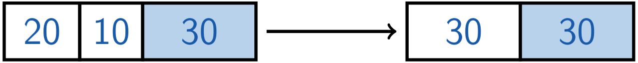
       

  2. Different sizes: If all requests the same size, then no fragmentation (that's why no external fragmentation with paging):

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

20	20	20	20	20	20	20

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

- Given a 128-byte limit on `malloc()`'d 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
- Given a 128-byte limit on `malloc()`'d space
  - What's a really bad combination of mallocs & frees?
- Next: two allocators (best fit, first fit) that, in practice, work pretty well
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Pathological examples

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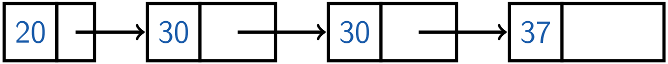
  - What's a bad stream of frees and then allocates?
  - Free every other chunk, then alloc 21 bytes
- Given a 128-byte limit on `malloc()`'d space
  - What's a really bad combination of mallocs & frees?
  - Malloc 128 1-byte chunks, free every other
  - Malloc 32 2-byte chunks, free every other (1- & 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 in 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)

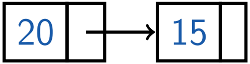
FIFO: put free object at end of list

- 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 in 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: 

  - If allocation ops are 10 then 20, best fit wins
  - When is FF better than best fit?

First fit: Nuances

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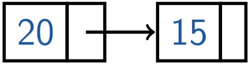
- Suppose memory has free blocks: 

  - 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

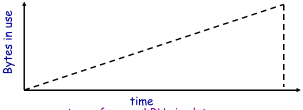
Buddy systems:

- Round up allocations to power of 2 to make management faster
- Result? Heavy internal fragmentation

Exploiting program behavior

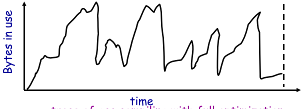
Known patterns of real programs

- So far we've treated programs as black boxes.
- Most real code exhibit one or more of the following:
  - *Ramps*: accumulate data monotonically over time



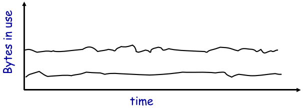
trace from an LRU simulator

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



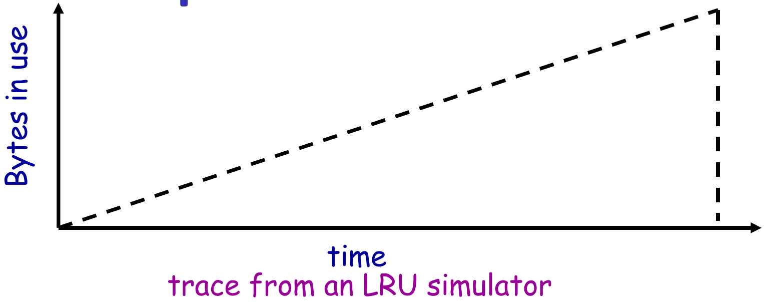
trace of gcc compiling with full optimization

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



trace of perl running a string processing script

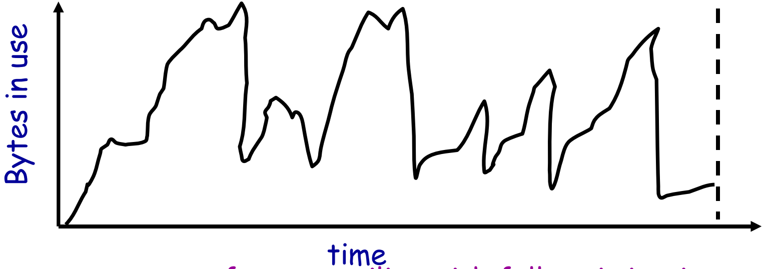
Pattern 1: ramps



In a practical sense: ramp == no calls to `free()`!

- Implication for fragmentation?
- What happens if you evaluate allocator with ramp programs only?

Pattern 2: peaks



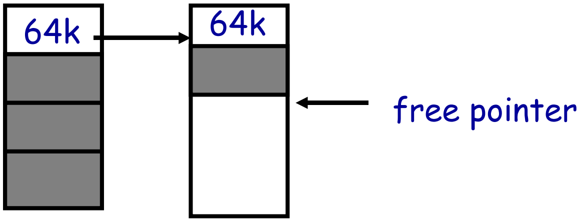
trace of gcc compiling with full optimization

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

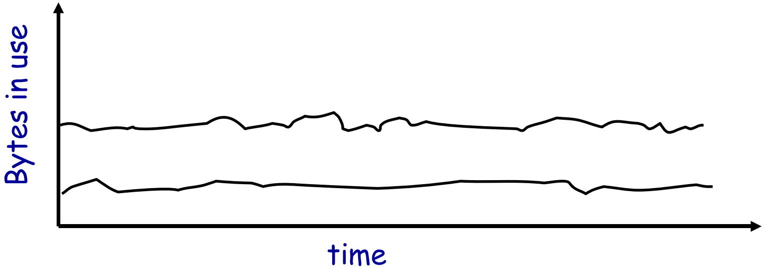
- Fragmentation a real danger
- What happens if peak allocated from contiguous memory?
- Interleave peak & ramp? Interleave two different peaks?

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



Pattern 3: Plateaus



trace of perl running a string processing script

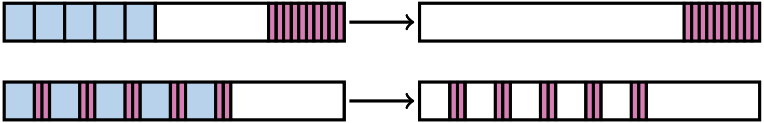
Plateaus: allocate many objects, use for a long time

- What happens if overlap with peak or different plateau?

Fighting fragmentation

Segregation = reduced fragmentation:

- Allocated at same time $\sim$ freed at same time
- Different type $\sim$ freed at different time



Implementation observations:

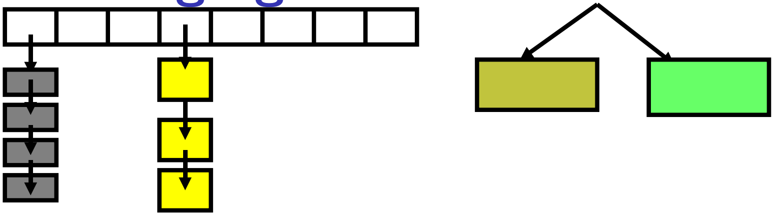
- Programs allocate a small number of different sizes
- Fragmentation at peak usage more important than at low usage
- Most allocations small ($<$ 10 words)
- Work done with allocated memory increases with size
- Implications?

Allocator designs

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

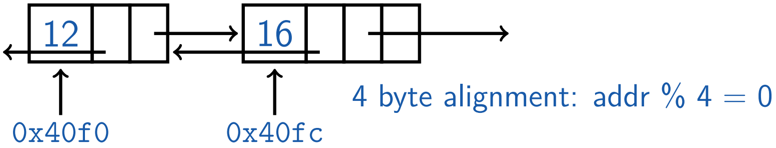
Simple, fast segregated free lists



- 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

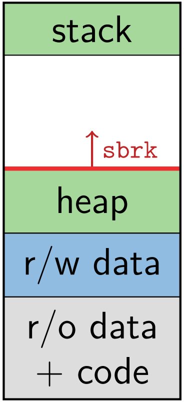
- Free list bookkeeping and alignment determine minimum allocatable size:
- If not implicit in page, must store size of block
- Must store pointers to next and previous freelist element



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

Getting more space from OS I

- 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;
}
```

Getting more space from OS II

For large allocations, `sbrk` a bad idea

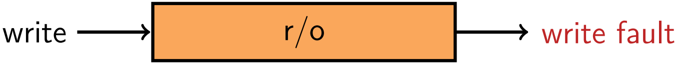
- May want to give memory back to OS
- Can't with `sbrk` unless big chunk last thing allocated
- So allocate large chunk using `mmap`'s `MAP_ANON`

User-level MMU tricks

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:

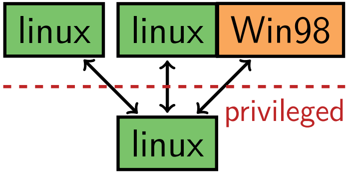
  - Set entire page to most restrictive permission; record in PT



  - 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!

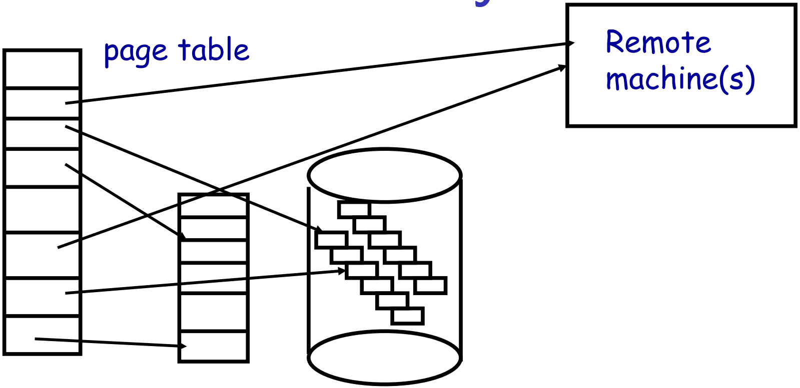


  - Slam OS into normal process
  - When does something "privileged," real OS gets woken up with a fault.
  - If operation is allowed, do it or emulate it; otherwise kill guest
  - IBM's VM/370. Vmware (sort of)

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*

Garbage collection

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

Garbage collection

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

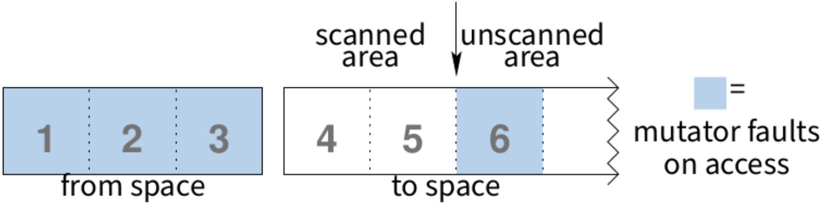
Concurrent garbage collection

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 1

- 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

Heap overflow detection 2

```
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;
}
```

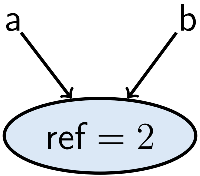
- But would be even faster to eliminate lines 1 & 2!

Heap overflow detection 3

- 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 1

- 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`)



- Works well for hierarchical data structures
  - E.g., pages of physical memory

Reference counting 2

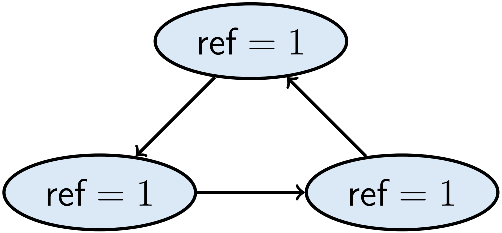
```
void foo(bar c) {
    bar a, b;
    a = c;          // c.refcnt++
    b = a;          // a.refcnt++
    a = nullptr;    // c.refcnt--
    return;         // b.refcnt--
  }
```

- ref count == 0? Free object

Reference counting pros/cons 1

Circular data structures always have ref count > 0

- No external pointers means lost memory



- Python GC summary

Reference counting pros/cons 2

- 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 real GC, object destructors can run asynchronously
  - With refcounts, must update count each time & possibly take lock (but C++11's std::move can avoid overhead)
  - With refcounts, destructors can introduce unexpected latencies

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