CS 241 Honors
Memory

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Overview

- Memory review
- Management techniques
  - Heap vs. stack
  - `free()`
  - `alloca()`
  - Smart pointers (C++)
- Garbage collection
  - Reference counting
  - Mark-and-sweep
  - Copying collector
  - Generational
  - In practice
- Concluding thoughts

Types of variables in program memory

- Static variables
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  - Allocation and reclaiming of memory is really cheap—why?

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- Local variables, function arguments
  - Live for the lifetime of the function call
  - Stored on the stack
  - Allocation and reclaiming of memory is really cheap—why?
- Heap allocation
  - Slower than stack allocation because of bookkeeping by memory manager
  - This memory is not automatically reclaimed, so will eventually fill up
  - Call `free()`! But it isn't always obvious when you are done with something

`malloc()` and `free()`

What's the big deal?

You all know from using it—manual heap memory management is a pain

Why is heap management so difficult?

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  - Dangling pointers, double deletion, memory leaks
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- Fragmentation
  - Bad locality of reference
  - Problem in virtual memory systems due to page faults, cache misses

free(), continued

Keeping mental track of your heap memory gets frustrating in complex programs, especially if you're trying to be careful about error handling

```c
a = malloc(...);
b = malloc(...);

if (/* do something and it fails */) {
  free(a);
  free(b);
  return;
}

if (/* do another thing */) {
  if (/* do a third thing and it fails */) {
    free(a);
    free(b);
    return;
  }
  /* ... */
}

c = malloc(...);
if (/* do a fourth thing and it fails */) {
  free(c);
  free(b);
  free(a);
  return;
}

/* ... */
```

free(), continued (the "goto cleanup" idiom)

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- Can be generalized to other resource types (opening/closing files)
- Makes things easier, but still have manual heap management

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Let's take a look at some of its limitations...

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You can't `realloc()` stack memory... *or can you?* (you can't)

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So, not a good idea

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- Instead of passing pointers around like mad, let's set some rules
- RAII (Resource Acquisition Is Initialization)—remember from CS 225, maybe?
  - Only allocate memory in your constructor and free it in your destructor
  - Put things on the stack as much as possible

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Concept of *ownership*:

- Instead of passing pointers around like mad, let's set some rules
- RAII (Resource Acquisition Is Initialization)—remember from CS 225, maybe?
  - Only allocate memory in your constructor and free it in your destructor
  - Put things on the stack as much as possible
- "Smart pointer" wraps an ordinary (raw) pointer and defines the semantics for how it is managed and who's managing it
- Using these rules, you should (almost) never need to manually `new`/`delete` memory

C++ smart pointers

Types of smart pointers

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  In other words, it can have multiple owners, and is released when the last one lets go

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- `std::shared_ptr`: Reference-counted version (we'll discuss what this means later)
  In other words, it can have multiple owners, and is released when the last one lets go
- `std::weak_ptr`: Stores a "temporary" reference without owning it
  Can be used to break cycles if two objects refer to each other (e.g., doubly linked lists)
  Useful for caches, which store references to objects that *should* be deleted if the cache is the only thing still refering to it

C++ smart pointers

Old way:

```
bool func() {
  size_t bufsize = 1024 * 1024 * 128;
  int* data = new int[bufsize];

  for (int i = 0; i < bufsize; i++) {
    data[i] = get_data();
    if (!data[i]) {
      delete[] data;
      return false;
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  }

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Using `std::unique_ptr`:

```
bool func() {
  size_t bufsize = 1024 * 1024 * 128;
  auto data = std::make_unique<int[]>(
        bufsize);

  for (int i = 0; i < bufsize; i++) {
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```

No calls to `new[]` or `delete[]` necessary

C++ will automatically allocate the memory we want when we call `std::make_unique`, and release it when the unique pointer goes out of scope when the function exits

C++ smart pointers

...but not everyone uses C++

What about when you *need* the heap?

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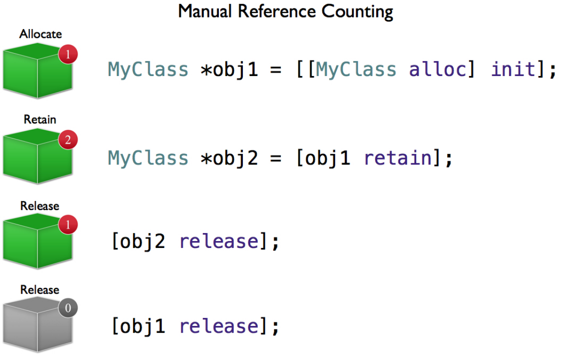
- How do you easily manage large objects?

What about when you *need* the heap?

- You can't always rely on the stack because it can overflow quickly
- How do you easily manage large objects?
- Garbage collection to the rescue! - Automagic Memory Management

GC: Reference counting

- Each object has count of how many objects point to it
- Need to track count whenever object pointers are set or removed/freed



Demo

Python!

GC: Reference Counting Problems

- Overhead of maintaining count

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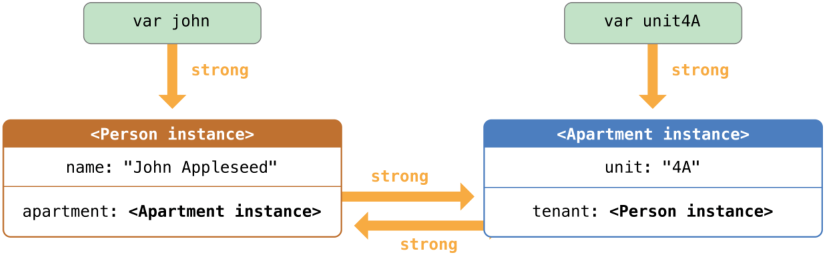
- Overhead of maintaining count
- Lumpy deletions: tend to have clusters of related objects.
- Cycles



GC: Tracing

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- Two Step Process
- Mark - Find and label all accessible objects
  - Follow all pointers from the "root set".
  - Perform DFS on pointers
  - Flag field set to marked

GC: Mark-and-Sweep

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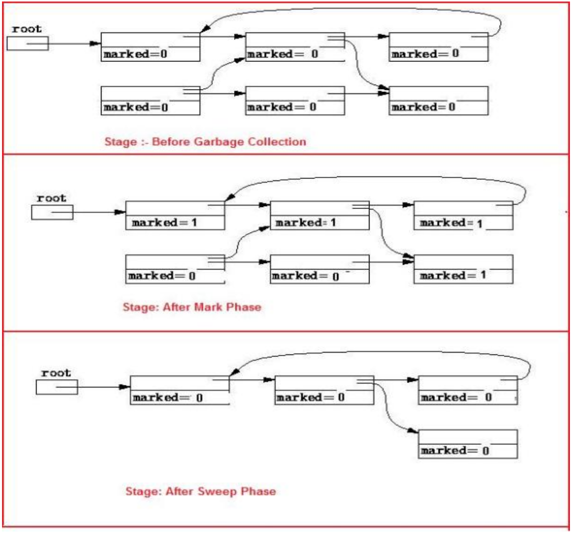
GC: Mark-and-Sweep

- Sweep - Remove all inaccessible objects
  - Iterate through memory
  - If marked, unmark
  - Else, free

GC: Mark-and-Sweep



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  - Program must halt
  - Fragmentation

GC: Mark-and-Sweep with Compaction

- Alleviates fragmentation
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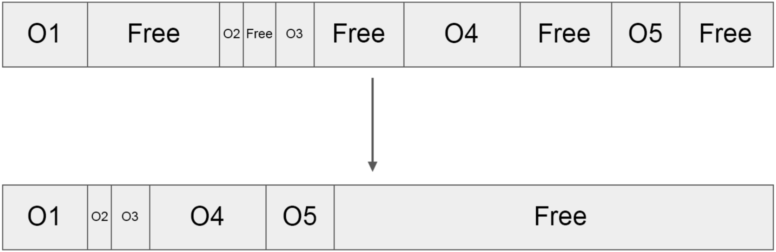

GC: Tri-Color Marking

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GC: Tri-Color Marking

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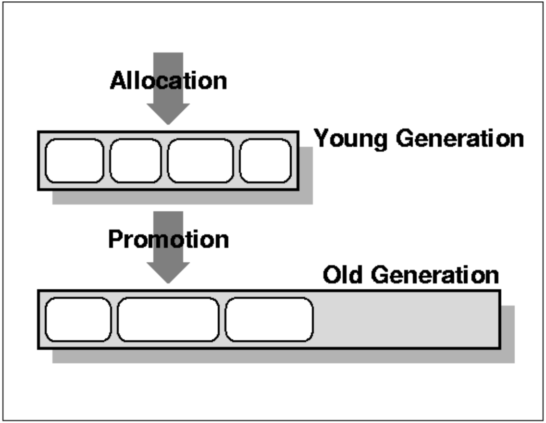
- Gray Set - Need to be scanned blocks
- Black Set - Accessible blocks
- White Set - Inaccessible blocks
- All blocks accessible from the root start in the gray set.
- All others start in the white set.
- Gray moves to black, all white set objects referenced moved to gray.

Generational GC

- Do we really need to scan everything all the time?
- Split the objects up into generations
- Scan each generation with a different frequency



Generational GC - Eden

- Compaction not important, needs fast GC
- When full, run mark phase and move objects up

Generational GC - Survivor Space 1

- Count for objects being copied back and forth
- When full, run mark phase and move objects up

Generational GC - Survivor Space 2

- Compaction not important
- Less frequent GC

Generational GC - Old Generation

- Mark/sweep with compaction since objects live longer
- Run less frequently, since slow process

Generational GC - Problems

- Objects in old generation could be pointing to objects in survivor space
- Mark phase in survivor space does not go through objects in old generation
- Maintain separate table for maintaining such pointers across generations
- Turns out such occurrences are less frequent in code bases
- Objects in old generation don't generally change much, so may not be too expensive in practice
- Add references from this table to root set of copying GC running in survivor space
- What about younger$\rightarrow$older generation references?

Garbage collection in C/C++?

- Doesn't come with one for performance reasons!
- Usually a bolted-on third party library
- Link the library and allow it to reclaim unused memory automatically
- `malloc` can be replaced with garbage collector's allocator, and `free` is a no-op

Garbage collection in C/C++?

```c
#include <assert.h>
#include <stdio.h>
#include <gc.h>

int main(void)
{
    int i;
    const size = 10000000;

    GC_INIT();
    for (i = 0; i < size; ++i)
    {
        int **p = GC_MALLOC(sizeof *p);
        int *q = GC_MALLOC_ATOMIC(sizeof *q);

        assert(*p == 0);
        *p = GC_REALLOC(q, 2 * sizeof *p);
        if (i == size-1)
            printf("Heap size = %zu\n", GC_get_heap_size());
    }

    return 0;
}
```

GC doesn't mean you forget about memory

- Explicitly let go of object by setting the reference to NULL. This is useful with global variables. Otherwise you hang onto system resources longer.
- Need to manage other system resources (like files); they are closed before GC by programmer

Conclusion

Thank you! Questions?