LAST TIME

- Finished covering most of C’s abstraction capabilities
  - Dynamic memory allocation on heap, structs, unions
- Began to see something very disturbing:
  - It’s very easy to write incorrect or unsafe programs in C!
- Unchecked array accesses and buffer overflows:
  - Allow an attacker to crash a program, modify its data in unintended ways, or even execute arbitrary code!
- Other memory management problems too:
  - Programs don’t free memory when they are done with it
  - Programs allocate memory and then access beyond its end
  - Programs access memory after they have freed it
- Idea: Most people don’t actually need all this power!
  - Provide a simplified memory management abstraction that makes it much easier to implement correct programs
**Higher-Level Language Facilities**

- Starting to enter realm of higher-level languages
- Much safer programming models:
  - Easier to write correct programs
  - Fewer potential security holes!
- Much greater abstracting capabilities
  - Greater modularity, encapsulation, code reuse
- Also requires much larger run-time support for various facilities
  - Usually slower than C/C++ programs, but much safer!
In next few lectures, will explore three language features:

- Implicit allocators and garbage collection
- The object-oriented programming model
- Exception handling

Specifically, how to map these features to C, x86
- Taking another step up the abstraction hierarchy...

Examples will draw from Java language features
- A higher level language than C, with C-like syntax
- (Not a huge step up the abstraction hierarchy...)
- Includes all of the above language features
- Itself implemented in C/C++ and assembly language
Implicit Heap Allocators

- Explicit heap allocators rely on the program to release memory when no longer in use
  - *but programs are notoriously bad at this…*
- A first step towards better programs:
  - Implicit allocators assume the responsibility for identifying when a program is finished with memory
  - Employ a process called garbage collection to identify when a memory block is no longer used by a program
- Use of an implicit allocator eliminates many memory management issues for programs
  - Incurs additional overhead for performing garbage collection
  - (A few other issues as well, all relatively minor)
Reachability Graph

- Garbage collectors are often built on the concept of a reachability graph
- Some allocated nodes are root nodes
  - Referenced from global environment, or stored on the stack
- All nodes reachable from the root nodes are live
- Unreachable nodes are garbage
  - May be reclaimed by allocator and reused for subsequent allocations
- How to determine this reachability graph?
Implicit Allocators and Pointers

- What about performing garbage collection in a language like C or C++?
- With such languages, garbage collection can be very difficult.
- Unfortunately, C/C++ allows:
  - Pointers into the middle of memory blocks
  - Pointers into the middle of structs and arrays
  - Recasting pointers into pointers of other types
  - Recasting pointers into integers and vice-versa
  - All kinds of crazy pointer arithmetic!
- Makes it very difficult to build an accurate reachability graph in a C/C++ run-time system.
CONSERVATIVE GARBAGE COLLECTORS

- In languages like C and C++:
  - Garbage collector attempts to identify any value that “looks like” a pointer
    - References a memory location that is currently valid
    - Assume this is a pointer to memory that is in use
  - If the value isn’t actually a pointer?
    - Only real drawback is that the garbage-collector thinks memory is in use, when it really isn’t in use
    - (Hopefully) doesn’t happen often enough to be a problem

- Conservative garbage collection:
  - All reachable blocks are identified as reachable
  - Some unreachable blocks are also identified as reachable
  - Not all garbage is reclaimed. But we can live with that.
Precise Garbage Collectors

- Another approach is to *strictly control* how programs can use and manipulate pointers
  - Specify rules on casting pointers, and disallow casting to/from non-pointer types
  - Completely forbid pointer arithmetic!
- Allows *precise* garbage collection
  - Garbage collector can determine the reachability graph *exactly*, for all memory blocks in the heap
  - All garbage can be reclaimed by the allocator
- Given other issues with pointer manipulation (e.g. buffer overflows), *makes tons of sense* to constrain pointers this way!!!
Like many higher-level languages, Java includes references.

A “reference” is simply a means for looking up and accessing a particular object:
- A pointer is a very primitive kind of reference: it contains the exact memory address of the object.

Introduce a higher-level reference abstraction:
- The reference is opaque to the program!
- Programs can no longer directly access or manipulate the memory address associated with a reference.
- (The reference’s type can also only be manipulated in very specific, controlled ways.)
- Gives the run-time system much greater flexibility in managing memory (e.g. moving allocated blocks).
INDIRECTION

- **Indirection** is a very important technique used in computer system design
  - The ability to reference something using a name or other value that represents the *actual* value
- Have already seen this technique multiple times
  - e.g. “branch to register,” labels as jump-targets in code, using pointers to access values, jump tables, ...
- References allow programs to *indirectly* access objects, while the runtime directly accesses them
- “All problems in computer science can be solved by another level of indirection.”
  - David Wheeler, inventor of the subroutine
Garbage Collection Algorithms

- Variety of algorithms used for garbage collection
- Simplest algorithm is called “mark and sweep”
- Every object has a flag associated with it
- Initially: all flags are 0
- Two phases:
  - First phase involves traversing entire object graph, marking all reachable objects
  - Second phase involves removing all unreachable objects
Mark-and-Sweep (1)

- Start by marking root nodes as reachable
- (Note: would implement marking phase as depth-first traversal, not breadth-first...)

```
root nodes
1
1
1
```

```
0
0
0
```

```
0
```

```
0
0
0
```

```
0
0
0
```

```
0
0
0
```
Mark-and-Sweep (2)

- Next, nodes reachable from root nodes
Mark-and-Sweep (3)

- Continue until all reachable nodes are marked.
- Now, any node with a 0 is unreachable, and may be reclaimed.
Mark-and-Sweep (4)

- Second phase:
  - If object is unreachable, reclaim it.
  - (If object is reachable, reset flag to 0 for next time.)
MARK-AND-SWEEP (5)

- Final result:
Mark-and-Sweep Characteristics

- This GC algorithm has several drawbacks
- Most important one:
  - To ensure that all garbage is identified, the program cannot run while the garbage collector is working!
  - Even on a multicore system, program and GC cannot run concurrently
- This is called a “stop-the-world” garbage collector
  - Entire program must be suspended while garbage collection is performed
- Clearly unacceptable for applications where response-time is critical
  - e.g. real-time applications, interactive applications
GARBAGE COLLECTOR CHARACTERISTICS

- Several kinds of garbage collector characteristics
- **Stop-the-world GC vs. concurrent GC**
  - Stop-the-world garbage collectors must suspend the program while performing garbage collection
  - Concurrent garbage collectors work in the background, while the program continues to run
    - Algorithm may also require “stop-the-world” phases, but they are kept as short as possible
    - Frequently, the “stop-the-world” phases are parallelized to minimize wait-time
- **Serial GC vs. Parallel GC**
  - Serial garbage collectors are not able to use multiple processors during GC phases
  - Parallel collectors are able to employ multiple processors to speed up collection phases
GC Characteristics (2)

- **Compacting GC vs. non-compacting GC**
  - Non-compacting collectors do nothing with the remaining live objects
    - This is the only real option for languages that allow programs to use explicit pointers into memory
    - Memory fragmentation can become a big problem!
  - Compacting garbage collectors move remaining live objects together, maximizing size of free space
  - Only possible to compact memory if language doesn’t expose explicit pointers to programs!
    - Another reason to only expose opaque references
Mark-and-Sweep Characteristics (2)

- In what situations is mark-and-sweep garbage collection the least expensive?
  - (Compacting mark-and-sweep, in particular?)

- If most objects are not reclaimed, mark-and-sweep will be relatively inexpensive
  - Mark phase always touches all objects, regardless...
  - Sweep phase will have to do less work if most objects don’t need reclaimed
  - Particularly true if GC must also compact memory!
**Other GC Strategies**

- Mark-and-sweep garbage collection must do a lot of work if many objects are deleted during sweep:
  - Must deallocate each garbage object individually (this overhead definitely adds up)
  - Must compact live objects to avoid fragmentation
- Mark-and-sweep prefers long-living objects 😊
- Another strategy: Copying garbage collectors
  - Instead of compacting live objects together, live objects are all copied (“evacuated”) to another, contiguous region of memory
  - Compaction is performed automatically!
  - All dead objects can be deallocated in one operation!
Stop-and-copy garbage collectors divide memory into two regions: “from-space” and “to-space”

- New objects are allocated in the to-space
- When to-space becomes full, it becomes the “from-space,” and vice versa:
  - Starting with root objects, all reachable objects are copied from from-space into to-space
  - At end, entire from-space can be reclaimed at once
- Program resumes execution, using new to-space
- Automatically compacts live objects, but also effectively halves memory available to programs
STOP-AND-COPY EXAMPLE

- Memory divided into from-space and to-space
- New objects are allocated in the to-space, until it becomes full
- Program is stopped; starting with root objects, reachable objects are copied to new to-space
- At end, entire from-space is reclaimed
STOP-AND-COPY GC

- Stop-and-copy garbage collection is fast when:
  - Not a lot of objects live through the GC phase!
  - The fewer objects you have to copy, the better.
- Stop-and-copy prefers short-lived objects 😊
- Observation: Different garbage collection algorithms are best for different situations...
- Questions:
  - Do all heap-allocated objects behave “the same” with respect to garbage collection?
  - Are there differences that we can take advantage of?
GENERATIONAL GARBAGE COLLECTION

- Some empirical observations about programs:
  - Most objects in a program are very short-lived
    - e.g. used for local variables, intermediate results, etc.
    - “Most objects die young.”
  - Longer-lived objects generally do not reference shorter-lived ones

- These ideas called the *generational hypothesis*
  - (Also “infant mortality,” but that’s just macabre.)

- Idea:
  - Design a garbage collector that takes advantage of this behavioral characteristic of OO program state
  - Called *generational garbage collection*
  - Optimization: “Make the common case fast.”
### Sun Hot-Spot Generational GC

- Sun Java VMs implement generational garbage collection
- Divides objects into “young objects,” “old objects”
- Young objects kept in a separate memory area
  - Uses stop-and-copy GC, since most will not live long
  - Three memory areas: Eden, and two survivor spaces
- Newest objects are allocated in Eden
  - Most never make it out alive...
- If new objects survive the first GC pass, moved into to-space

![Diagram of memory areas]

* Eden
  - Objects marked for garbage collection
  - New objects are allocated here

* From-space
  - Contains objects that are not yet eligible for garbage collection
  - Objects will be copied to here if they survive GC

* To-space
  - Objects that survived the GC pass are moved here
  - New objects are allocated in Eden

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¢ Newest objects are allocated in Eden
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Sun Hot-Spot Generational GC (2)

- Survivor spaces for slightly older “young objects”
  - Give young objects “additional chances to die” before they are considered “old objects”
- As before, when to-space fills up, turn into from-space, and perform stop-and-copy GC
- An important difference:
  - Objects considered “old enough” are promoted from from-space into “old generation” memory
Sun Hot-Spot Generational GC (3)

- After young-object garbage collection, both Eden and the from-space are now empty
  - Objects have either been reclaimed, or copied to another memory area

- Two benefits of stop-and-copy GC here:
  - Most objects die, so GC is fast
  - Allocating new objects also fast

```
Eden

<table>
<thead>
<tr>
<th>to-space</th>
<th>from-space</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

old generation
```


Finally, old generation also needs periodic GC
Most of these objects are expected to survive...
  • Stop-and-copy garbage collection is not appropriate!
Old generation is managed with a compacting mark-and-sweep algorithm
  • A concurrent implementation that minimizes “stop-the-world” pauses
Generational Garbage Collection

- Generational garbage collection is very complex!
- Takes advantage of two important details:
  - Different garbage collection algorithms are good in different situations
  - Program state tends to fall into two major categories: young, short-lived objects, and old, long-lived objects
- Provides a much more effective garbage collection system than the individual GC algorithms could possibly provide on their own!
GENERAL-PURPOSE SOLUTIONS

- Another very important system-design pattern: creating general solutions from specialized ones
- Can frequently solve a problem in multiple ways
  - e.g. mark-and-sweep GC vs. stop-and-copy GC
  - Each solution works well in different situations
- We want our computers to be general-purpose...
- We want our operating systems to support a wide range of program behaviors and usage scenarios
- The most powerful, generic solutions frequently blend multiple techniques in a very elegant way
  - Generational garbage collection is a great example!
  - This is a common theme in computer system design
Some implicit allocators are based on reference counting, instead of on a reachability graph.

Each object keeps a reference count:
- A simple integer count of how many other objects reference the object.

When code first references an object, its reference-count is automatically incremented.

When code finishes working with the object, its reference count is automatically decremented.

When an object’s reference count hits zero, it is automatically reclaimed:
- Instead of periodic, complicated garbage-collection sweeps, objects are immediately reclaimed.
REFERENCE COUNTING AND CYCLES

- Major drawback of reference counting:
  - Cannot properly release cycles of objects!
- Our earlier example:
  - All objects have a nonzero reference-count...
  - ...but some of the objects are unreachable!
- Despite this limitation, many systems still use reference-counting for automatically freeing objects
  - e.g. the Python runtime
Several techniques for dealing with cycles

Cycle detection algorithms
- Use more standard reachability-graph techniques to detect and reclaim cycles
- Since it’s only needed for a subset of objects, won’t have a heavy impact
- Approaches usually focus on identifying objects that could be part of a cycle, and starting from there

More complex allocator, but keeps the coder’s life simpler!
Another approach: weak references

- Simply don’t allow cycles in reference graph
- When objects need to refer to each other, one object uses a weak reference
  - Doesn’t increment target object’s reference count
  - Target of a weak reference may go away unexpectedly

Properly breaks cycles...

Programmer must design the program to use weak references properly

- Can be very difficult to get this correct!
Ref-Counting, Garbage Collection

- Other drawbacks with reference counting
  - Cost of incrementing and decrementing reference-counts really adds up
  - Languages with garbage collection don’t incur this overhead
  - Some ways to optimize away reference-count updates

- Nonetheless, still quite a common approach
  - Easy to implement!
SUMMARY

- Implicit allocators allow us to eliminate many memory management issues
  - Provide a simplified abstraction to programs
- Programs allocate memory, but implicit allocator uses garbage collection to determine when to free
  - e.g. mark and sweep, stop and copy
  - More advanced allocators blend these techniques to create very powerful, general-purpose approaches, e.g. generational garbage collection
- Many languages replace pointers with references
  - Program indirectly references objects, while runtime can still directly access and manipulate them
  - Eliminates many other kinds of serious security bugs!