Lecture #37

Today: A little side excursion into nitty-gritty stuff: Storage management.
Scope and Lifetime

- **Scope** of a declaration is portion of program text to which it applies (is *visible*).
  - Need not be contiguous.
  - In Java, is static: independent of data.

- **Lifetime** or *extent* of storage is portion of program execution during which it exists.
  - Always contiguous
  - Generally dynamic: depends on data

- Classes of extent:
  - *Static*: entire duration of program
  - *Local* or *automatic*: duration of call or block execution (local variable)
  - *Dynamic*: From time of allocation statement (*new*) to deallocation, if any.
Explicit vs. Automatic Freeing

- Java has no explicit means to free dynamic storage.
- However, when no expression in any thread can possibly be influenced by or change an object, it might as well not exist:

```java
IntList wasteful() {
    IntList c = new IntList(3, new IntList(4, null));
    return c.tail;
    // variable c now deallocated, so no way
    // to get to first cell of list
}
```

- At this point, Java runtime, like Scheme’s, recycles the object c pointed to: garbage collection.
Under the Hood: Allocation

- Java pointers (references) are represented as integer addresses.
- Corresponds to machine’s own practice.
- In Java, cannot convert integers ↔ pointers,
- But crucial parts of Java runtime implemented in C, or sometimes machine code, where you can.
- Crude allocator in C:

```c
char store[STORAGE_SIZE]; // Allocated array
size_t remainder = STORAGE_SIZE;

/** A pointer to a block of at least N bytes of storage */
void* simpleAlloc(size_t n) { // void*: pointer to anything
    if (n > remainder) ERROR();
    remainder = (remainder - n) & ~0x7; // Make multiple of 8
    return (void*) (store + remainder);
}
```
Example of Storage Layout: Unix

- OS gives way to turn chunks of unallocated region into heap.
- Happens automatically for stack.
Explicit Deallocating

- C/C++ normally require explicit deallocation, because of
  - Lack of run-time information about what is array
  - Possibility of converting pointers to integers.
  - Lack of run-time information about unions:

        union Various {
            int Int;
            char* Pntr;
            double Double;
        } X; // X is either an int, char*, or double

- Java avoids all three problems; automatic collection possible.

- Explicit freeing can be somewhat faster, but rather error-prone:
  - Memory corruption
  - Memory leaks
Free Lists

- Explicit allocator grabs chunks of storage from OS and gives to applications.
- Or gives recycled storage, when available.
- When storage is freed, added to a *free list* data structure to be recycled.
- Used both for explicit freeing and some kinds of automatic garbage collection.
Free List Strategies

- Memory requests generally come in multiple sizes.
- Not all chunks on the free list are big enough, and one may have to search for a chunk and break it up if too big.
- Various strategies to find a chunk that fits have been used:
  - **Sequential fits:**
    - Link blocks in LIFO or FIFO order, or sorted by address.
    - Coalesce adjacent blocks.
    - Search for *first fit* on list, *best fit* on list, or *next fit* on list after last-chosen chunk.
  - **Segregated fits:** separate free lists for different chunk sizes.
  - **Buddy systems:** A kind of segregated fit where some newly adjacent free blocks of one size are easily detected and combined into bigger chunks.
- Coalescing blocks reduces *fragmentation* of memory into lots of little scattered chunks.
Garbage Collection: Reference Counting

- Idea: Keep count of number of pointers to each object. Release when count goes to 0.

```
Y: □
X: □ → 1 □ → 1 □ → 1 □
    |                      |
    v                      v
1 A → 1 B → 1 C

X = Y;

Y: □
X: □ → 0 □ → 3 □ → 1 □
    |                      |
    v                      v
1 A → 1 B → 1 C

Y = X.tail;

Y: □
X: □ → 1 □ → 2 □ → 1 □
    |                      |
    v                      v
1 A → 1 B → 1 C

Y: □
X: □ → 2 □ → 1 □
    |                      |
    v                      v
0 A → 1 B → 1 C

... etc., until:

Y: □
X: □ → 2 □ → 1 □
    |                      |
    v                      v
2 → 1
Garbage Collection: Mark and Sweep

Roots (locals + statics)

1. Traverse and mark graph of objects.
2. Sweep through memory, freeing unmarked objects.

Before sweep:

<table>
<thead>
<tr>
<th>A</th>
<th>B*</th>
<th>C</th>
<th>D</th>
<th>G</th>
<th>F</th>
<th>A</th>
<th>D*</th>
<th>E*</th>
<th>F</th>
<th>C</th>
<th>G*</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td></td>
<td>D</td>
<td>G</td>
<td>F</td>
<td>A</td>
<td></td>
<td>7</td>
<td>G</td>
<td>D</td>
<td></td>
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</tbody>
</table>

After sweep:

<table>
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<th>G</th>
<th>D</th>
<th>G</th>
<th>7</th>
<th>G</th>
<th>D</th>
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Cost of Mark-and-Sweep

- Mark-and-sweep algorithms don't move any existing objects—pointers stay the same.
- The total amount of work depends on the amount of memory swept—i.e., the total amount of active (non-garbage) storage + amount of garbage. Not necessarily a big hit: the garbage had to be active at one time, and hence there was always some “good” processing in the past for each byte of garbage scanned.
Copying Garbage Collection

• Another approach: *copying garbage collection* takes time proportional to amount of active storage:

  - Traverse the graph of active objects breadth first, *copying* them into a large contiguous area (called “to-space”).
  - As you copy each object, mark it and put a *forwarding pointer* into it that points to where you copied it.
  - The next time you have to copy an already marked object, just use its forwarding pointer instead.
  - When done, the space you copied from (“from-space”) becomes the next to-space; in effect, all its objects are freed in constant time.
**Copying Garbage Collection Illustrated**

(a) **Roots**
- **from:**
  - B
  - 5
  - E
- **to:**

(b) **Roots**
- **from:**
  - B
  - 5
  - E
- **to:**

(c) **Roots**
- **from:**
  - B
  - 5
  - E
- **to:**

(d) **Roots**
- **from:**
  - B
  - 5
  - E
- **to:**

**B**: Old object  
**B’**: New object  
*: marked  

---

(a) **forwarding pointers**

(b) **Copy roots**

(c) **Copy from to-space in (b). Only D is new**

(d) **Copy from to-space in (c). No new objects**

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Most Objects Die Young: Generational Collection

- Most older objects stay active, and need not be collected.
- Would be nice to avoid copying them over and over.
- *Generational garbage collection* schemes have two (or more) from spaces: one for newly created objects (*new space*) and one for “tenured” objects that have survived garbage collection (*old space*).
- A typical garbage collection collects only in new space, ignores pointers from new to old space, and moves objects to old space.
- As roots, uses usual roots plus pointers in old space that have changed (so that they might be pointing to new space).
- When old space full, collect all spaces.
- This approach leads to much smaller *pause times* in interactive systems.
There's Much More

- These are just highlights.
- Lots of work on how to implement these ideas efficiently.
- *Distributed garbage collection:* What if objects scattered over many machines?
- *Real-time collection:* where predictable pause times are important, leads to *incremental* collection, doing a little at a time.