EECS 390 – Lecture 12

Memory Management

3/6/24

Agenda

- Storage Duration
- RAII and Scope-Based Resource Management
- Garbage Collection

Static Storage

- Variables at global, namespace, or static class scope can be accessed at any time, so the associated object's lifetime must span the whole program
- Compiler/linker can determine which objects have static storage duration, so they are often placed in a special ***data segment***
- C and C++ allow local variables to have static storage duration with the `static` keyword
- In some languages, initialization of static objects may be deferred until first use

Automatic Storage

- Non-static local variables come into existence upon entry to their function or block
- Stored inside ***activation record*** or ***frame*** for the block
- Frame created when block is entered, destroyed upon final exit from block

```
void foo(int x) {
  int y = x * x;
  if (y < 100) {
    int z = 100 - y;
    cout << z << endl;
  }
  cout << y << endl;
}
```

Stack-Based Memory Management

- In many languages, activation records are stored on a stack
  - Upon creation, frame pushed onto stack
  - Upon final exit, frame popped from stack
- Cannot be used in languages with full support for nested function definitions
  - Static (lexical) scope requires access to definition environment even after associated function exits

```
def foo(x):
    def bar(y):
        return x + y
    return bar

fn = foo(3)
fn(4)
```

Dynamic Storage

- Objects that are not tied to a specific scope have ***dynamic*** storage duration
  - Compiler cannot deduce lifetime from code
- Usually created explicitly by programmer
  - Examples: `malloc(4 * sizeof int)`, `new int[4]`
- Dynamic objects cannot be placed on stack, since their lifetime can exceed that of the block where they are created
- Instead, a special structure called a ***heap*** is used to store dynamic objects

Managing Dynamic Storage

- Language runtime must provide heap management
  - Find free space when dynamic object is allocated, manage free space when objects are deallocated
- Objects must be reclaimed when they are no longer in use
- User-level management: explicit calls to `free()`, `delete`
- Automatic memory management: garbage collection
  - More on this later

Internal Resources

- A data abstraction may have its own internal resources that it manages
- Example: vector
  - Allocates storage space upon construction
  - Upon insertion, if space is exhausted, allocates larger space, moves items, deallocates old storage
- Internal resources are part of the implementation, and the user of an abstraction should not have to manage its internal resources
- Internal memory automatically handled in garbage-collected languages

Dispose Pattern

- Extend the interface of an abstraction to provide functions that must be called when the abstraction is created and when it is no longer needed

- Example:

```
typedef struct { ... } vector;

void vector_init(vector *);
void vector_destroy(vector *);
```

- Relies on user to remember to call both functions at the appropriate times
  - Analogous to `malloc()`, `free()`

Constructors and Destructors

- Initialization functions formalized in object-oriented languages as ***constructors***
- Some languages formalize destruction functions as ***destructors***
  - Garbage-collected languages provide finalizers instead; more on this later
- A language can ensure that a constructor is always called when an object is created, and the destructor when it is destroyed
  - Static objects: upon program start and end
  - Automatic objects: when they go in and out of scope
  - Dynamic objects: when `new` or `delete` is applied to them

In some languages, constructor on first use for static objects.

Resource Acquisition is Initialization (RAII)

- General pattern for resource management using constructors and destructors
  - Also called ***scope-based resource management***

- Example:

```
int main() {
  vector<int> values;
  {
    ifstream input("some_file");
    int x;
    while (input >> x)
      values.push_back(x);
  }
  ...
}
```

Better name would be ***lifetime-based resource management***, since dynamic objects can also manage resources.

Scope-Based Resource Management

- RAII generally does not work for non-memory resources in garbage-collected languages
- Some languages provide specific constructs for scope-based resource management
- Example:

```
with open('some_file') as f:
    values = [int(x) for x in f.read().split()]
```

Garbage Collection

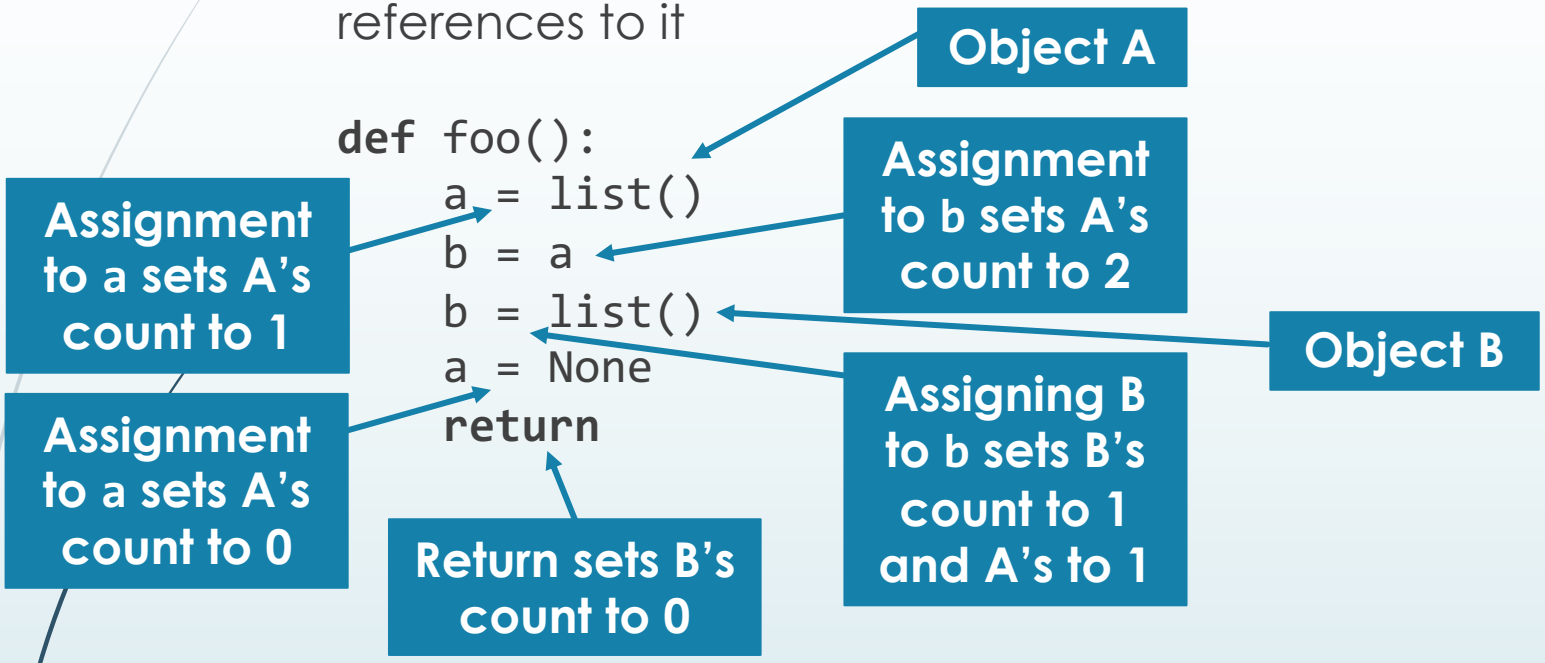
- Languages that provide automatic memory management must implement a means of detecting when objects are no longer in use and collecting them

```
def foo():
    a = list() # object A
    b = a
    b = list() # object B
    a = None   # A no longer in use
    return     # B no longer in use after return
```

- Main types of garbage collection:
  - Reference counting
  - Tracing collectors

Reference Counting

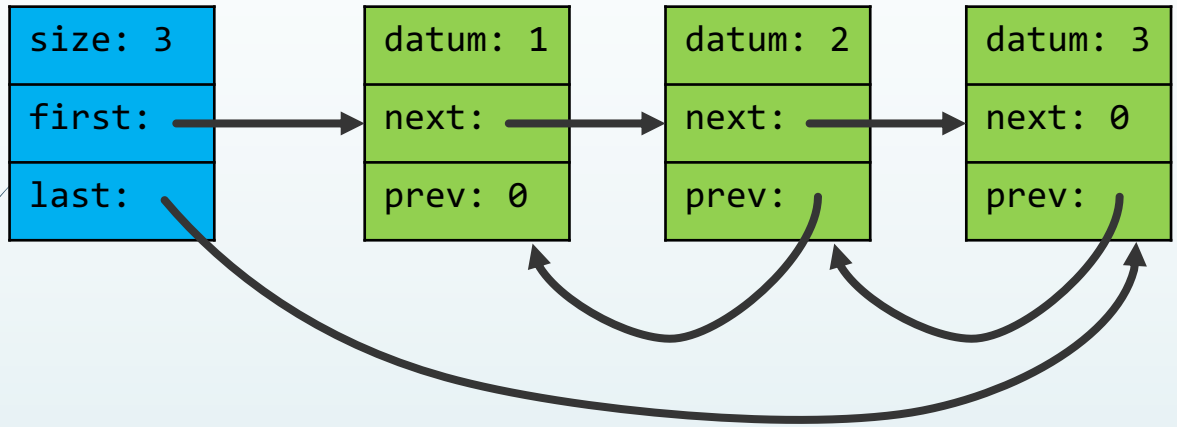
- Each object has a count of the number of pointers or references to it



- When the count of an object reaches 0, it is garbage and is collected

Circular References

- Reference counting fails to detect garbage with circular references



- Implementations such as CPython include cycle detection algorithms
- Languages also might provide ***weak pointers*** (or references) that do not increment reference count

C++ Smart Pointers

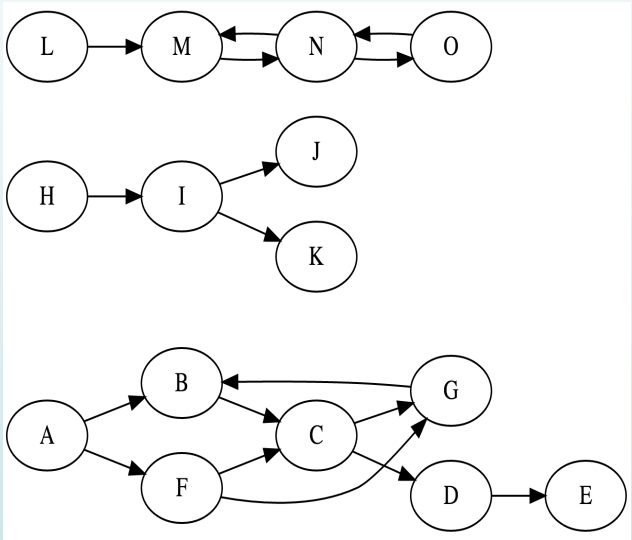
- Pointer-like objects that do reference counting

```
shared_ptr<Object> p1(new Object());
shared_ptr<Object> p2 = p1;  // count is now 2
p1.reset();   // count decremented to 1
p2 = nullptr; // count decremented, object deleted
```

- `shared_ptr`: reference counting pointer, deletes an object when count is 0
- `weak_ptr`: weak pointer that does not increment count
- `unique_ptr`: ensures that only one pointer to an object exists at a time

Tracing Collectors

- Periodic collection
- Start out from ***root set*** of objects
  - Generally those with static and automatic duration[1]
- Recursively follow all pointers/references
- Objects that are reached are live, rest are dead
- ***Mark and sweep***: mark all objects reached during search, then sweep rest
- ***Stop and copy***: copy objects to new locations as they are encountered
  - Need to change pointers



[1]Also thread-local duration for languages with support for it.

Finalizers

- Analogous to destructor, called when an object is about to be collected
  - Java: `finalize()`
  - Python: `__del__()`
- Problems
  - May not be called in a timely manner, particularly with tracing collectors
  - Can lead to object resurrection if a reference to the object is leaked
  - Do not run in a well-defined order
  - Are not guaranteed to run in many implementations