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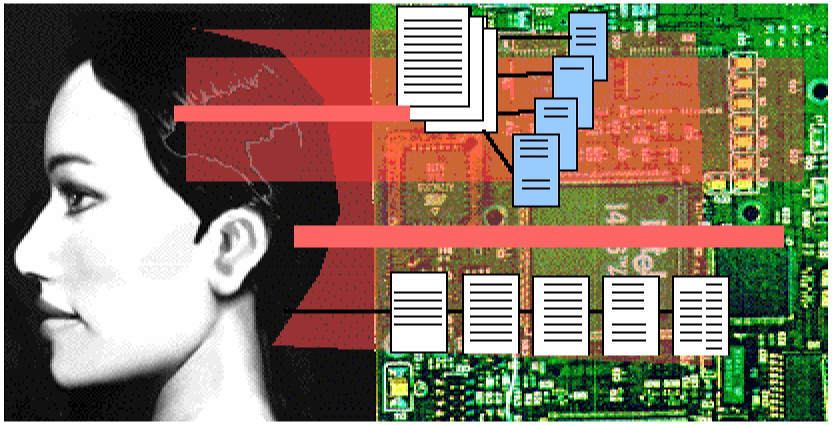
CS61C : Machine Structures

Lecture #6: Memory Management



2006-07-05

Andy Carle

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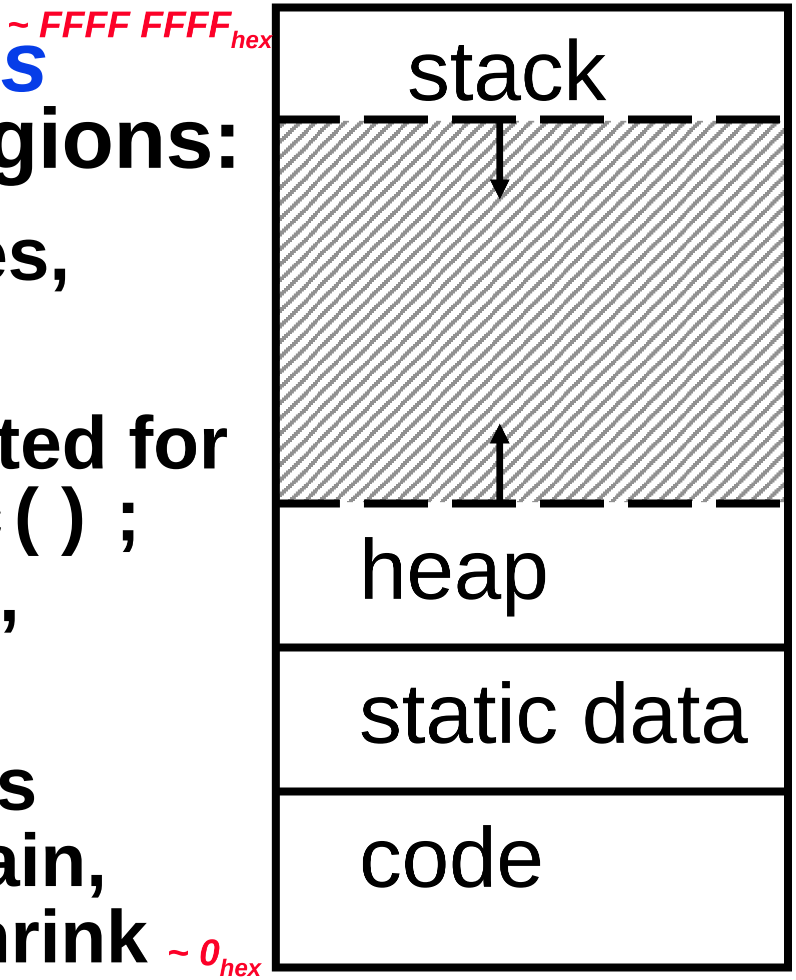
Memory Management (1/2)

- Variable declaration allocates memory
  - outside a procedure -> static storage
  - inside procedure -> stack
    - freed when procedure returns.
- Malloc request
  - Pointer: static or stack
  - Content: on heap

```
int myGlobal;
main() {
 int myTemp;
 int *f=
   malloc(16);
}
```

Memory Management (2/2)

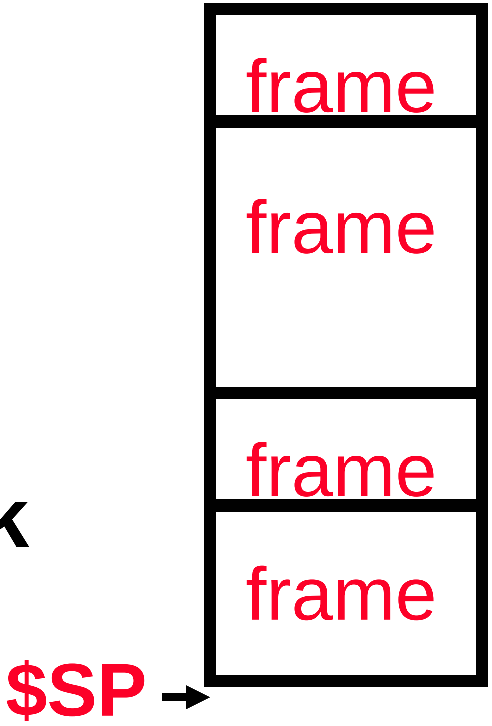
- **A program's *address space* contains 4 regions:**
  - **stack: local variables, grows downward**
  - **heap: space requested for pointers via `malloc()` ; resizes dynamically, grows upward**
  - **static data: variables declared outside main, does not grow or shrink**
  - **code: loaded when program starts, does not change**



For now, OS somehow prevents accesses between stack and heap (gray hash lines). Wait for virtual memory

The Stack (1/4)

- Terminology:
  - Stack is composed of frames
  - A frame corresponds to one procedure invocation
  - Stack frame includes:
    - Return address of caller
    - Space for other local variables
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



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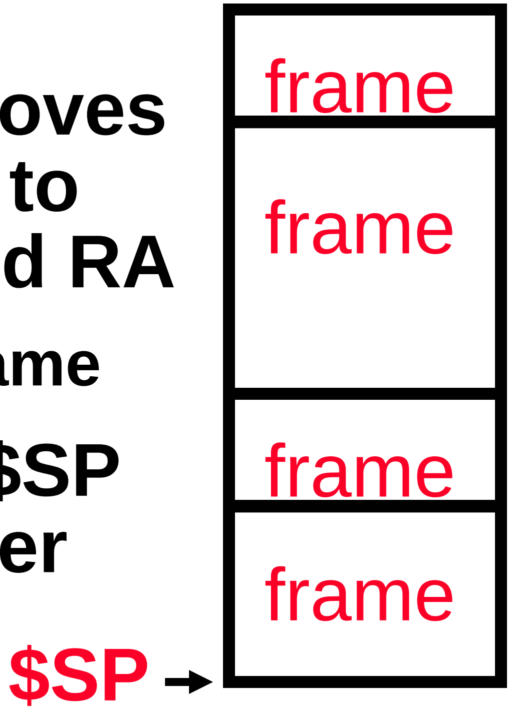
The Stack (2/4)

- **Implementation:**
  - **By convention, stack grows down in memory.**
  - **Stack pointer ($SP) points to next available address**
  - **PUSH: On invocation, callee moves $SP down to create new frame to hold callee's local variables and RA**
    - **(old SP – new SP) ➔ size of frame**
  - **POP: On return, callee moves $SP back to original, returns to caller**



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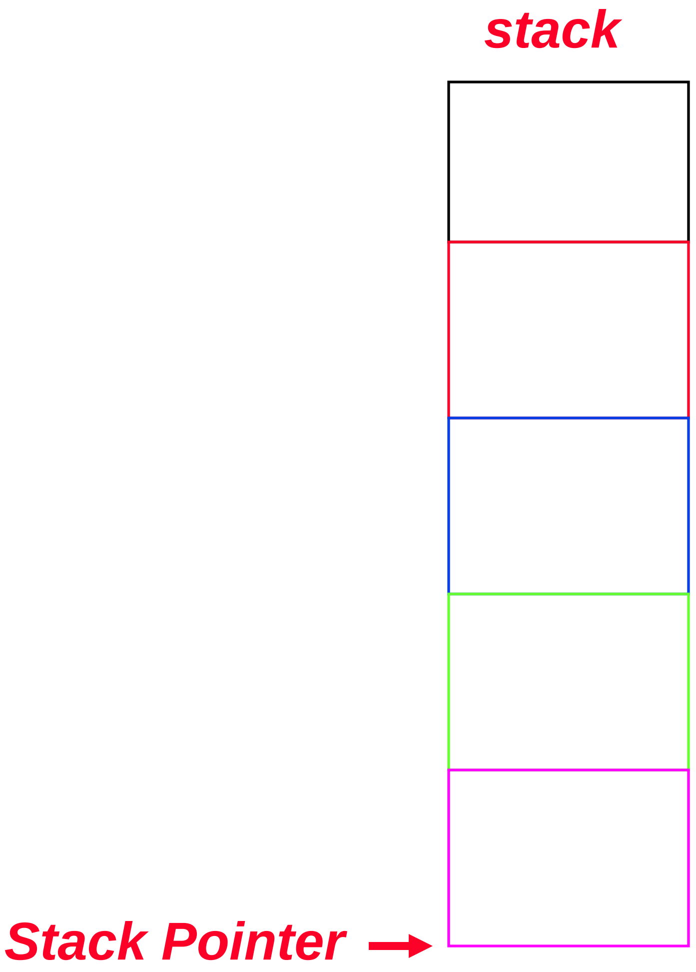
The Stack (3/4)

- **Last In, First Out (LIFO) memory usage**

```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
     void c (int o)
     { d(3);
     }void d (int p)
      {
      }
```



The Stack (4/4): Dangling Pointers

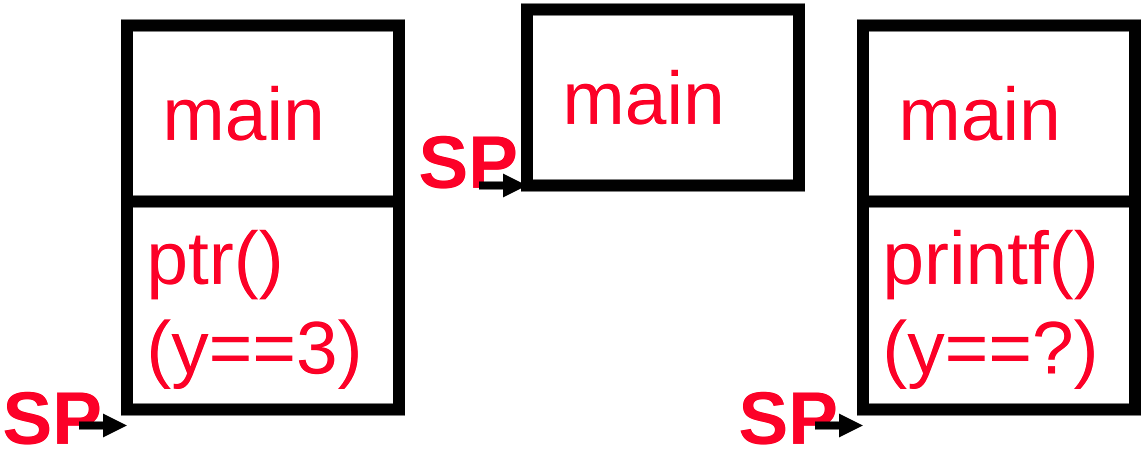
- **Pointers in C allow access to deallocated memory, leading to hard-to-find bugs !**

```
int *ptr () {
   int y;
   y = 3;
   return &y;
 }

main () {
   int *stackAddr;
   stackAddr = ptr();
   printf("%d", *stackAddr); /* 3 */

   printf("%d", *stackAddr); /* XXX */

}
```



Static and Code Segments

- Code (Text Segment)
  - Holds instructions to be executed
  - Constant size
- Static Segment
  - Holds global variables whose addresses are known at compile time
    - Compare to the heap (malloc calls) where address isn't known

The Heap (Dynamic memory)

- Large pool of memory, not allocated in contiguous order
  - back-to-back requests for heap memory could return blocks very far apart
  - where Java `new` command allocates memory
- In C, specify number of bytes of memory explicitly to allocate item

```
int *ptr;
ptr = (int *) malloc(4);
/* malloc returns type (void *),
so need to cast to right type */
```

  - `malloc()`: Allocates raw, uninitialized memory from heap

Memory Management

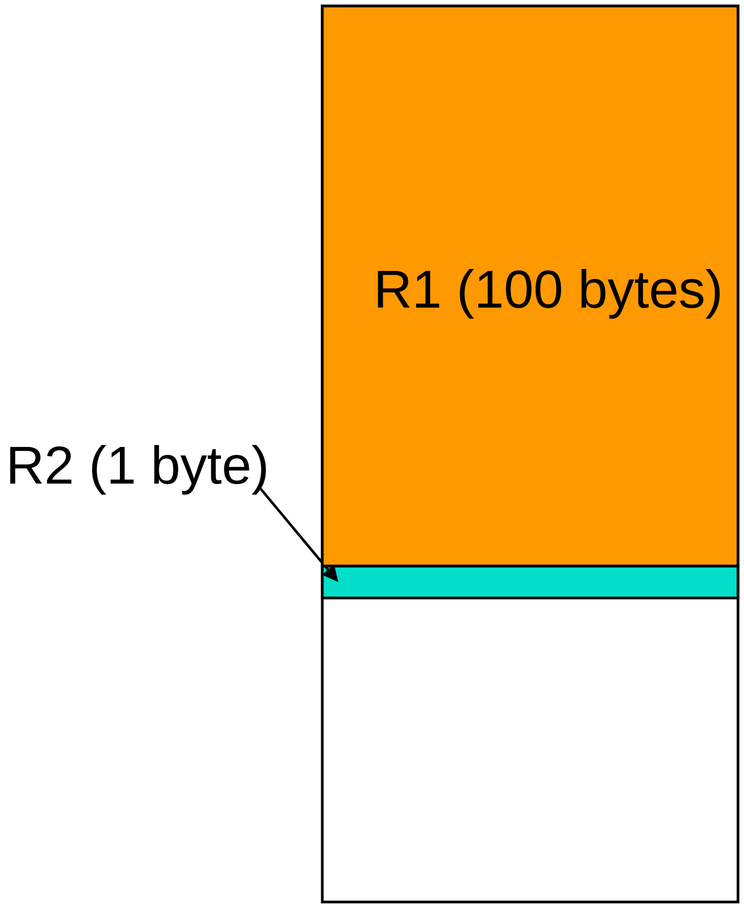
- How do we manage memory?
- Code, Static storage are easy: they never grow or shrink
- Stack space is also easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- Managing the heap is tricky: memory can be allocated / deallocated at any time

Heap Management Requirements

- Want `malloc()` and `free()` to run quickly.
- Want minimal memory overhead
- Want to avoid *fragmentation* – when most of our free memory is in many small chunks
  - In this case, we might have many free bytes but not be able to satisfy a large request since the free bytes are not contiguous in memory.

Heap Management

- An example
  - Request R1 for 100 bytes
  - Request R2 for 1 byte
  - Memory from R1 is freed
  - Request R3 for 50 bytes



Heap Management

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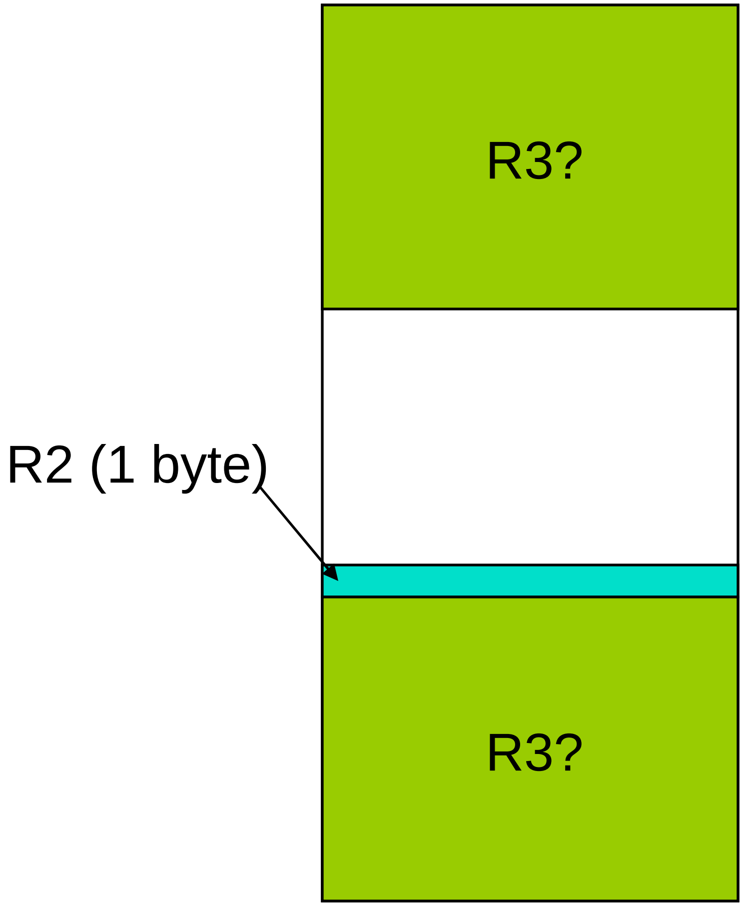

K&R Malloc/Free Implementation

- From Section 8.7 of K&R
  - Code in the book uses some C language features we haven't discussed and is written in a very terse style, don't worry if you can't decipher the code
- Each block of memory is preceded by a header that has two fields:
  size of the block and
  a pointer to the next block
- All free blocks are kept in a linked list, the pointer field is unused in an allocated block

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K&R Implementation

- **`malloc()` searches the free list for a block that is big enough. If none is found, more memory is requested from the operating system.**
- **`free()` checks if the blocks adjacent to the freed block are also free**
  - **If so, adjacent free blocks are merged (coalesced) into a single, larger free block**
  - **Otherwise, the freed block is just added to the free list**

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Choosing a block in `malloc()`

- If there are multiple free blocks of memory that are big enough for some request, how do we choose which one to use?
  - **best-fit**: choose the smallest block that is big enough for the request
  - **first-fit**: choose the first block we see that is big enough
  - **next-fit**: like first-fit but remember where we finished searching and resume searching from there

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PRS Round 1

- A con of first-fit is that it results in many small blocks at the beginning of the free list
- A con of next-fit is it is slower than first-fit, since it takes longer in steady state to find a match
- A con of best-fit is that it leaves lots of tiny blocks

Tradeoffs of allocation policies

- **Best-fit:** Tries to limit fragmentation but at the cost of time (must examine all free blocks for each malloc). Leaves lots of small blocks (why?)
- **First-fit:** Quicker than best-fit (why?) but potentially more fragmentation. Tends to concentrate small blocks at the beginning of the free list (why?)
- **Next-fit:** Does not concentrate small blocks at front like first-fit, should be faster as a result.

Administrivia

- HW2 Due Today
- HW3 Out, Due Monday
- Proj1 Coming Soon

Slab Allocator

- A different approach to memory management (used in GNU `libc`)
- Divide blocks in to “large” and “small” by picking an arbitrary threshold size. Blocks larger than this threshold are managed with a freelist (as before).
- For small blocks, allocate blocks in sizes that are powers of 2
  - e.g., if program wants to allocate 20 bytes, actually give it 32 bytes

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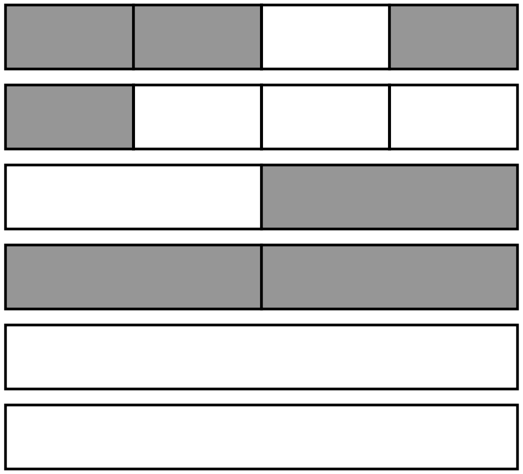
Slab Allocator

- Bookkeeping for small blocks is relatively easy: just use a *bitmap* for each range of blocks of the same size
- Allocating is easy and fast: compute the size of the block to allocate and find a free bit in the corresponding bitmap.
- Freeing is also easy and fast: figure out which slab the address belongs to and clear the corresponding bit.

Slab Allocator



16 byte blocks:

32 byte blocks:

64 byte blocks:

16 byte block bitmap: 11011000

32 byte block bitmap: 0111

64 byte block bitmap: 00

Slab Allocator Tradeoffs

- Extremely fast for small blocks.
- Slower for large blocks
  - But presumably the program will take more time to do something with a large block so the overhead is not as critical.
- Minimal space overhead
- No fragmentation (as we defined it before) for small blocks, but still have wasted space!

Internal vs. External Fragmentation

- **With the slab allocator, difference between requested size and next power of 2 is wasted**
  - **e.g., if program wants to allocate 20 bytes and we give it a 32 byte block, 12 bytes are unused.**
- **We also refer to this as fragmentation, but call it *internal* fragmentation since the wasted space is actually within an allocated block.**
- **External fragmentation: wasted space between allocated blocks.**

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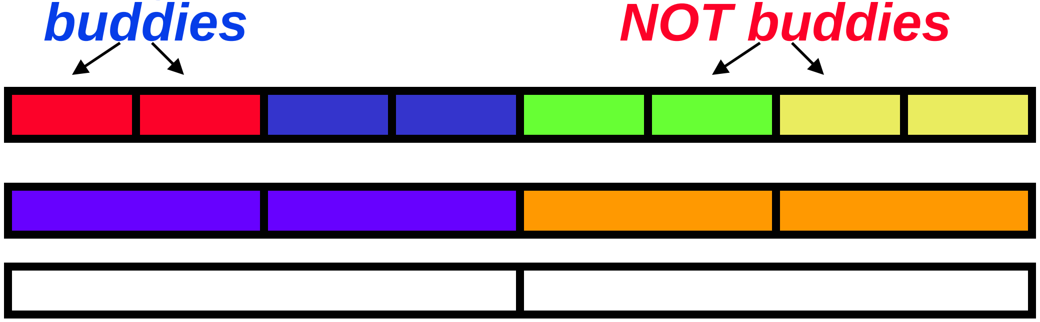
Buddy System

- Yet another memory management technique (used in Linux kernel)
- Like GNU's "slab allocator", but only allocate blocks in sizes that are powers of 2 (internal fragmentation is possible)
- Keep separate free lists for each size
    - e.g., separate free lists for 16 byte, 32 byte, 64 byte blocks, etc.

Buddy System

- If no free block of size n is available, find a block of size 2n and split it in to two blocks of size n
- When a block of size n is freed, if its neighbor of size n is also free, coalesce the blocks in to a single block of size 2n
  - **Buddy** is block in other half larger block



- Same speed advantages as slab allocator

Allocation Schemes

- So which memory management scheme (K&R, slab, buddy) is best?
  - There is no single best approach for every application.
  - Different applications have different allocation / deallocation patterns.
  - A scheme that works well for one application may work poorly for another application.

Automatic Memory Management

- **Dynamically allocated memory is difficult to track – why not track it automatically?**
- **If we can keep track of what memory is in use, we can reclaim everything else.**
  - **Unreachable memory is called *garbage*, the process of reclaiming it is called *garbage collection*.**
- **So how do we track what is in use?**

Tracking Memory Usage

- Techniques depend heavily on the programming language and rely on help from the compiler.
- Start with all pointers in global variables and local variables (root set).
- Recursively examine dynamically allocated objects we see a pointer to.
  - We can do this in constant space by reversing the pointers on the way down
- How do we recursively find pointers in dynamically allocated memory?

Tracking Memory Usage

- Again, it depends heavily on the programming language and compiler.
- Could have only a single type of dynamically allocated object in memory
  - E.g., simple Lisp/Scheme system with only cons cells (61A's Scheme not "simple")
- Could use a *strongly typed* language (e.g., Java)
  - Don't allow conversion (casting) between arbitrary types.
  - C/C++ are not strongly typed.
- Here are 3 schemes to collect garbage

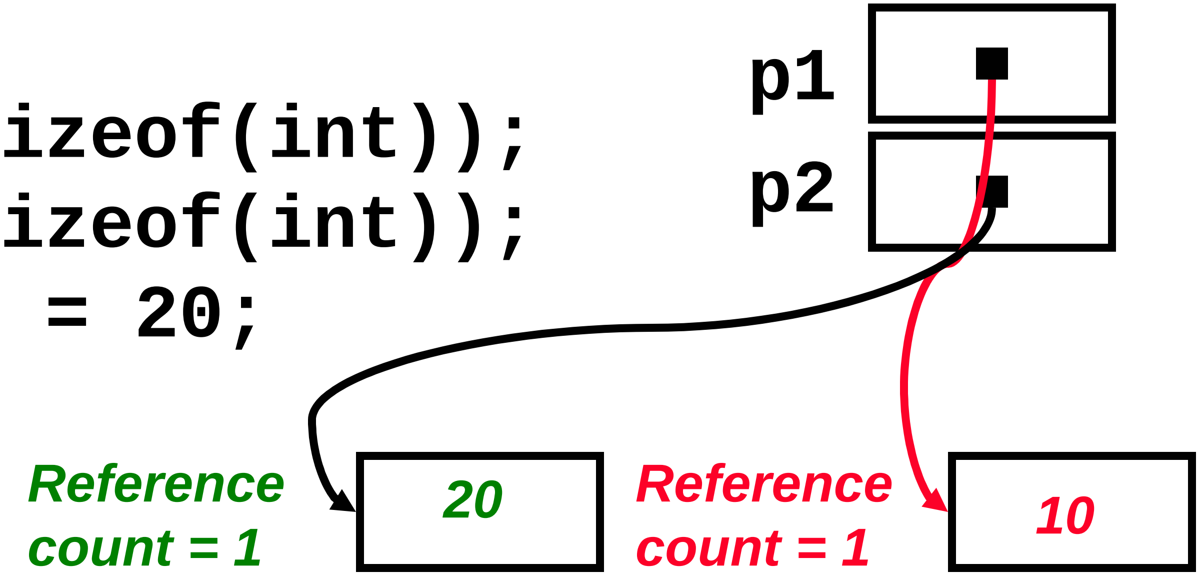
Scheme 1: Reference Counting

- For every chunk of dynamically allocated memory, keep a count of number of pointers that point to it.
- When the count reaches 0, reclaim.
- Simple assignment statements can result in a lot of work, since may update reference counts of many items

Reference Counting Example

- For every chunk of dynamically allocated memory, keep a count of number of pointers that point to it.
  - When the count reaches 0, reclaim.

```
int *p1, *p2;
p1 = malloc(sizeof(int));
p2 = malloc(sizeof(int));
*p1 = 10; *p2 = 20;
```



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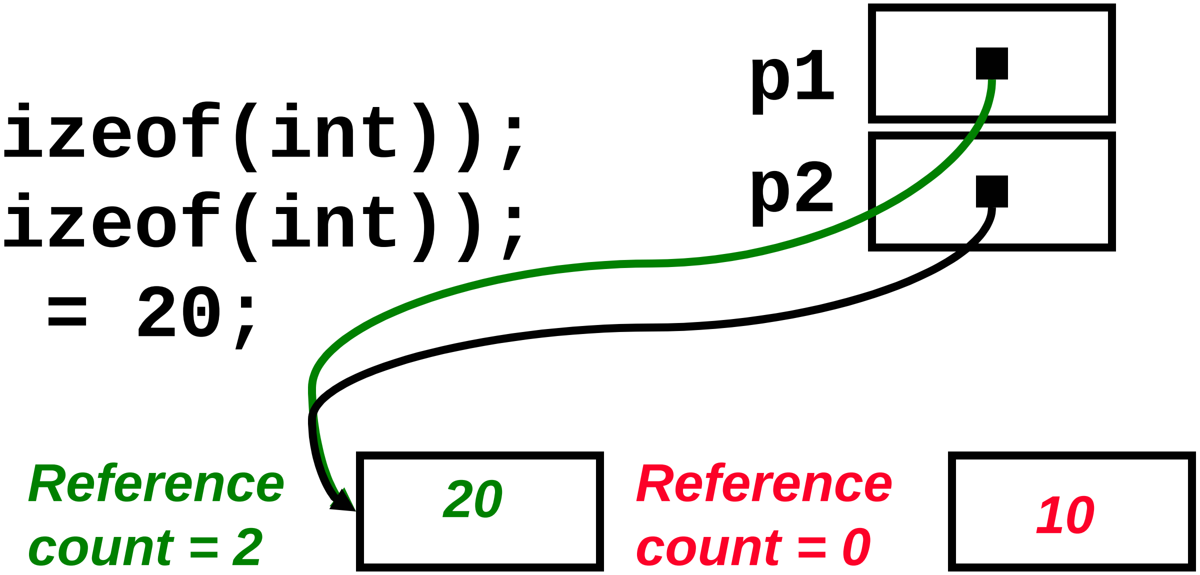

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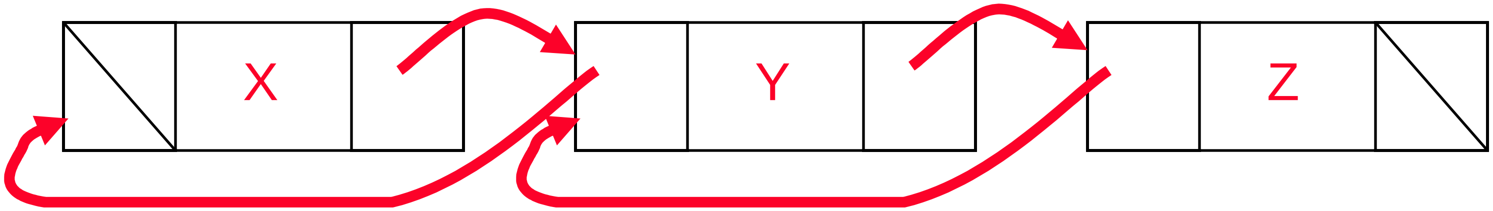
Reference Counting (p1, p2 are pointers)

`p1 = p2;`

- Increment reference count for p2
- If p1 held a valid value, decrement its reference count
- If the reference count for p1 is now 0, reclaim the storage it points to.
  - If the storage pointed to by p1 held other pointers, decrement all of their reference counts, and so on…
- Must also decrement reference count when local variables cease to exist.

Reference Counting Flaws

- Extra overhead added to assignments, as well as ending a block of code.
- Does not work for circular structures!
  - E.g., doubly linked list:



Scheme 2: Mark and Sweep Garbage Col.

- Keep allocating new memory until memory is exhausted, then try to find unused memory.
- Consider objects in heap a graph, chunks of memory (objects) are graph nodes, pointers to memory are graph edges.
  - Edge from A to B => A stores pointer to B
- Can start with the root set, perform a graph traversal, find all usable memory!
- 2 Phases: (1) Mark used nodes;(2) Sweep free ones, returning list of free nodes

Mark and Sweep

- Graph traversal is relatively easy to implement recursively

```
void traverse(struct graph_node *node) {
    /* visit this node */
    foreach child in node->children {
        traverse(child);
    }
}
```

- But with recursion, state is stored on the execution stack.
  - Garbage collection is invoked when not much memory left
- As before, we could traverse in constant space (by reversing pointers)

Scheme 3: Copying Garbage Collection

- Divide memory into two spaces, only one in use at any time.
- When active space is exhausted, traverse the active space, copying all objects to the other space, then make the new space active and continue.
  - Only reachable objects are copied!
- Use “forwarding pointers” to keep consistency
  - Simple solution to avoiding having to have a table of old and new addresses, and to mark objects already copied (see bonus slides)

PRS Round 2

A. Of {K&R, Slab, Buddy}, there is no best (it depends on the problem).

B. Since automatic garbage collection can occur any time, it is more difficult to measure the execution time of a Java program vs. a C program.

C. We don’t have automatic garbage collection in C because of efficiency.

Summary (1/2)

- C has 3 pools of memory
  - Static storage: global variable storage, basically permanent, entire program run
  - The Stack: local variable storage, parameters, return address
  - The Heap (dynamic storage): `malloc()` grabs space from here, `free()` returns it.
- `malloc()` handles free space with freelist. Three different ways to find free space when given a request:
  - First fit (find first one that's free)
  - Next fit (same as first, but remembers where left off)
  - Best fit (finds most "snug" free space)

Summary (2/2)

- Several techniques for managing heap w/ malloc/free: best-, first-, next-fit, slab,buddy
  - 2 types of memory fragmentation: internal & external; all suffer from some kind of frag.
  - Each technique has strengths and weaknesses, none is definitively best
- Automatic memory management relieves programmer from managing memory.
  - All require help from language and compiler
  - Reference Count: not for circular structures
  - Mark and Sweep: complicated and slow, works
  - Copying: move active objects back and forth