CSE 31
Computer Organization

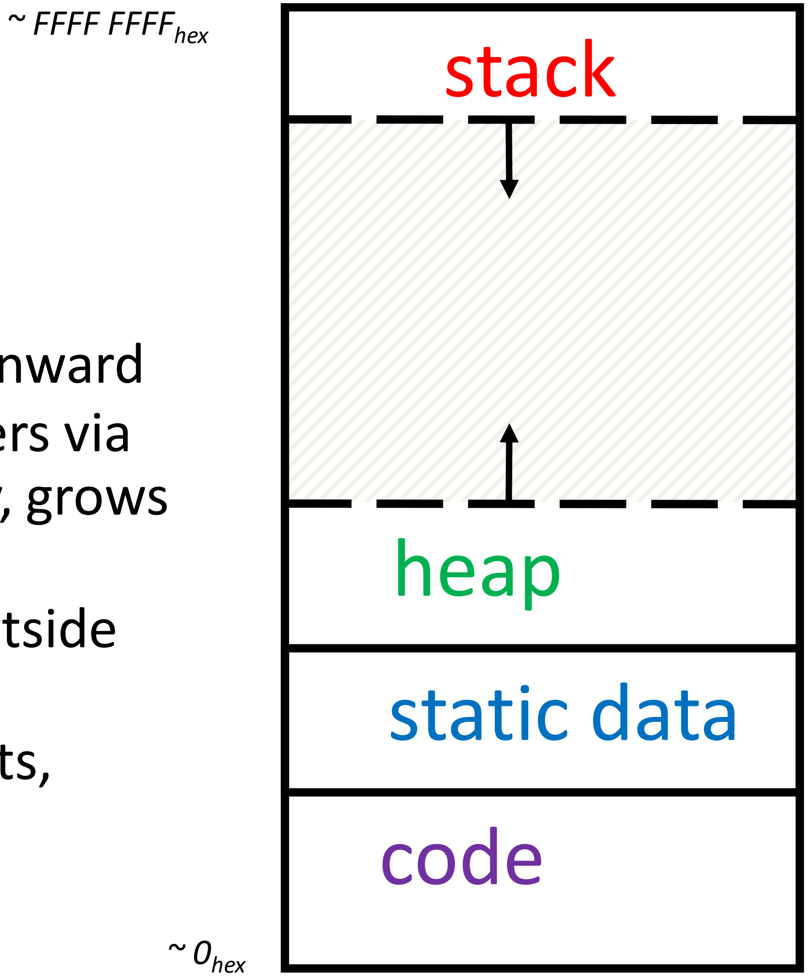
Lecture 5 – C Memory Management (2)

Announcement

- Lab #2 this week
  - Due at 11:59pm on the same day of your next lab
  - You must demo your submission to your TA within 14 days
- Reading assignment
  - Chapter 6, 8.7 of K&R (C book) to review on C/C++ programming

Normal C Memory Management

- 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

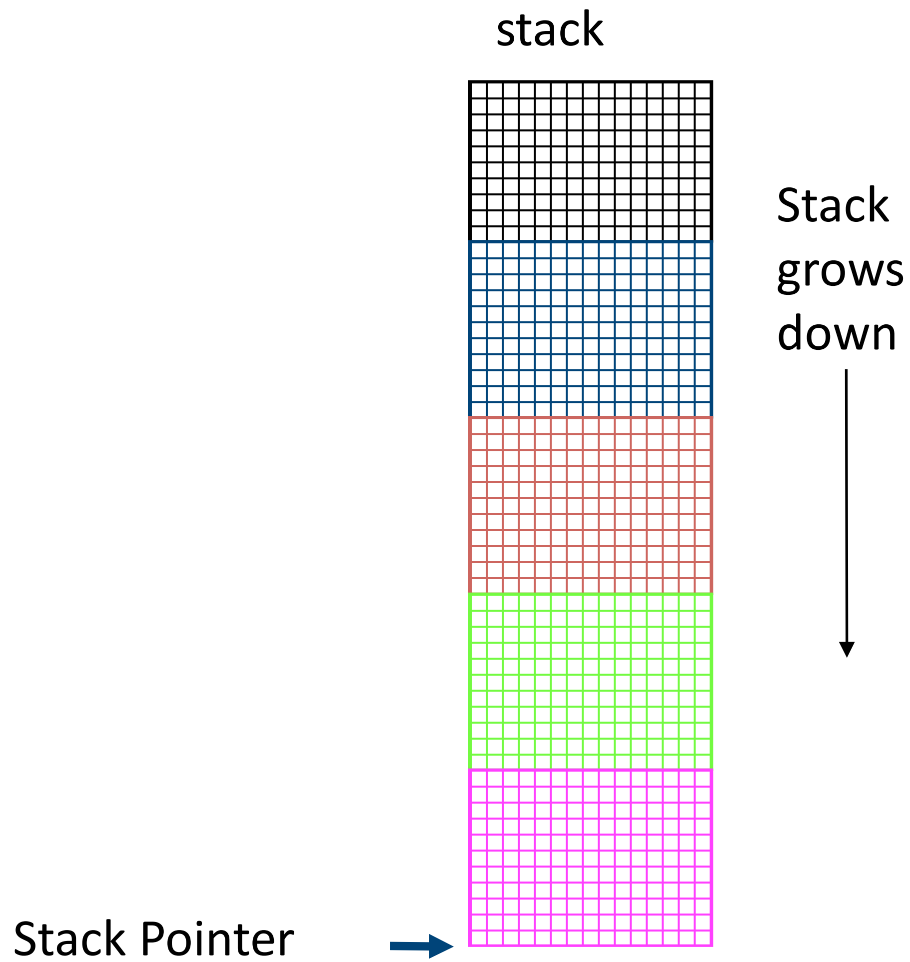


For now, OS somehow prevents accesses between stack and heap (gray hash lines). Wait for virtual memory

Stack

- Last In, First Out (LIFO) data structure

```
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) {
}
```



Stack

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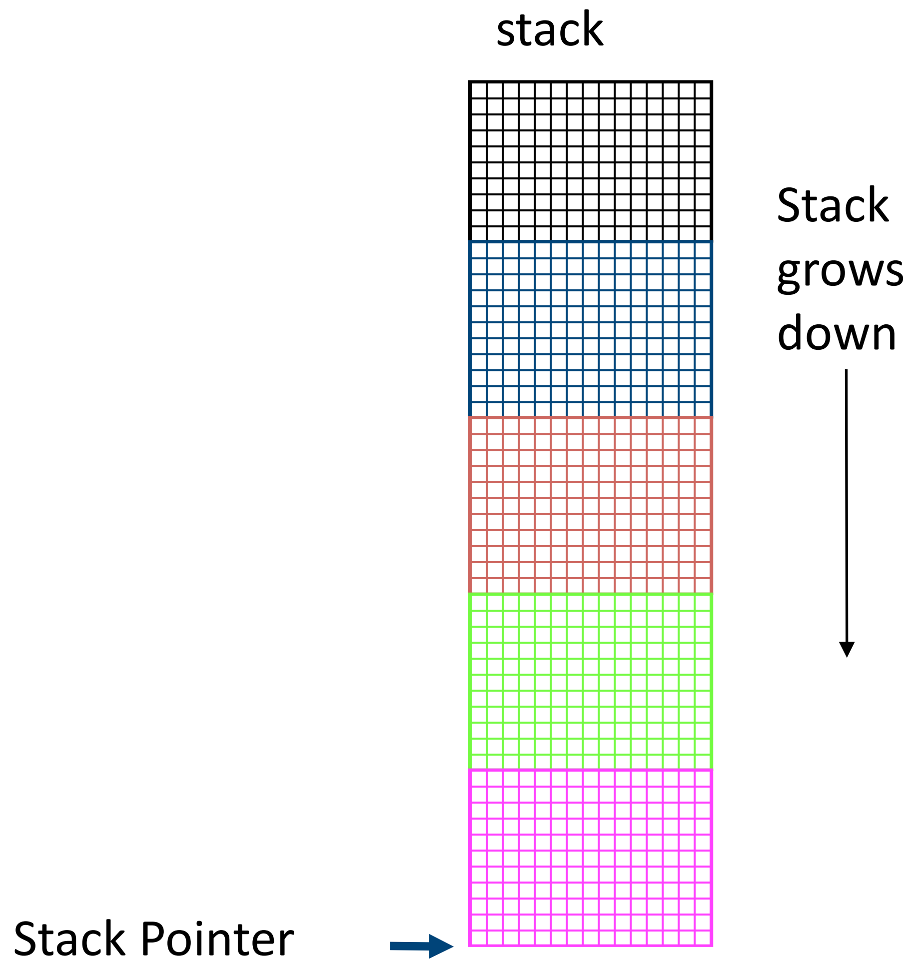
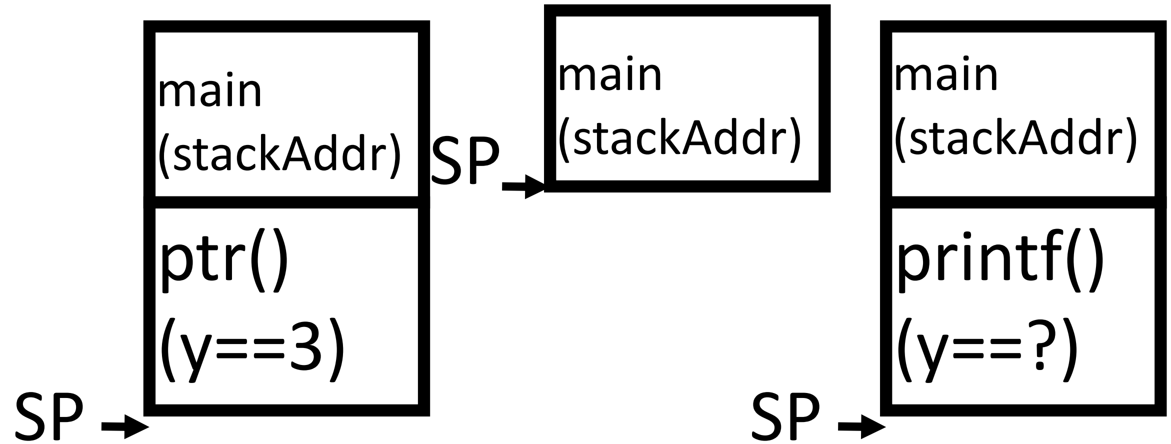


Who cares about stack management?

- 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,content;
        stackAddr = ptr();
        content = *stackAddr;
        printf("%d", content); /* 3 */
        content = *stackAddr;
        printf("%d", content); /*-2*/
};
```

The Heap (Dynamic memory)

- Large pool of memory, <u>not</u> allocated in contiguous order
  - back-to-back requests for heap memory could result blocks very far apart
  - where Java/C++ ***new*** command allocates memory
- In C, specify number of <u>bytes</u> of memory explicitly to allocate item

```
int *ptr;
ptr = (int *) malloc(sizeof(int));
/* 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
    - Simple
    - They never grow or shrink
  - Stack
    - Simple
    - Stack frames are created and destroyed in last-in, first-out (LIFO) order
  - Heap
    - Tricky
    - Memory can be allocated / deallocated at any time

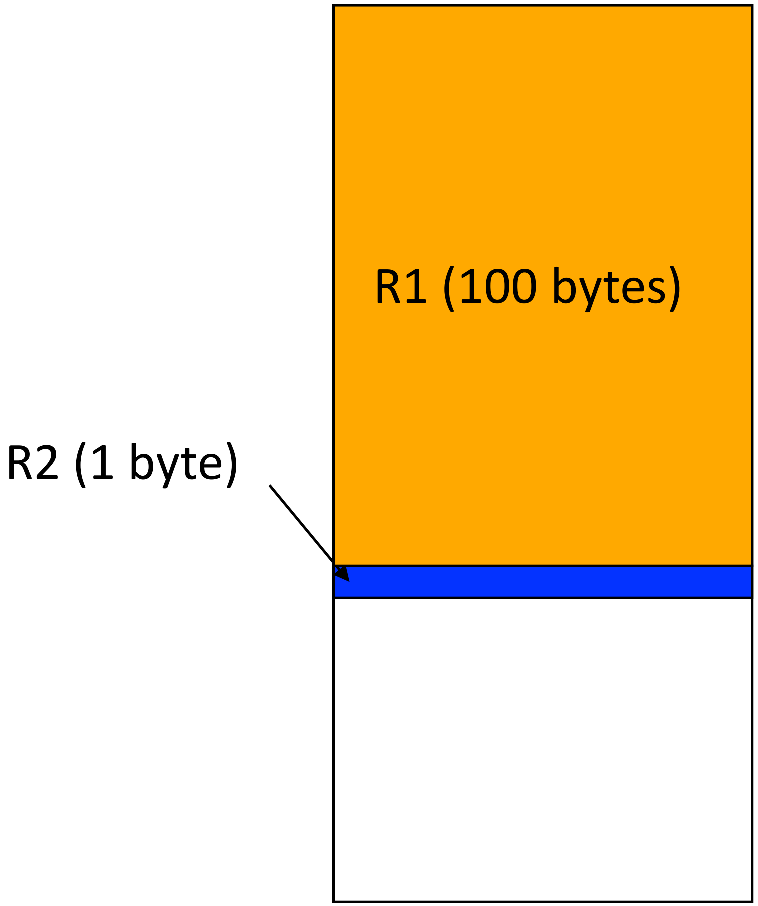
Heap Management Requirements

- 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.

* This is technically called *external fragmention*

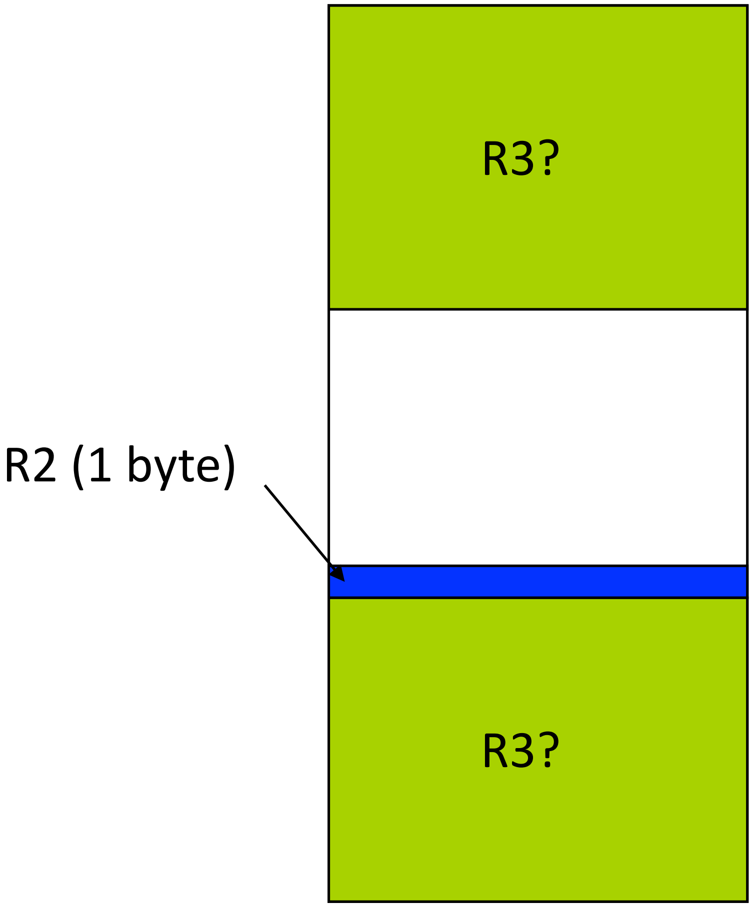
Heap Management

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



Heap Management

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



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
  - a pointer to the next block
- All free blocks are kept in a circular linked list, the pointer field is unused in an allocated block

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. If what it gets can't satisfy the request, it fails.
- `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

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

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.

Quiz – Pros and Cons of fits

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

	123
a)	FFT
b)	FTT
c)	TFF
d)	TFT
e)	TTT

Quiz – Pros and Cons of fits

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	123
a)	FFT
b)	FTT
c)	TFF
d)	**TFT**
e)	TTT

Summary

- 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)

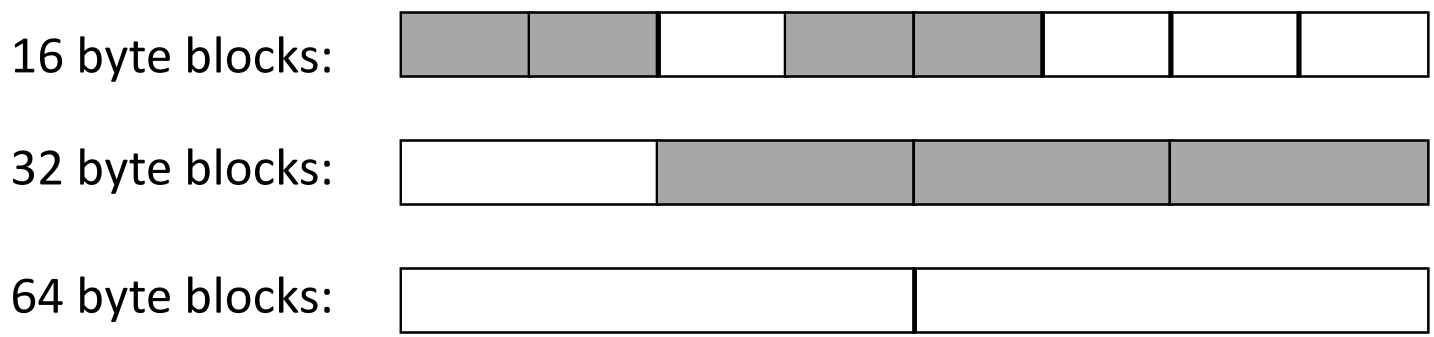
Slab Allocator

- A different approach to memory management (used in GNU `libc`)
- Divide blocks in to "large" and "small" by picking an arbitrary threshold size (say 128kB). 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

Slab Allocator

- Bookkeeping for small blocks is relatively easy
  - 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 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 external fragmentation (as we defined it before)
  - For small blocks, but still have wasted space!

Internal vs. External Fragmentation

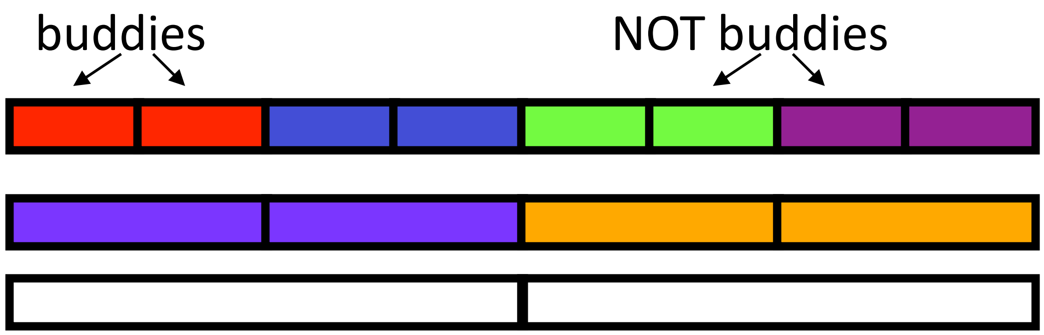
- With the slab allocator, difference between requested size and next power of 2 is wasted
  - e.g., if program wants to allocate 20 bytes and we give it a 32 byte block, 12 bytes are unused.
- We also refer to this as fragmentation, but call it **internal fragmentation** since the wasted space is actually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

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, combine the blocks in to a single block of size `2n`
  - Buddy is a 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
- Could use a strongly typed language (e.g., Java)
  - Don't allow conversion (casting) between arbitrary types.
  - C/C++ are not strongly typed.
- We will cover 3 schemes to collect garbage

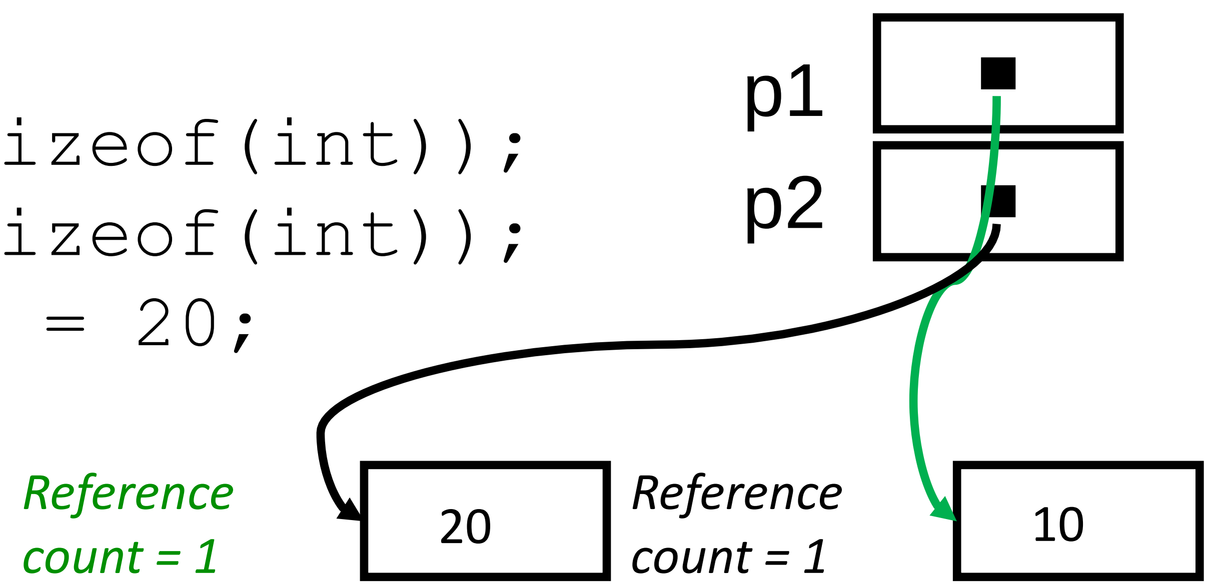
Scheme 1: Reference Counting

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

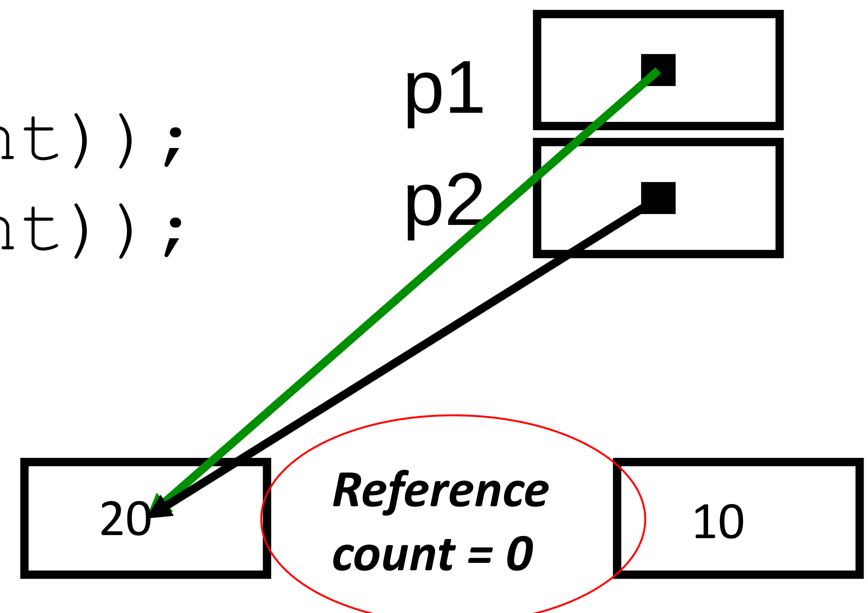


Reference Counting Example

- 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;
p1 = p2;
```

Reference count = 2



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: