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CS61C : Machine Structures

Lecture 6 – C Memory Management

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Hello to Justin H from Seattle, WA

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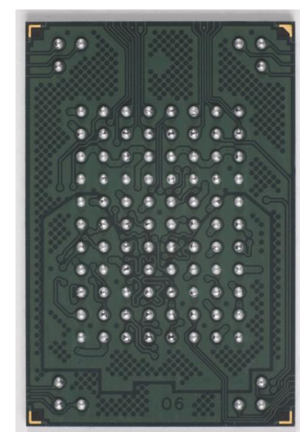
Intel: High Speed Memory ⇒



Intel says it has found a way to make its NAND flash memory five times faster (200MB/s) than before. They call it "high-speed NAND", and it is expected to be available this summer. Great for hybrid (disk + flash) drives !

www.computerworld.com/action/article.do?command=viewArticleBasic&articleId=9060581

Review

- Use handles to change pointers
- Create abstractions (and your own data structures) with structures
- Dynamically allocated heap memory must be manually deallocated in C.
    - Use `malloc()` and `free()` to allocate and de-allocate persistent storage.

Don't forget the globals!

- **Remember:**
  - **Structure declaration <u>does not</u> allocate memory**
  - **Variable declaration <u>does</u> allocate memory**
- **So far we have talked about several different ways to allocate memory for data:**
  1. **Declaration of a local variable**

     `int i; struct Node list; char *string; int ar[n];`
  2. **"Dynamic" allocation at runtime by calling allocation function (alloc).**

```
ptr = (struct Node *) malloc(sizeof(struct Node)*n);
```

- **One more possibility exists…**
  3. **Data declared outside of any procedure (i.e., before `main`).**
  - **Similar to #1 above, but has "global" scope.**

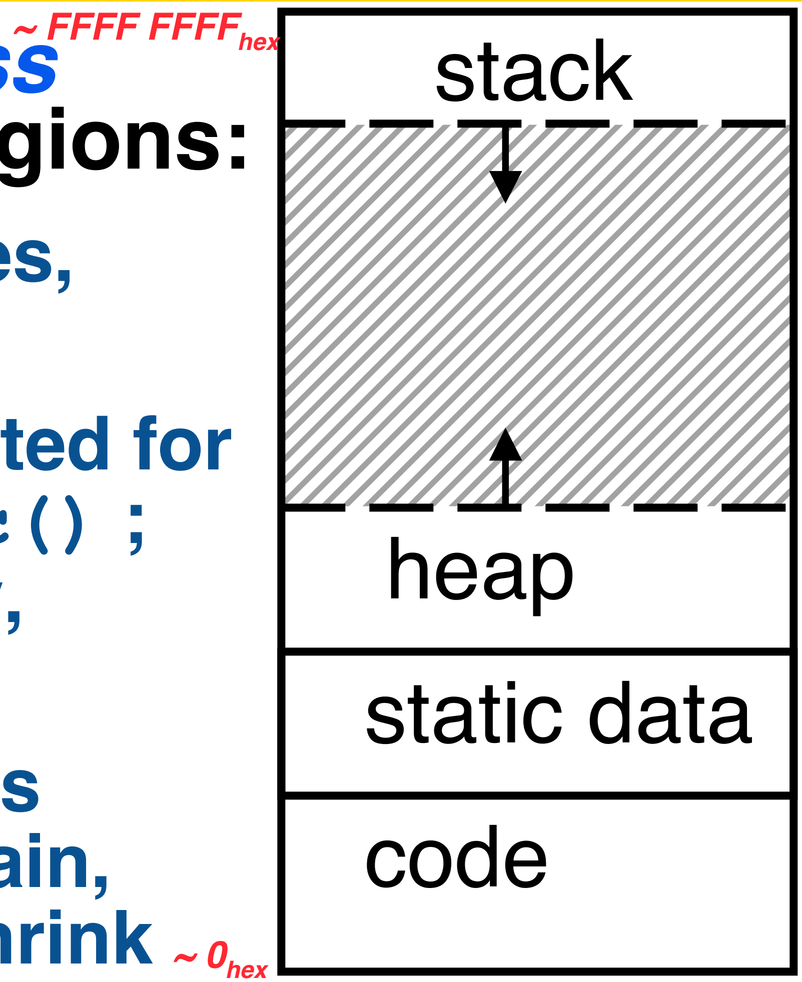
```
int myGlobal;
main() {
}
```

C Memory Management

- C has 3 pools of memory
  - Static storage: global variable storage, basically permanent, entire program run
  - The Stack: local variable storage, parameters, return address (location of "activation records" in Java or "stack frame" in C)
  - The Heap (dynamic malloc storage): data lives until deallocated by programmer
- C requires knowing where objects are in memory, otherwise things don't work as expected
  - Java hides location of objects

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

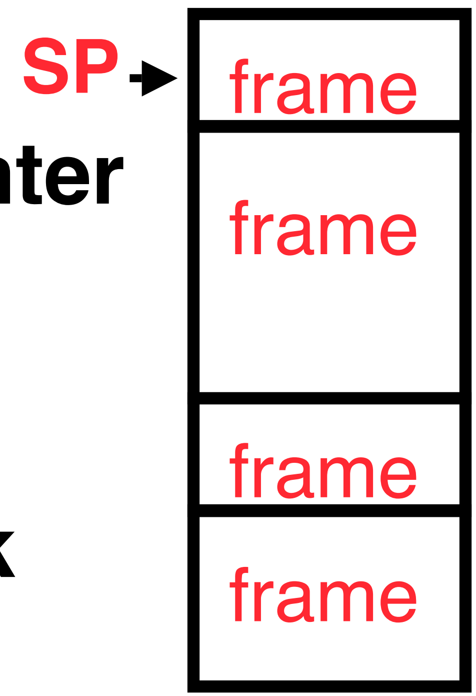
Where are variables allocated?

- If declared <u>outside</u> a procedure, allocated in "static" storage
- If declared <u>inside</u> procedure, allocated on the "stack" and freed when procedure returns.
  - NB: `main()` is a procedure

```
int myGlobal;
main() {
  int myTemp;
}
```

The Stack

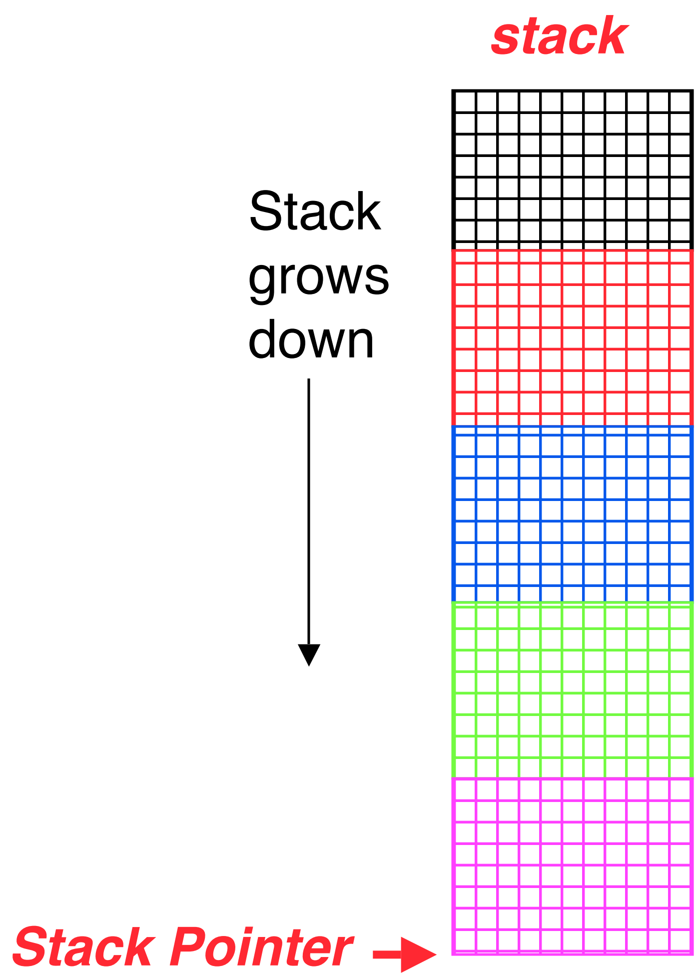
- **Stack frame includes:**
  - Return "instruction" address
  - Parameters
  - Space for other local variables
- **Stack frames contiguous blocks of memory; stack pointer tells where top stack frame is**
- **When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames**



Stack

- Last In, First Out (LIFO) data structure

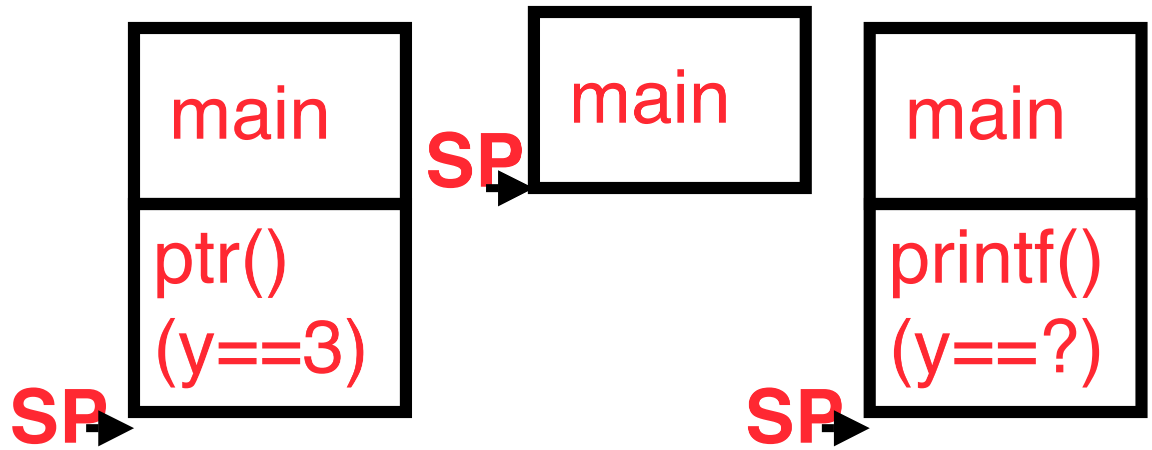
```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
      void c (int o)
      { d(3);
      }
        void d (int p)
        {
        }
```



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); /*13451514 */
 };
```



The Heap (Dynamic memory)

- Large pool of memory, not allocated in contiguous order
  - back-to-back requests for heap memory could result 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(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 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

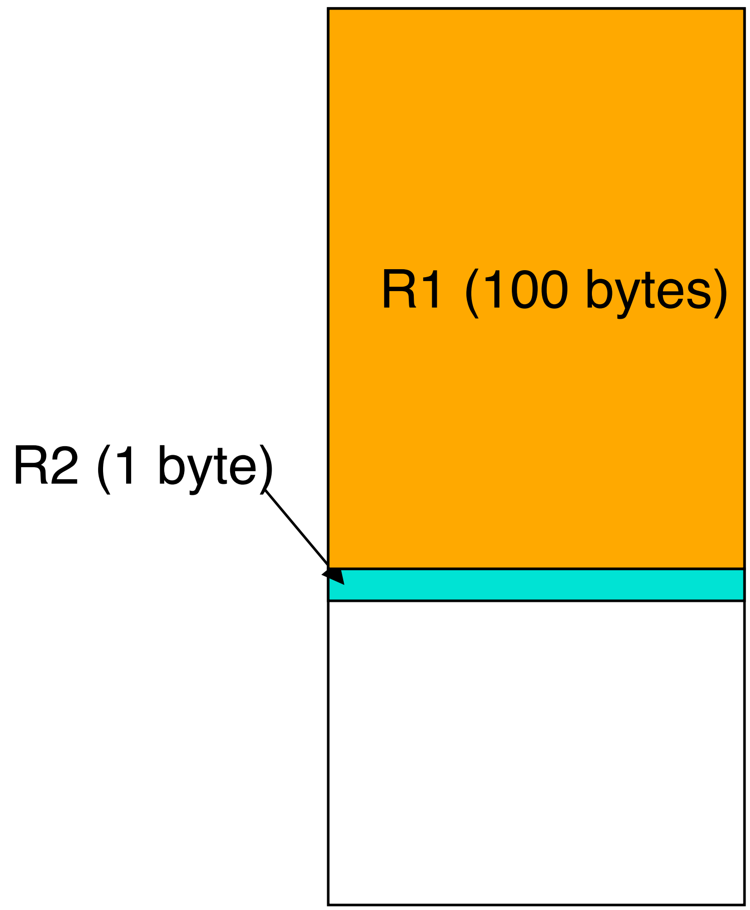
Heap Management Requirements

- 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.

* 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
  - Request R3 for 50 bytes



Heap Management

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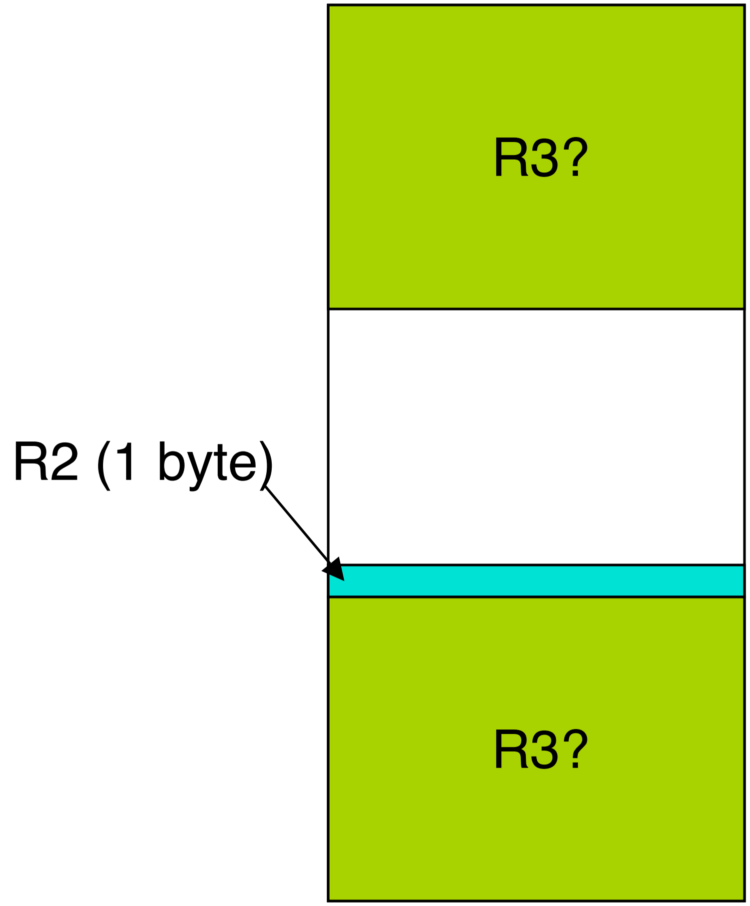


K&R Malloc/Free Implementation

- 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 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

Peer Instruction – Pros and Cons of fits

A. The con of **first-fit** is that it results in many **small blocks** at the beginning of the free list

B. The con of **next-fit** is it is **slower than first-fit**, since it takes longer in steady state to find a match

C. The con of **best-fit** is that it **leaves lots of tiny blocks**

	ABC
0:	FFF
1:	FFT
2:	FTF
3:	FTT
4:	TFF
5:	TFT
6:	TTF
7:	TTT

And in conclusion…

- 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)

Bonus slides

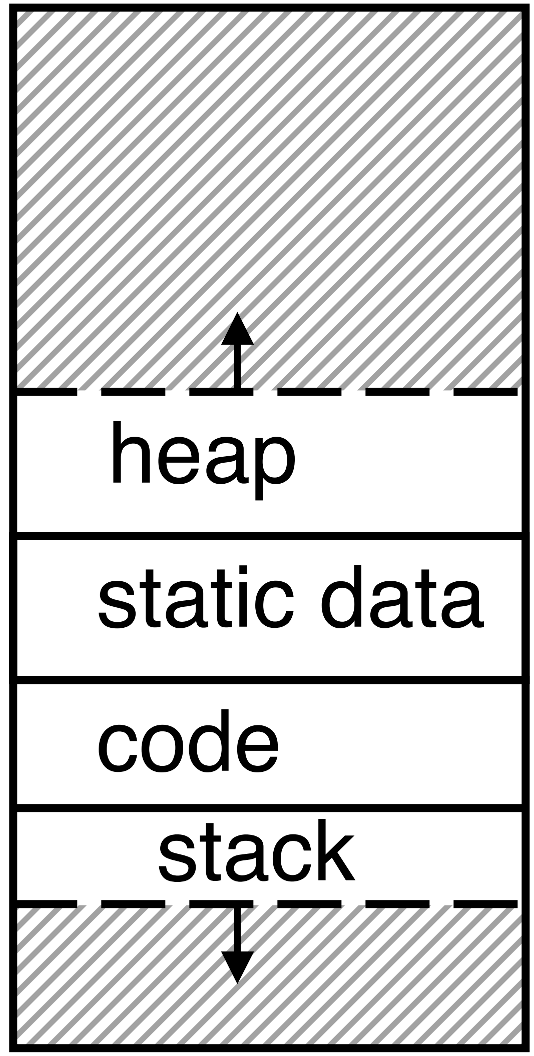
- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Intel 80x86 C Memory Management

- A C program's 80x86 *address space* :
  - 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
  - stack: local variables, grows downward

~ 08000000_{hex}



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.