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# CS61C : Machine Structures

## Lecture 6 – C Memory Management

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**Tape ogre awakens!** ⇒ IBM Zurich has made a new tape material that can store 29.5 gigabits/in$^2$, i.e., a cartridge that can hold 35 terabytes of data, more than 40 times the current capacity.

www.technologyreview.com/computing/24406

# 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 does not allocate memory
  - Variable declaration does 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];`

3. “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.

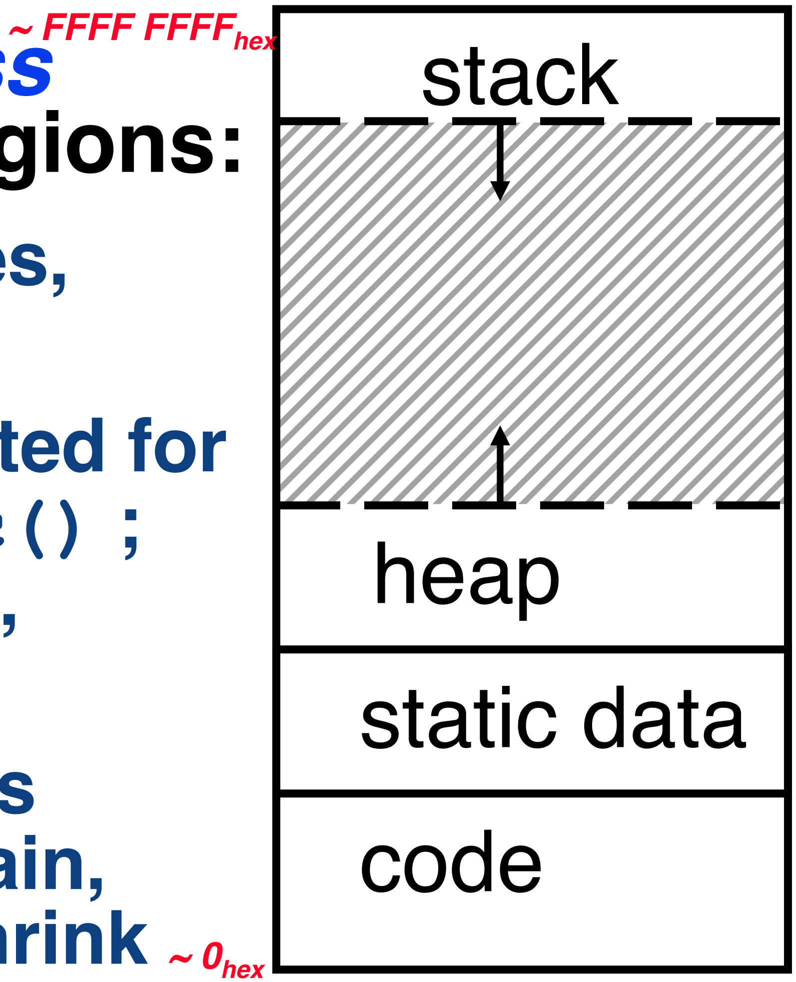
```
int myGlobal;
main() {
}
```

# 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*

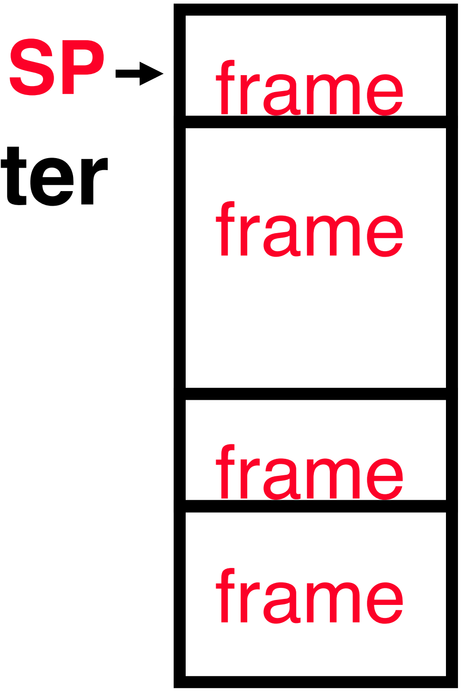
# Where are variables allocated?

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

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

# The Stack

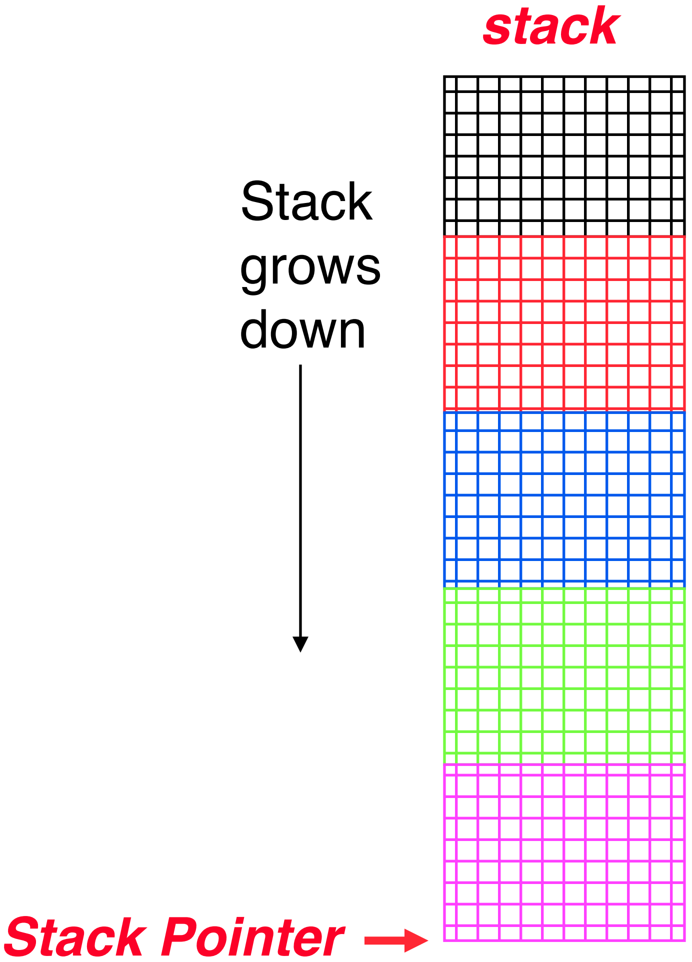
- Stack frame includes:
  - Return "instruction" address
  - Parameters
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer tells where top stack frame is
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



# 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)
    {
    }
```



***stack***

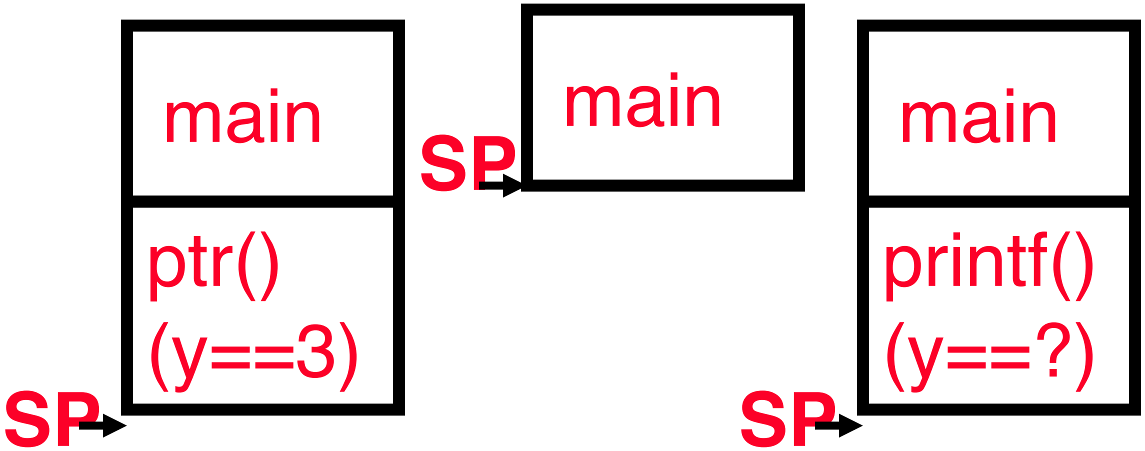
Stack grows down

***Stack Pointer***

# 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

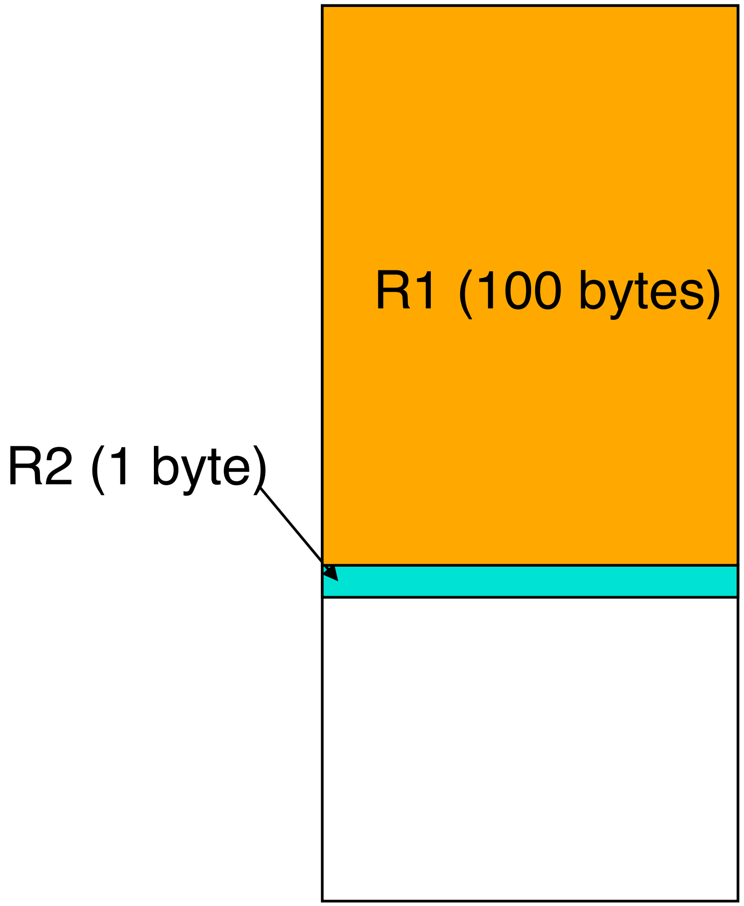
# Heap Management Requirements

- 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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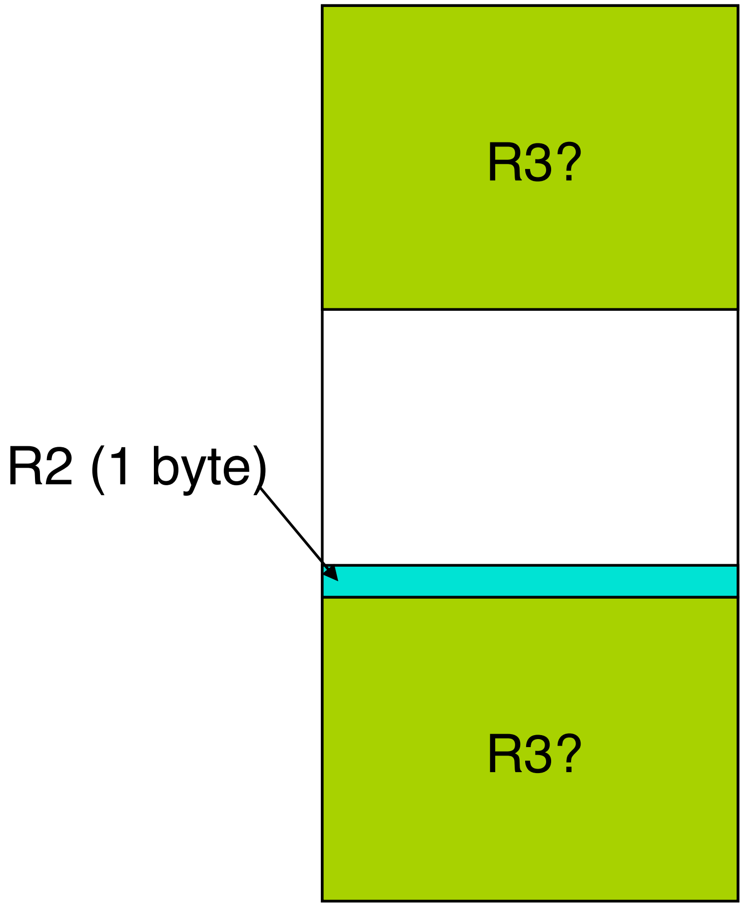


# K&R Malloc/Free Implementation

- 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

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 |

# 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)

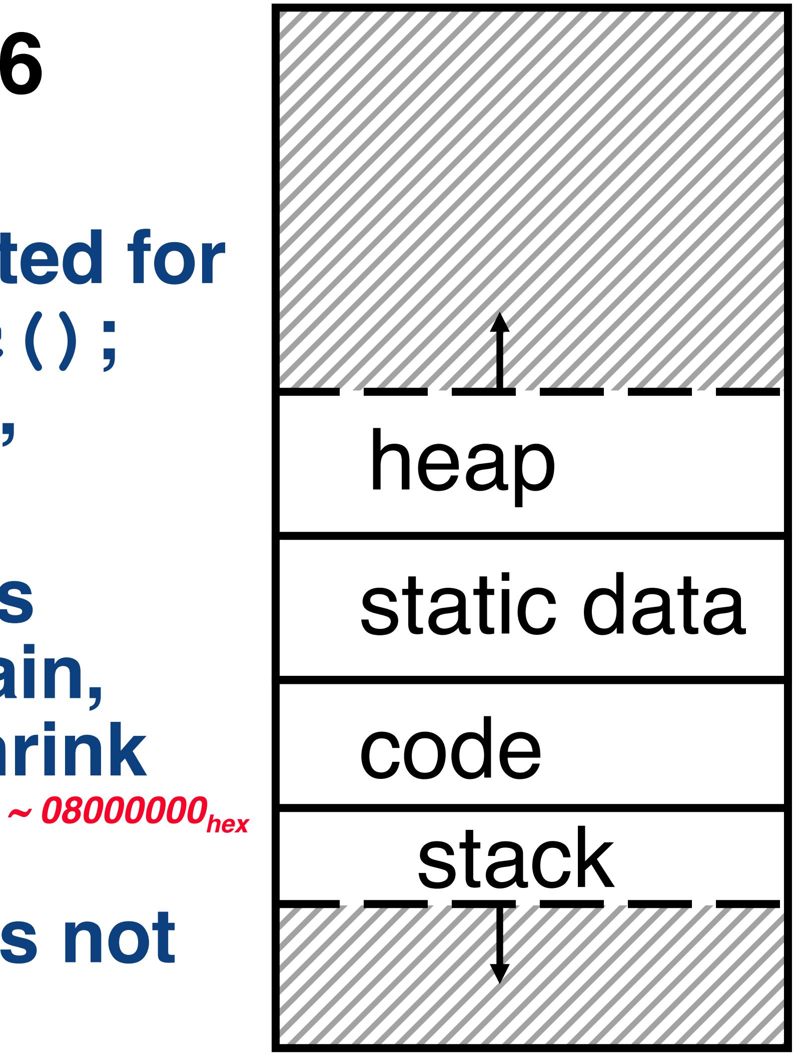
# Bonus slides

- 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



# 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.