CS61C : Machine Structures

Lecture #4 – C Memory Management

2005-09-12

There is one handout today at the front and back of the room!

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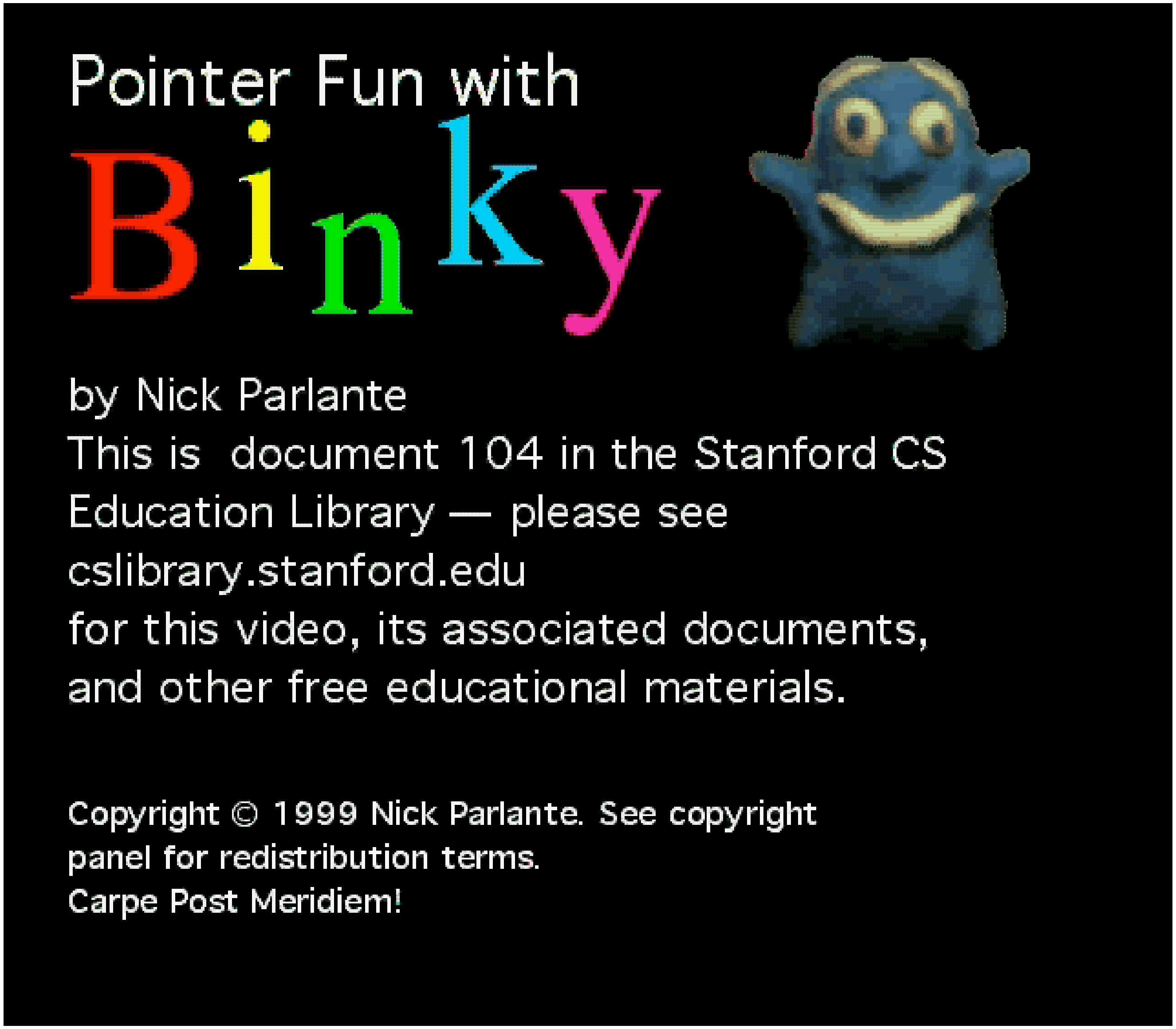
Football! ⇒ Joe Ayoob leads the #16 Bears over Washington 56-17. Lynch breaks pinky! 2-0 Illini @ home next…

calbears.collegesports.com/sports/m-footbl/recaps/091005aaa.html

Review

- C99 is the update to the ANSI standard
- Pointers and arrays are virtually same
- C knows how to increment pointers
- C is an efficient language, w/little protection
  - Array bounds not checked
  - Variables not automatically initialized
- (Beware) The cost of efficiency is more overhead for the programmer.
  - "C gives you a lot of extra rope but be careful not to hang yourself with it!"
- Use handles to change pointers
- P. 53 is a precedence table, useful for (e.g.,)
  - `x = ++*p;` ⇒ `*p = *p + 1 ; x = *p;`

Binky Pointer Video (thanks to NP @ SU)



C structures : Overview

- A `struct` is a data structure composed for simpler data types.
  - Like a class in Java/C++ but without methods or inheritance.

```
struct point {
    int x;
    int y;
};
void PrintPoint(struct point p)
{
    printf("(%d,%d)", p.x, p.y);
}
```

C structures: Pointers to them

- The C arrow operator (`->`) dereferences and extracts a structure field with a single operator.
- The following are equivalent:

```
struct point *p;

printf("x is %d\n", (*p).x);
printf("x is %d\n", p->x);
```

How big are structs?

- Recall C operator `sizeof()` which gives size in bytes (of type or variable)
- How big is `sizeof(p)`?

```
struct p {
    char x;
    int y;
};
```

  - 5 bytes? 8 bytes?
  - Compiler may word align integer `y`

Linked List Example

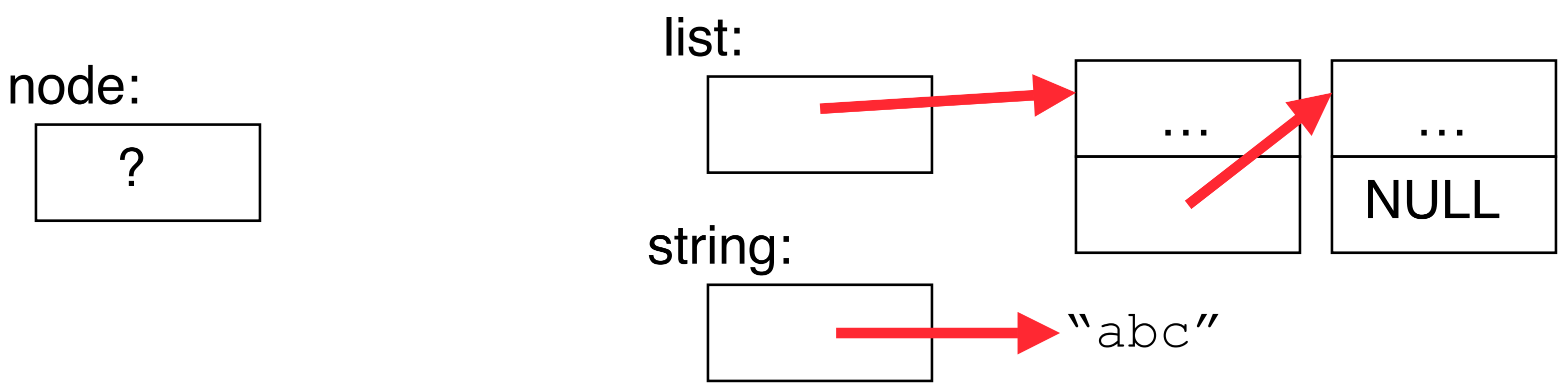
- Let's look at an example of using structures, pointers, `malloc()`, and `free()` to implement a linked list of strings.

```
struct Node {
    char *value;
    struct Node *next;
};
typedef struct Node *List;

/* Create a new (empty) list */
List ListNew(void)
{ return NULL; }
```

Linked List Example

```
/* add a string to an existing list */
List list_add(List list, char *string)
{
  struct Node *node =
    (struct Node*) malloc(sizeof(struct Node));
  node->value =
    (char*) malloc(strlen(string) + 1);
  strcpy(node->value, string);
  node->next = list;
  return node;
}
```



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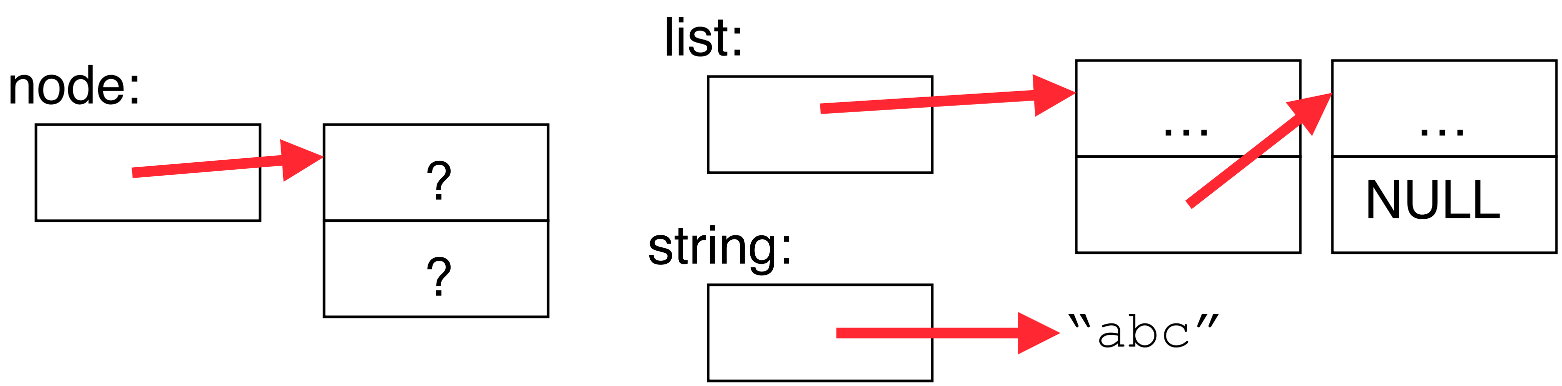

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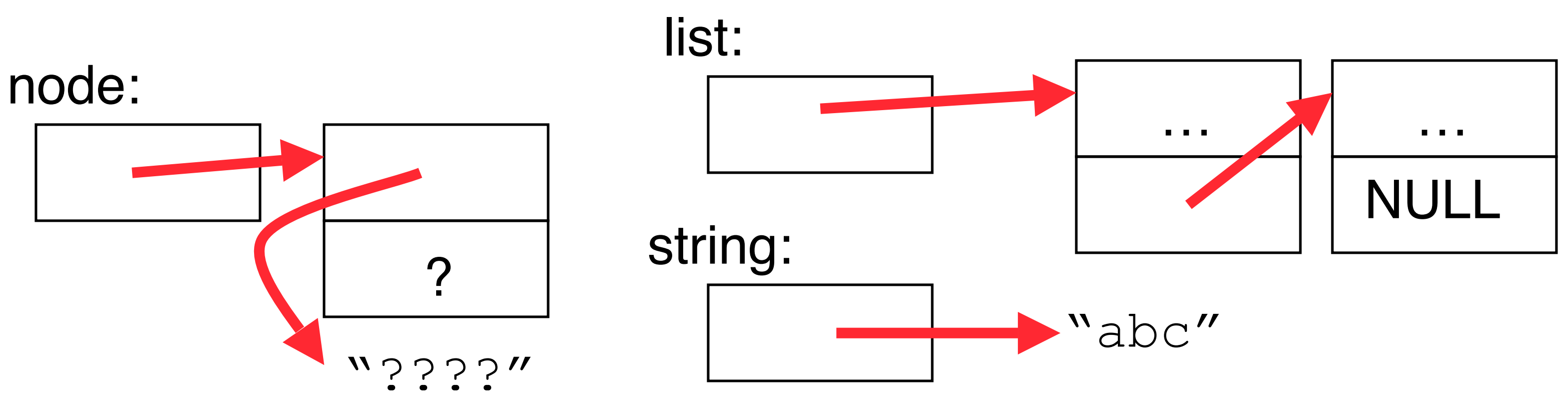

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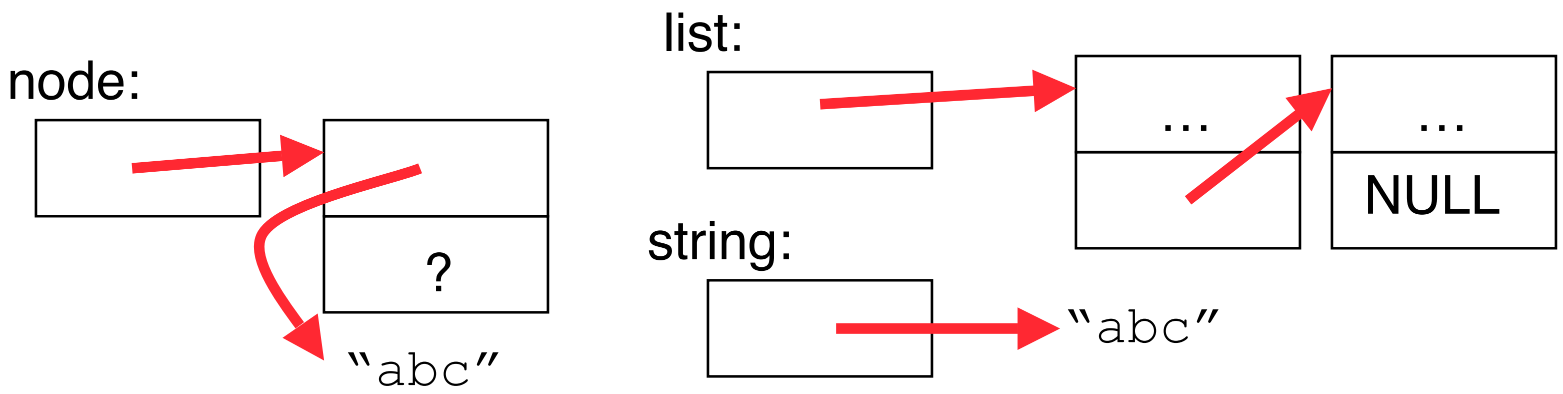

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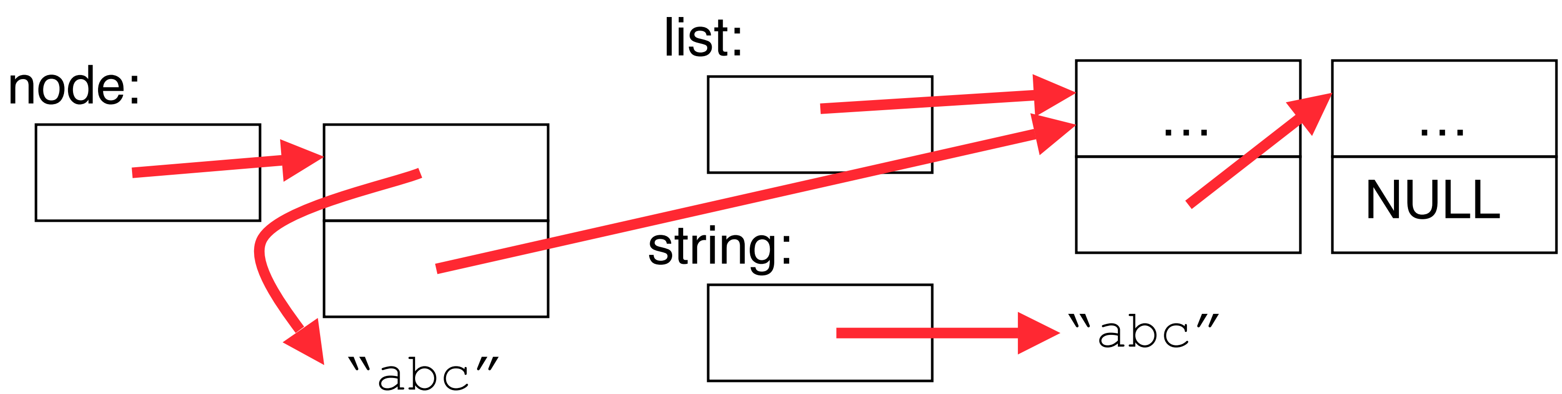

Linked List Example

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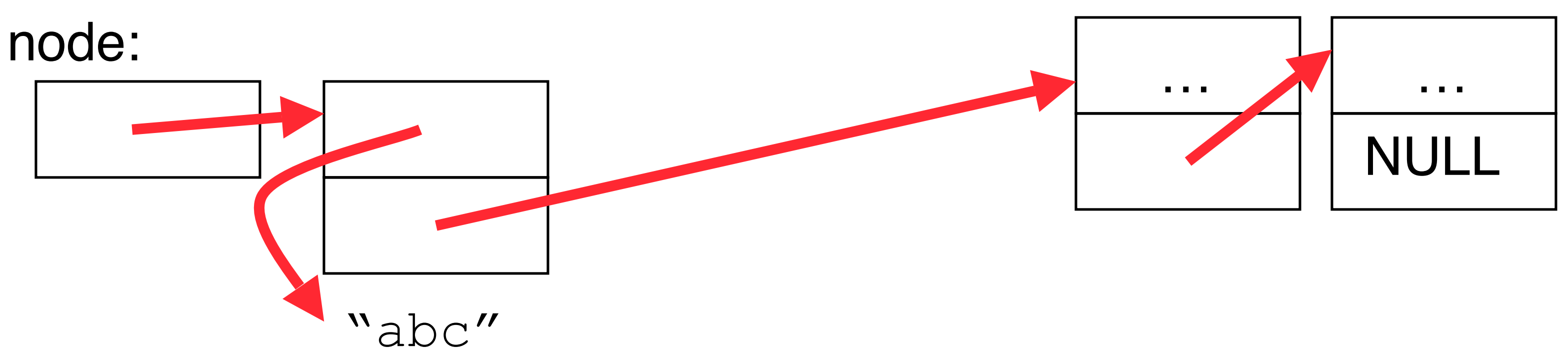


“And in Semi-Conclusion…”

- Use handles to change pointers
- Create abstractions with structures
- Dynamically allocated heap memory must be manually deallocated in C.
  - Use `malloc()` and `free()` to allocate and deallocate memory from heap.

Peer Instruction

Which are guaranteed to print out 5?

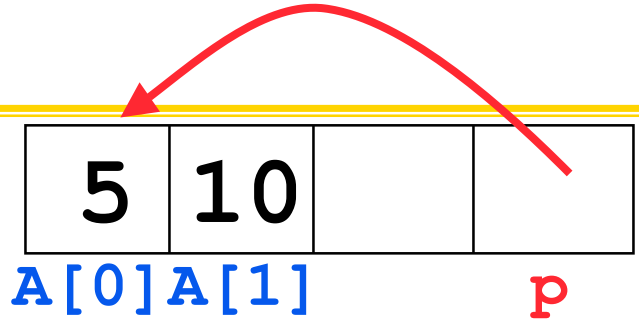
```
I:    main() {
        int *a-ptr; *a-ptr = 5; printf("%d", *a-ptr); }

II:   main() {
        int *p, a = 5;
        p = &a; ...
        /* code; a & p NEVER on LHS of = */
        printf("%d", a); }

III: main() {
        int *ptr;
        ptr = (int *) malloc (sizeof(int));
        *ptr = 5;
        printf("%d", *ptr); }
```

	I	II	III
1:	–	–	–
2:	–	–	YES
3:	–	YES	–
4:	–	YES	YES
5:	YES	–	–
6:	YES	–	YES
7:	YES	YES	–
8:	YES	YES	YES

Peer Instruction




```
int main(void){
  int A[] = {5,10};
  int *p = A;

  printf("%u %d %d %d\n",p,*p,A[0],A[1]);
   p =  p + 1;
  printf("%u %d %d %d\n",p,*p,A[0],A[1]);
  *p = *p + 1;
  printf("%u %d %d %d\n",p,*p,A[0],A[1]);
  }
```

If the first `printf` outputs 100 5 5 10, what will the other two `printf` output?

```
1: 101 10 5 10        then 101 11 5 11
2: 104 10 5 10        then 104 11 5 11
3: 101 <other> 5 10   then 101 <3-others>
4: 104 <other> 5 10   then 104 <3-others>
5: One of the two printfs causes an ERROR
6: I surrender!
```

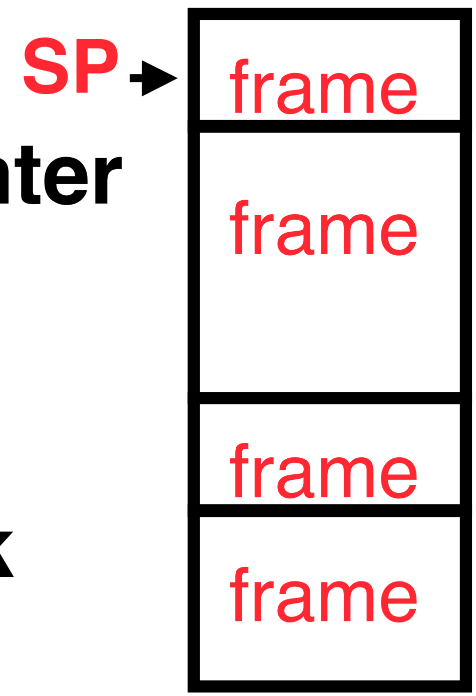
Where is data allocated?

- Structure declaration does not allocate memory
- Variable declaration does allocate memory
  - If declare outside a procedure, allocated in static storage
  - If declare inside procedure, allocated on the stack and freed when procedure returns.
    - NB: `main()` is a procedure

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

The Stack

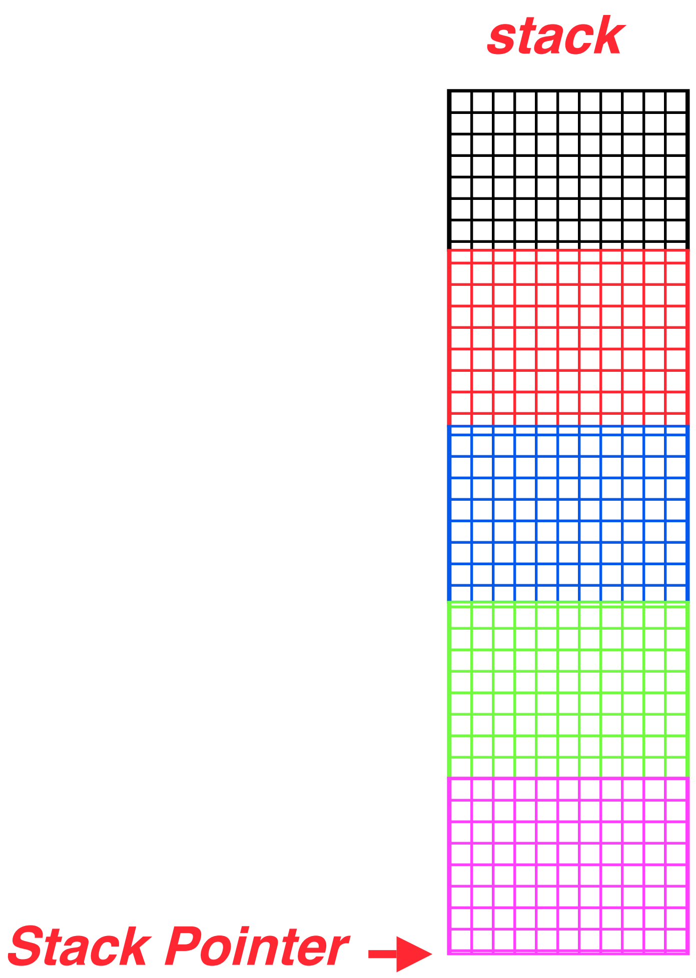
- Stack frame includes:
  - Return address
  - Parameters
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer tells where top stack frame is
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



Stack

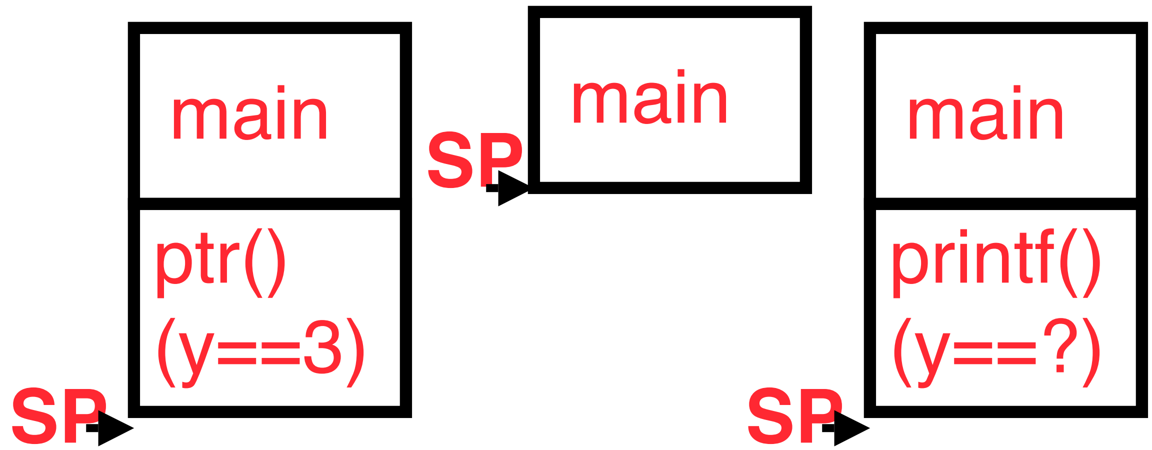
- Last In, First Out (LIFO) memory usage

```
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)
        {
        }
```



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 */
};
```


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 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

The Heap (Dynamic memory)

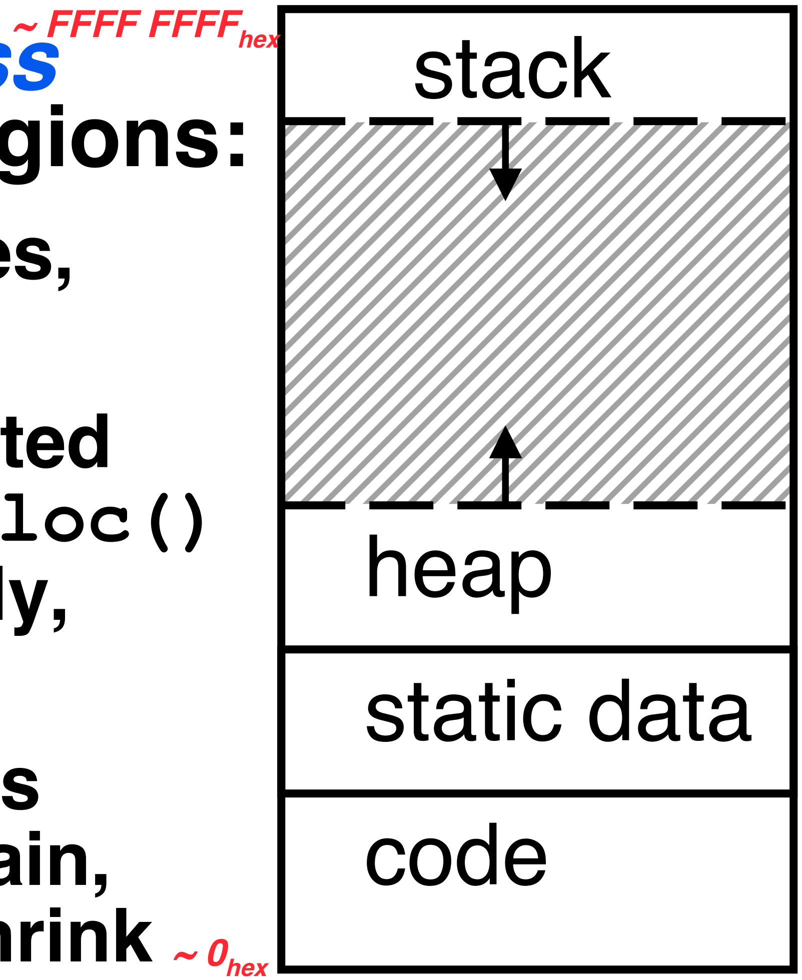
- Large pool of memory, not allocated in contiguous order
  - back-to-back requests for heap memory could result blocks very far apart
  - where Java `new` command allocates memory
- In C, specify number of bytes of memory explicitly to allocate item

```
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

Review: Normal C Memory Management

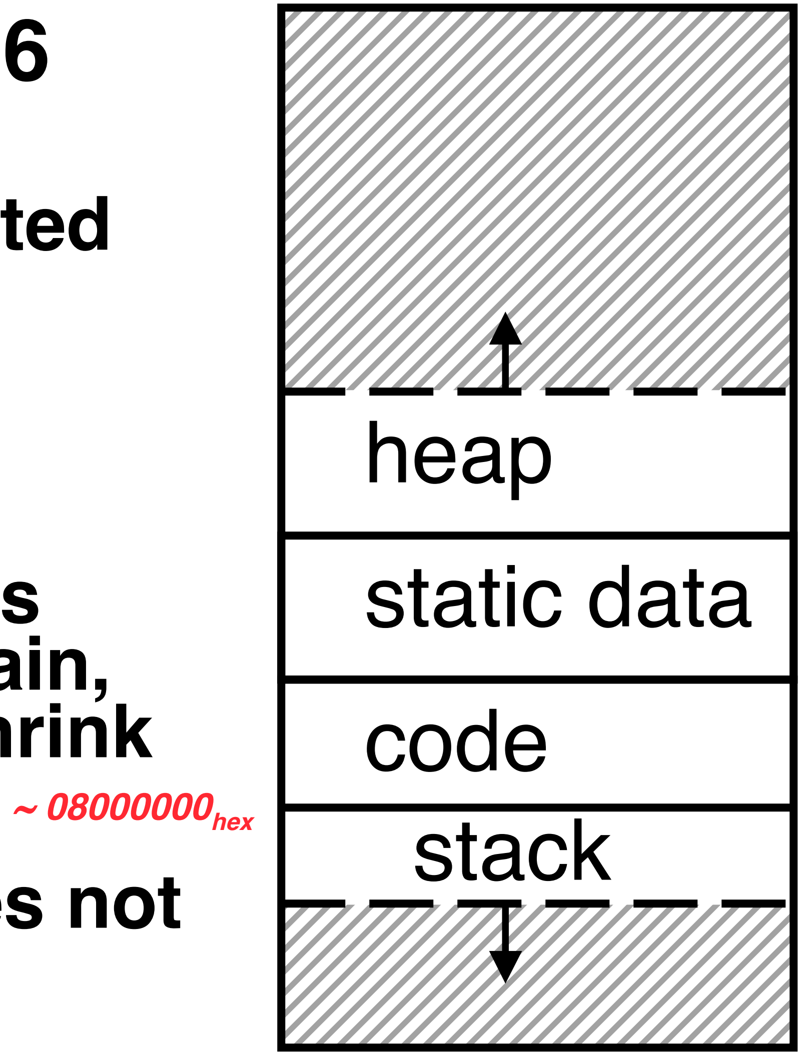
- A program's ***address space*** contains 4 regions:
  - **stack**: local variables, grows downward
  - **heap**: space requested for pointers via `malloc()` ; resizes dynamically, grows upward
  - **static data**: variables declared outside main, does not grow or shrink
  - **code**: loaded when program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



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

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



Memory Management

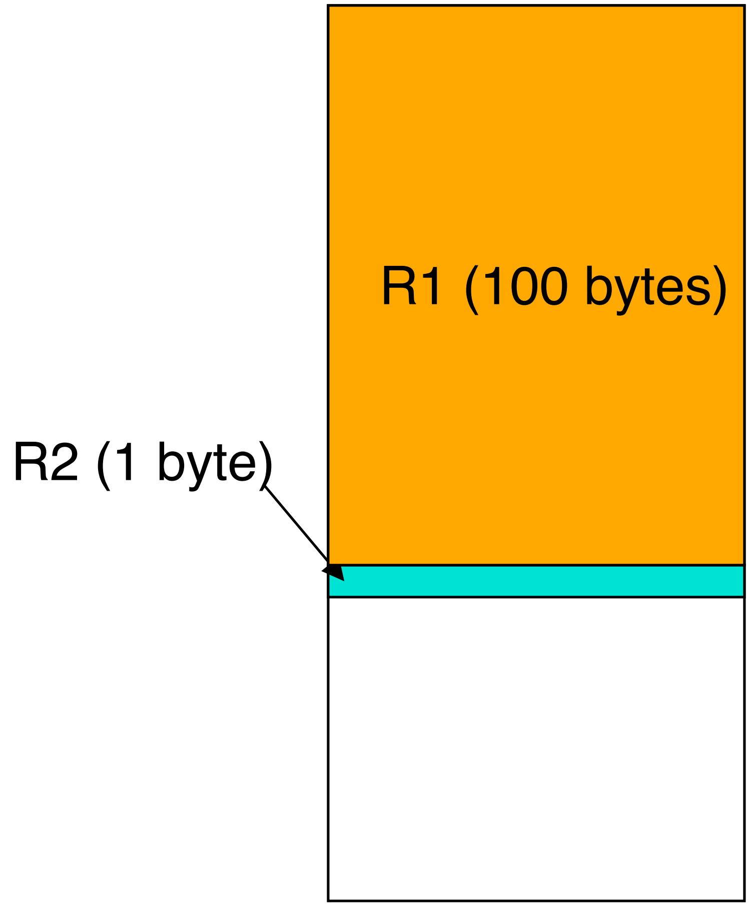
- How do we manage memory?
- Code, Static storage are easy: they never grow or shrink
- Stack space is also easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- Managing the heap is tricky: memory can be allocated / deallocated at any time

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



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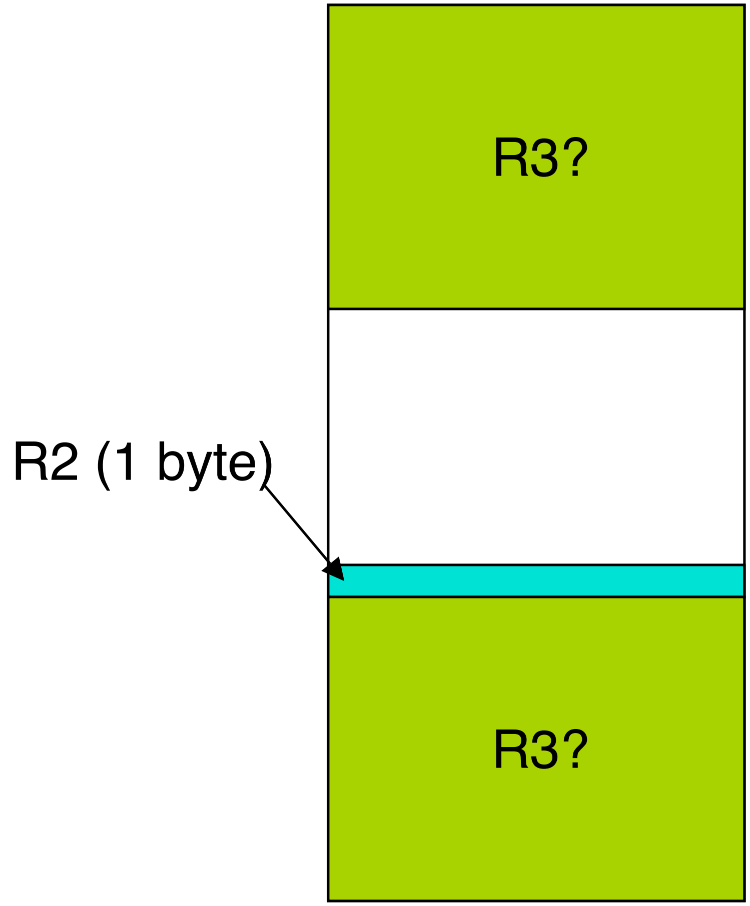

K&R Malloc/Free Implementation

- 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

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

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.

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)