Memory Allocation

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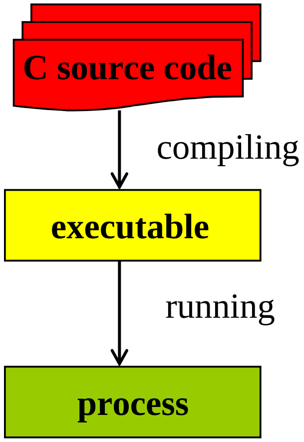
COS 217

Goals for Today's Lecture

- Behind the scenes of running a program
  - Code, executable, and process
  - Main memory vs. virtual memory
- Memory layout for UNIX processes, and relationship to C
  - Text: code and constant data
  - Data: initialized global and static variables
  - BSS: uninitialized global and static variables
  - Heap: dynamic memory
  - Stack: local variables
- C functions for memory management
  - **`malloc`**: allocate memory from the heap
  - **`free`**: deallocate memory from the heap

Code vs. Executable vs. Process

- C source code
  - C statements organized into functions
  - Stored as a collection of files (.c and .h)
- Executable module
  - Binary image generated by compiler
  - Stored as a file (e.g., *a.out*)
- Process
  - Instance of a program that is executing
    - With its own address space in memory
    - With its own id and execution state
  - Managed by the operating system



C source code

compiling

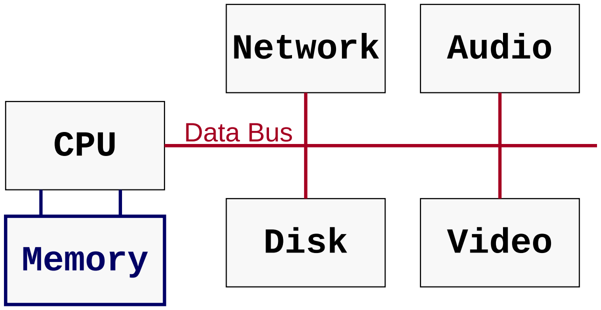
executable

running

process

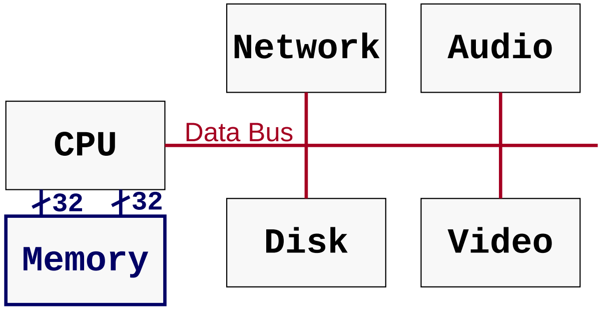
Main Memory on a Computer

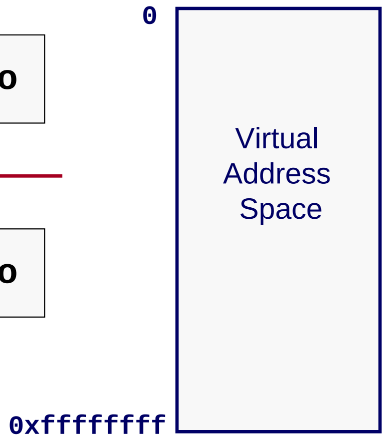
- What is main memory?
  - Storage for variables, data, code, etc.
  - May be shared among many processes



Virtual Memory for a Process

- What is virtual memory?
  - Contiguous addressable memory space for a single process
  - May be swapped into physical memory from disk in pages
  - Let's you pretend each process has its own contiguous memory



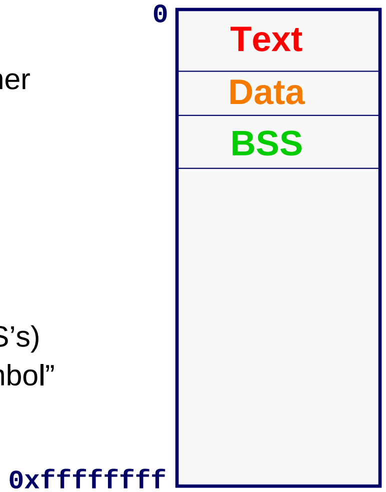


What to Store: Code and Constants

- Executable code and constant data
  - Program binary, and any shared libraries it loads
  - Necessary for OS to read the commands
- OS knows everything in advance
  - Knows amount of space needed
  - Knows the contents of the memory
- Known as the "text" segment
- Note: Some systems (e.g. hats) store some constants in "rodata" section

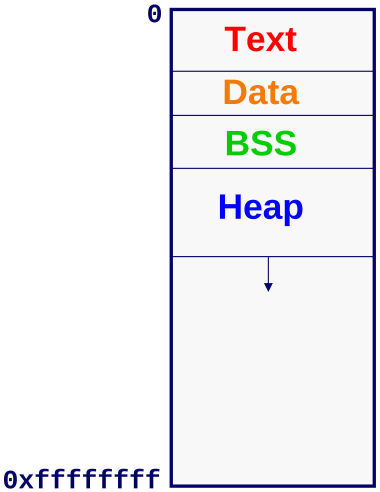
What to Store: "Static" Data

- Variables that exist for the entire program
  - Global variables, and "static" local variables
  - Amount of space required is known in advance
- Data: initialized in the code
  - Initial value specified by the programmer
    - E.g., "`int x = 97`;"
  - Memory is initialized with this value
- BSS: not initialized in the code
  - Initial value not specified
    - E.g., "`int x`;"
  - All memory initialized to 0 (on most OS's)
  - BSS stands for "Block Started by Symbol"



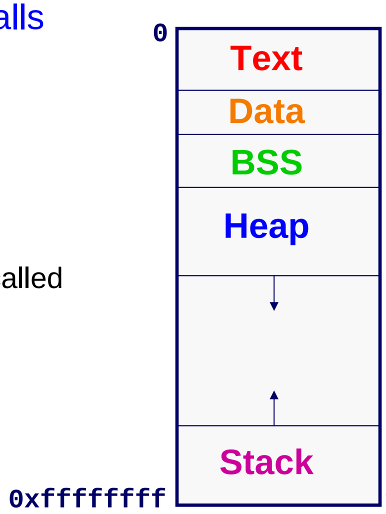
What to Store: Dynamic Memory

- Memory allocated while program is running
  - E.g., allocated using the **`malloc()`** function
    - And deallocated using the **`free()`** function
- OS knows nothing in advance
  - Doesn't know the amount of space
  - Doesn't know the contents
- So, need to allow room to grow
  - Known as the "heap"
  - Detailed example in a few slides
  - More in programming assignment #4



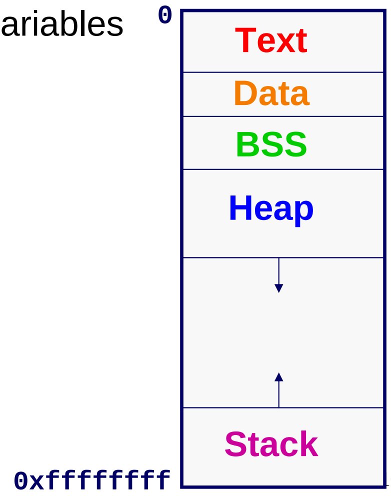
What to Store: Temporary Variables

- Temporary memory during lifetime of a function or block
  - Storage for function parameters and local variables
- Need to support nested function calls
  - One function calls another, and so on
  - Store the variables of calling function
  - Know where to return when done
- So, must allow room to grow
  - Known as the “stack”
  - Push on the stack as new function is called
  - Pop off the stack as the function ends
- Detailed example later on


0
Text
Data
BSS
Heap
Stack
0xffffffff

Memory Layout: Summary

- Text: code, constant data
- Data: initialized global & static variables
- BSS: uninitialized global & static variables
- Heap: dynamic memory
- Stack: local variables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Text
Data
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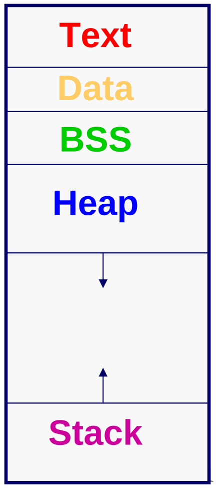
Memory Layout Example

```
char* string = “hello”;
int iSize;

char* f(void)
{
    char* p;
    iSize = 8;
    p = malloc(iSize);
    return p;
}
```


Text
Data
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Memory Layout Example: Text

```
char* string = “hello”;
int iSize;

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    return p;
}
```

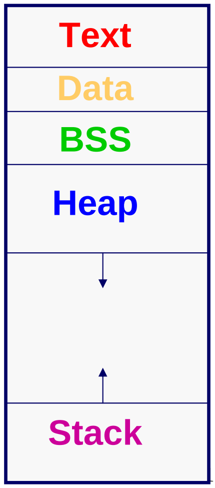
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Memory Layout Example: Data

```
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}
```

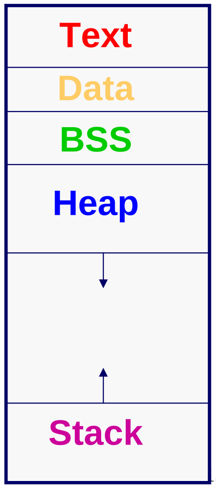

Memory Layout Example: BSS

```
char* string = “hello”;
int iSize;

char* f(void)
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    return p;
}
```

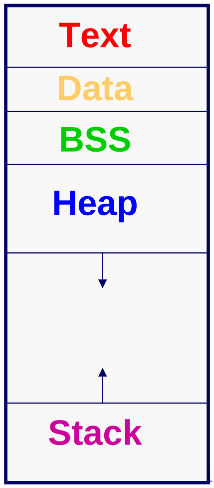

Memory Layout Example: Heap

```
char* string = “hello”;
int iSize;

char* f(void)
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    char* p;
    iSize = 8;
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    return p;
}
```

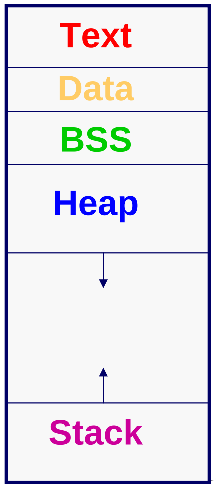

Memory Layout Example: Stack

```
char* string = “hello”;
int iSize;

char* f(void)
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    return p;
}
```
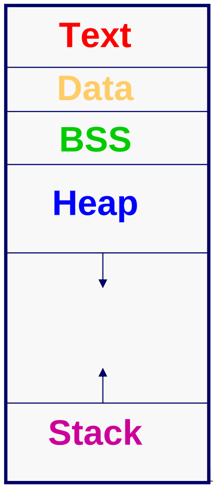
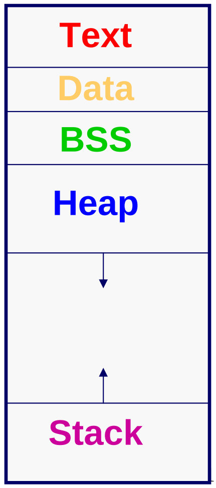



Memory Allocation & Deallocation

- How, and when, is memory allocated?
  - Global and static variables = program startup
  - Local variables = function call
  - Dynamic memory = **`malloc()`**
- How is memory deallocated?
  - Global and static variables = program finish
  - Local variables = function return
  - Dynamic memory = **`free()`**
- All memory deallocated when program ends
  - It is good style to free allocated memory anyway



Memory Allocation Example

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char* string = “hello”;
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{
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    return p;
}
```

Data: “hello” at startup

BSS: 0 at startup

Stack: at function call

Heap: 8 bytes at malloc

Memory Deallocation Example

```
char* string = “hello”;
int iSize;

char* f(void)
{
    char* p;
    iSize = 8;
    p = malloc(iSize);
    return p;
}
```

Available till termination

Available till termination

Deallocate on return from f

Deallocate on free()

Memory Initialization

- Local variables have undefined values

```
int count;
```

- Memory allocated by **`malloc()`** has undefined values

```
char* p = (char *) malloc(8);
```

- If you need a variable to start with a particular value, use an explicit initializer

```
int count = 0;
p[0] = ’\0’;
```

- Global and static variables are initialized to 0 by default

```
static int count = 0;
```

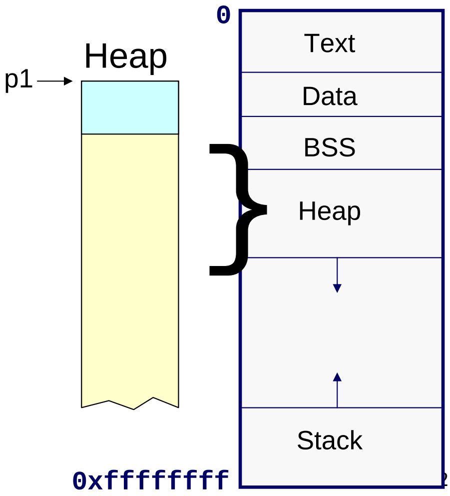
is the same as

```
static int count;
```

It is bad style to depend on this

Heap: Dynamic Memory

```
#include <stdlib.h>
void *malloc(size_t size);
void free(void *ptr);
```



```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
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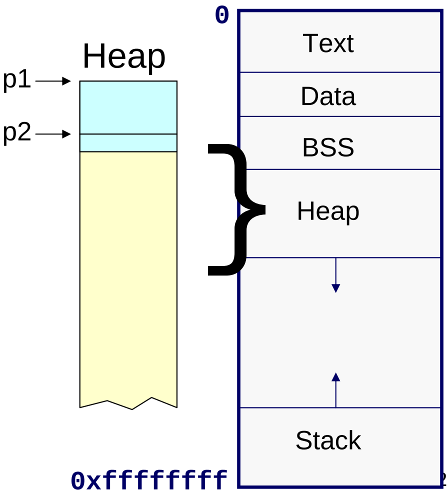

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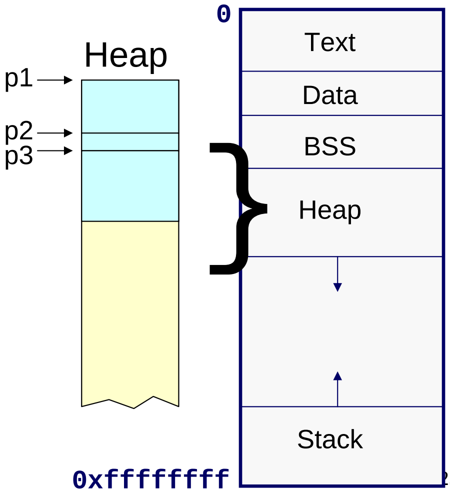

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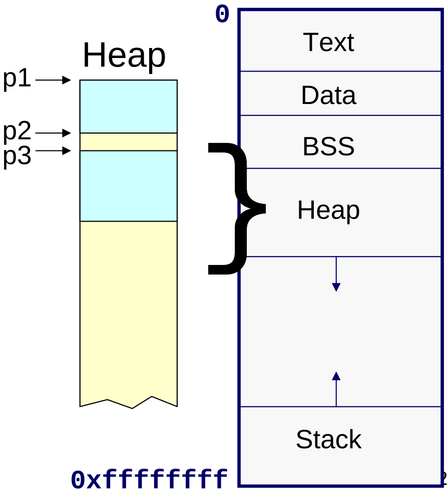

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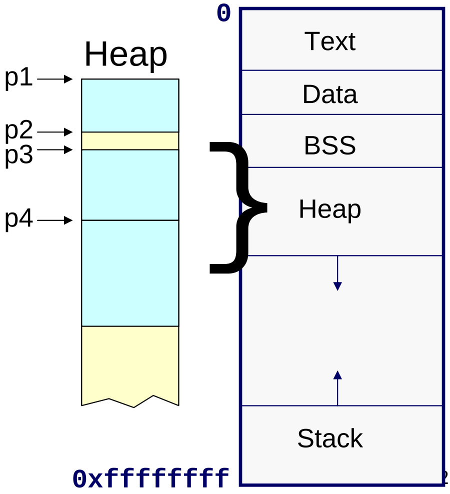

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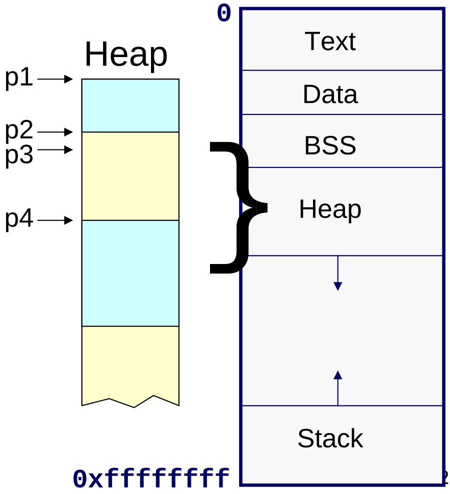

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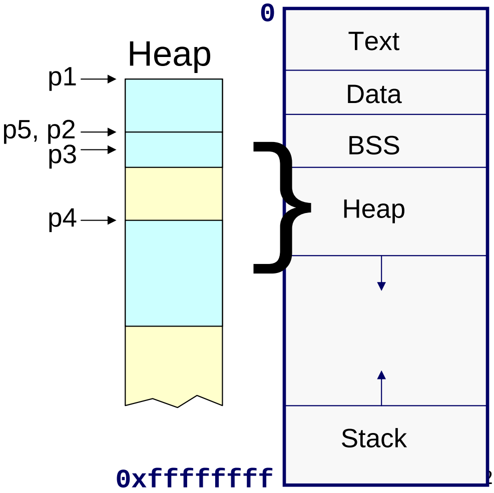

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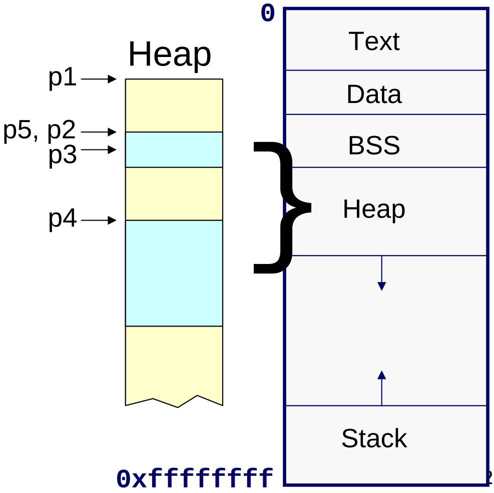

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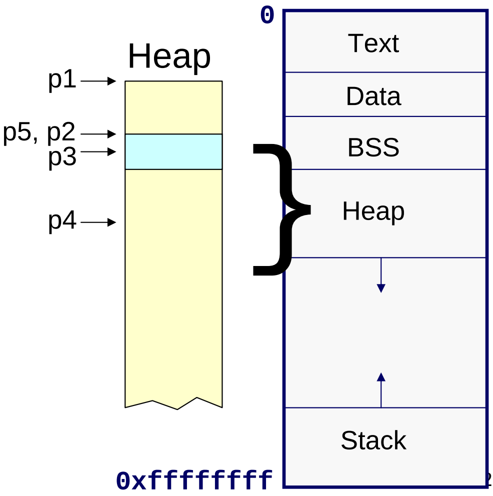

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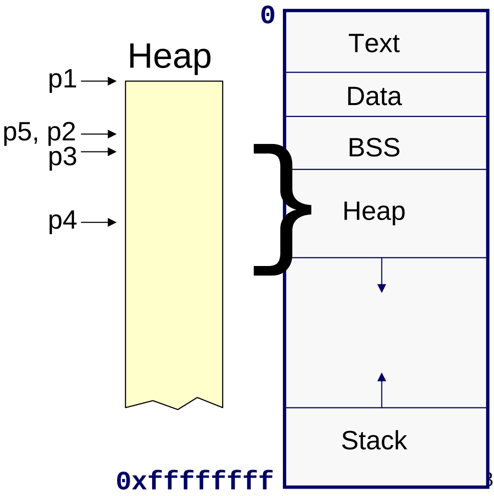


How Do Malloc and Free Work?

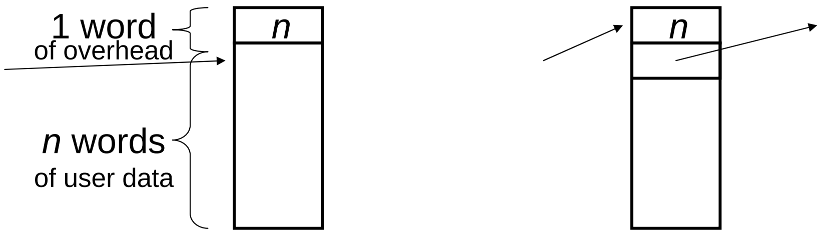
- Simple answer
  - Doesn't matter
  - Good modularity means you can use it without understanding it
- Real answer

malloc(s)

$n = \lceil s / \text{sizeof(int)} \rceil$

free(p)

put p into linked list of free objects



Using Malloc and Free

- Types
  - **`void*`**: generic pointer to any type (can be converted to other types)
  - **`size_t`**: unsigned integer type returned by **`sizeof()`**
- **`void* malloc(size_t size)`**
  - Returns a pointer to space of size **`size`**
  - … or **`NULL`** if the request cannot be satisfied
  - E.g., **`int* x = (int *) malloc(sizeof(int));`**
- **`void* calloc(size_t nobj, size_t size)`**
  - Returns a pointer to space for array of **`nobj`** objects of size **`size`**
  - … or **`NULL`** if the request cannot be satisfied
  - Bytes are initialized to 0
- **`void free(void* p)`**
  - Deallocate the space pointed to by the pointer **`p`**
  - Pointer **`p`** must be pointer to space previously allocated
  - Do nothing if **`p`** is **`NULL`**

Using realloc and (never) alloca

- `void* realloc(void* ptr, size_t size)`
  - "Grows" the allocated buffer
  - Moves/copies the data if old space insufficient
  - … or `NULL` if the request cannot be satisfied
- `void* alloca(size_t size)`
  - **Not guaranteed to exist (not in any official standard)**
  - Allocates space on local stack frame
  - Space automatically freed when function exits
  - Particularly useful for following:

```
int calc(int numItems) {
  ~~int items[numItems];~~
  int *items = alloca(numItems * sizeof(int));
}
```

Sorting w/o Linked Lists

```
 int alloc = 4, used = 0;
 Item *temp, *buf = NULL;

while ((temp = NextItem()) != NULL) {
  if (used >= alloc) {
    alloc *= 2;
    buf = realloc(buf,
                  alloc*sizeof(Item));
  }
  buf[used++] = temp;
}

qsort(…);
```

Avoid Leaking Memory

- Memory leaks "lose" references to dynamic memory

```
int f(void)
{
    char* p;
    p = (char *) malloc(8 * sizeof(char));
    …
    return 0;
}

int main(void) {
    f();
    …
}
```

Avoid Dangling Pointers

- Dangling pointers point to data that's not there anymore

```
char *f(void)
{
    char p[8];

    …
    return p;
}

int main(void) {
    char *res = f();
    …
}
```

Debugging Malloc Problems

- Symptom: “random” failures, especially on call return
  - Corrupted the stack frame return info
- Symptom: calls to malloc/free fail
  - Corrupted the malloc bookkeeping data
- Symptom: program magically works if printf inserted
  - Corrupted storage space in stack frame
- “Debugging” mallocs exist
  - Doing “man malloc” on Linux reveals MALLOC_CHECK_
  - Searching “debug malloc” yields dmalloc, other libraries
  - Larger problems: valgrind, electric fence, etc.

Summary

- Five types of memory for variables
  - Text: code, constant data (constant data in rodata on hats)
  - Data: initialized global & static variables
  - BSS: uninitialized global & static variables
  - Heap: dynamic memory
  - Stack: local variables
- Important to understand differences between
  - Allocation: space allocated
  - Initialization: initial value, if any
  - Deallocation: space reclaimed
- Understanding memory allocation is important
  - Make efficient use of memory
  - Avoid “memory leaks” from dangling pointers