Process Layout

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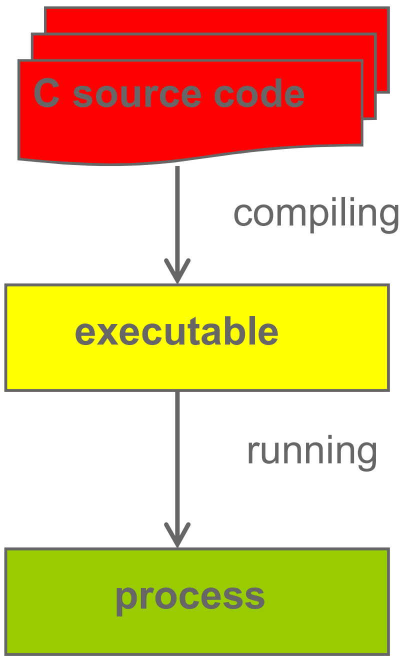
Code → Executable → Process

- 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



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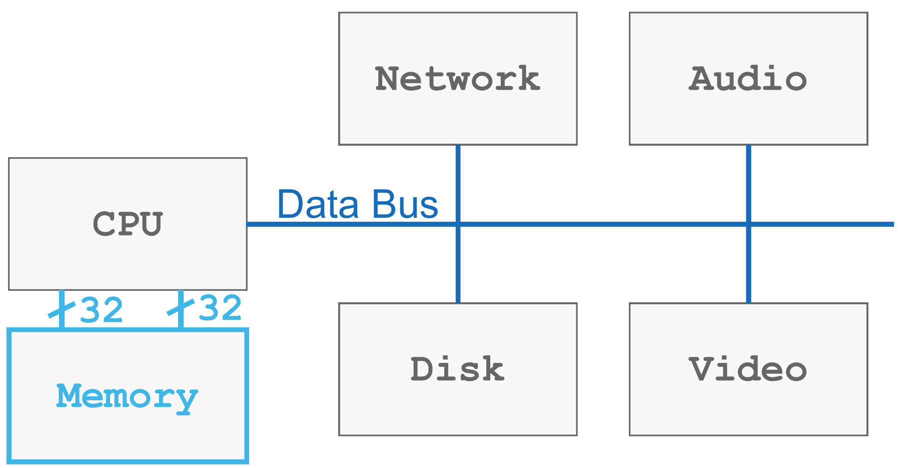
Process Execution

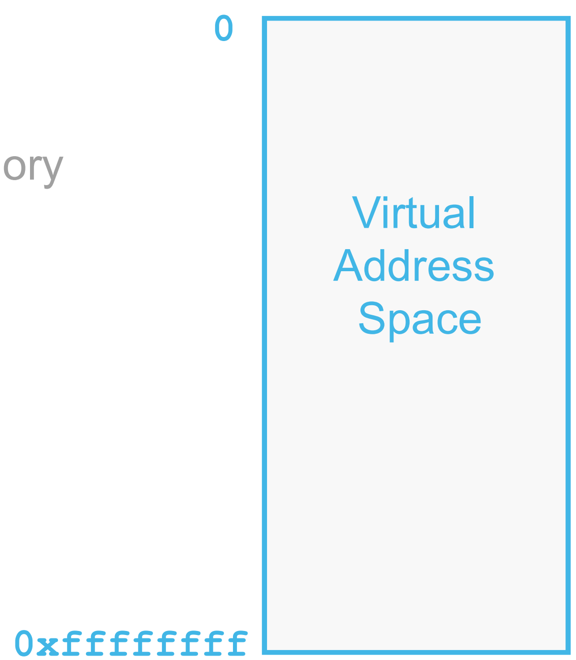
- What is virtual memory?

  Contiguous addressable memory space for a single process

  May be swapped into physical memory from disk in pages

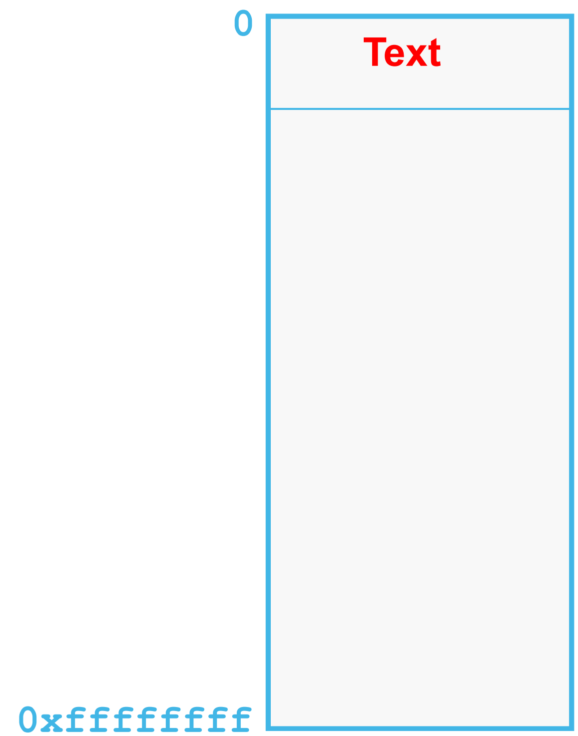
  Let's you pretend each process has its own contiguous memory





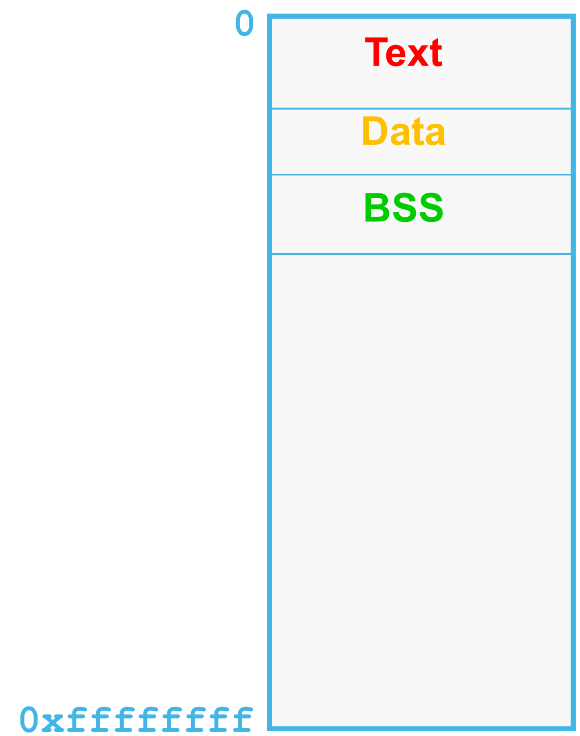
What to Store: Code and Constants

- 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



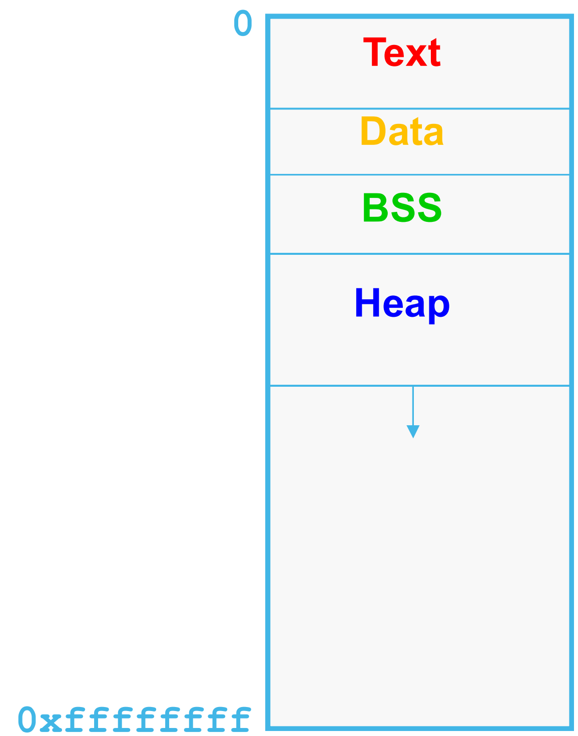
What to Store: "Static" Data

- 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"



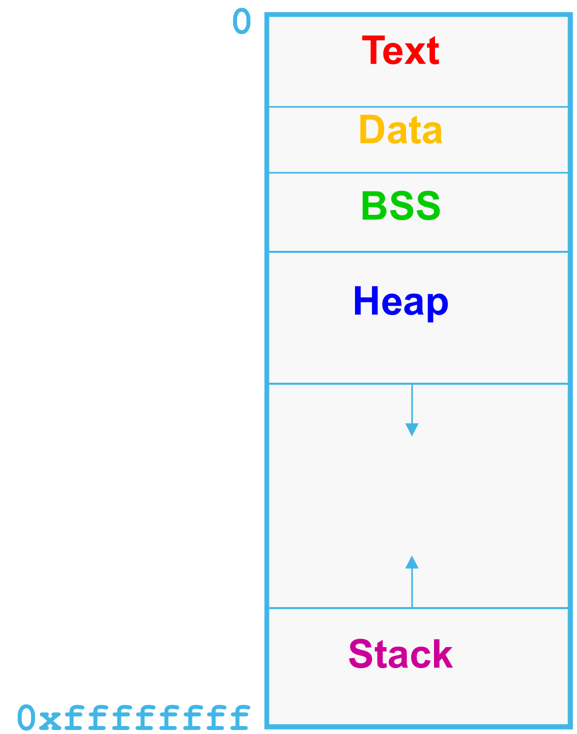
What to Store: Dynamic Memory

- 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



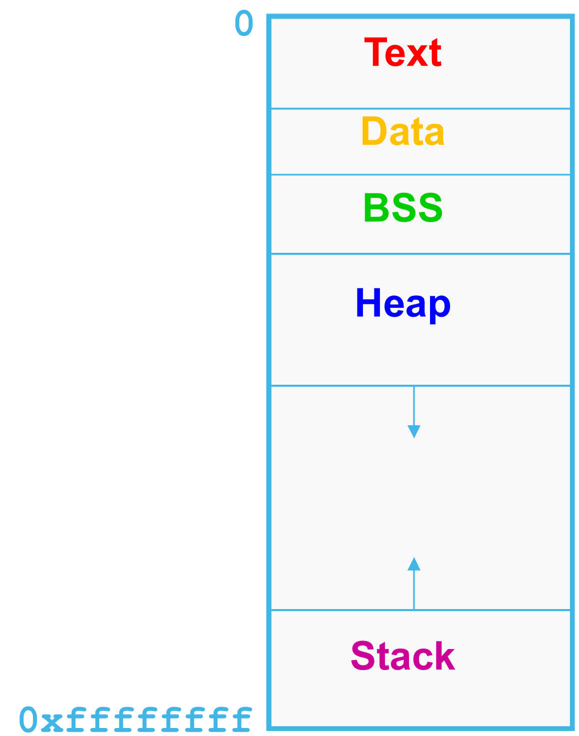
What to Store: Temporary Variables

- 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



Memory Layout: Summary

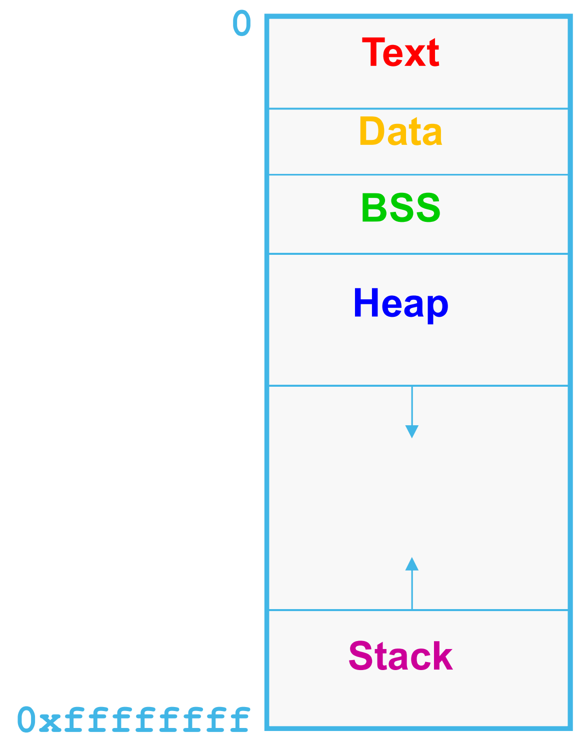
- Text: code, constant data
- Data: initialized global & static variables
- BSS: uninitialized global & static variables
- Heap: dynamic memory
- Stack: local variables



Memory Layout: Example

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

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



Memory Layout: Example

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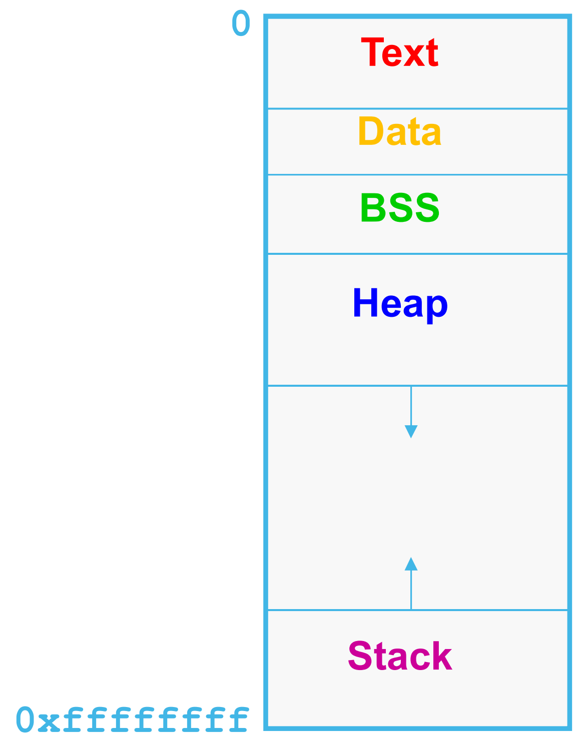
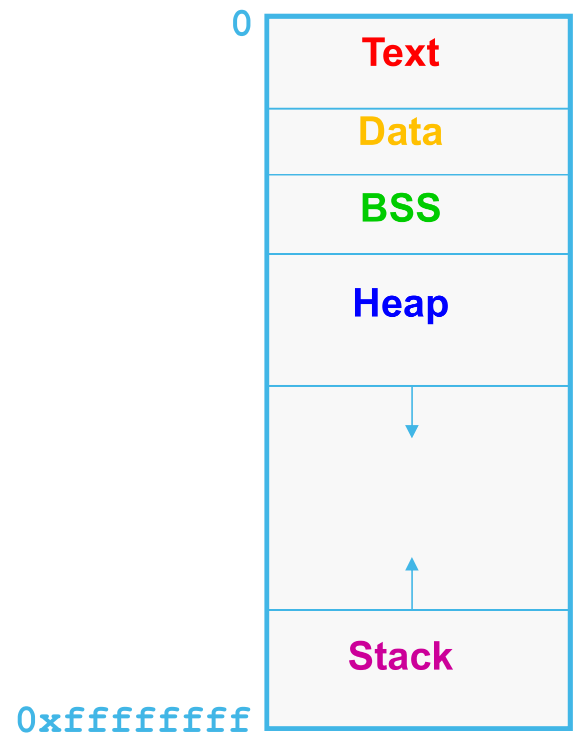
    return p;
}
```



Memory Layout: Data

```
char* string = "hello";
int iSize;

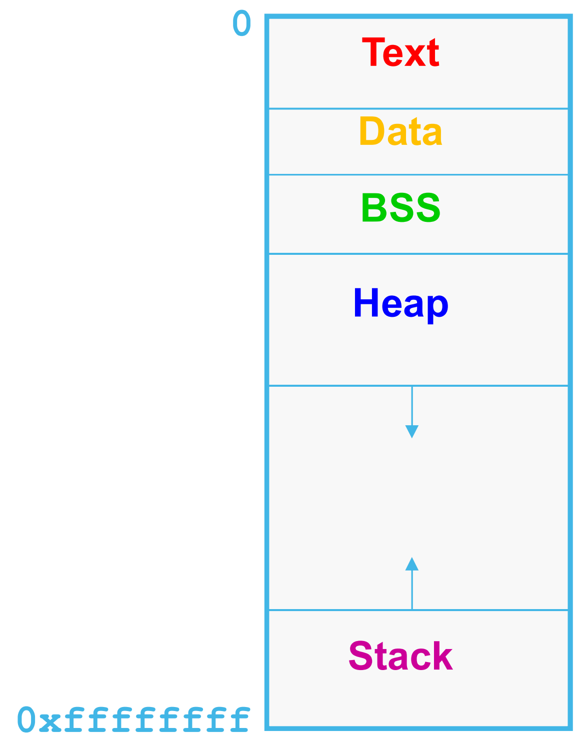
char* f(void)
{
    char* p;
    iSize = 8;
    p = malloc(iSize);
    return p;
}
```



Memory Layout: BSS

```
char* string = "hello";
int iSize;

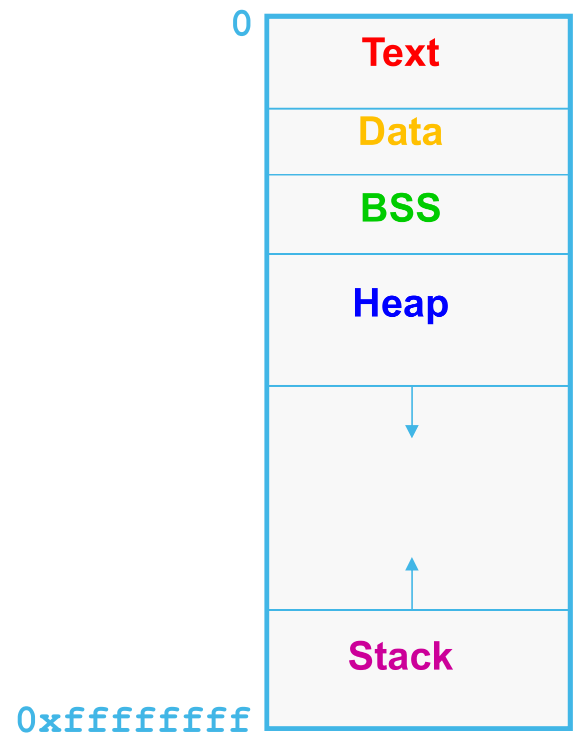
char* f(void)
{
    char* p;
    iSize = 8;
    p = malloc(iSize);
    return p;
}
```



Memory Layout: Heap

```
char* string = "hello";
int iSize;

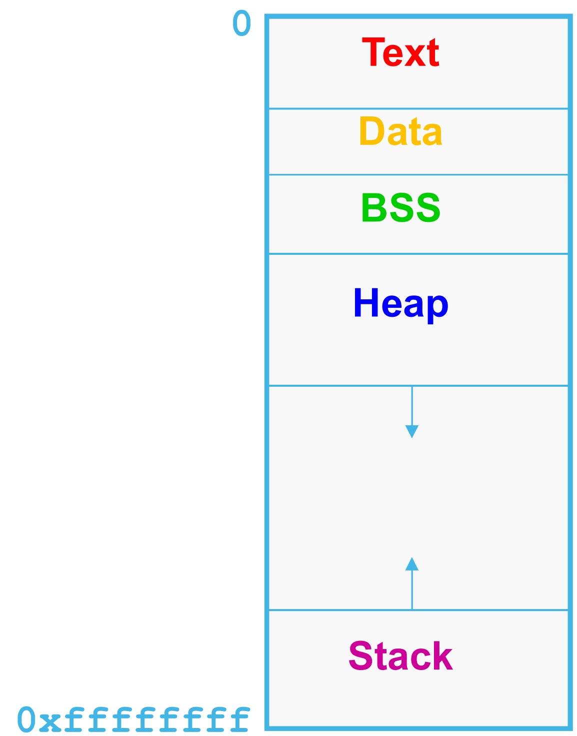
char* f(void)
{
    char* p;
    iSize = 8;
    p = malloc(iSize);
    return p;
}
```



Memory Layout: Stack

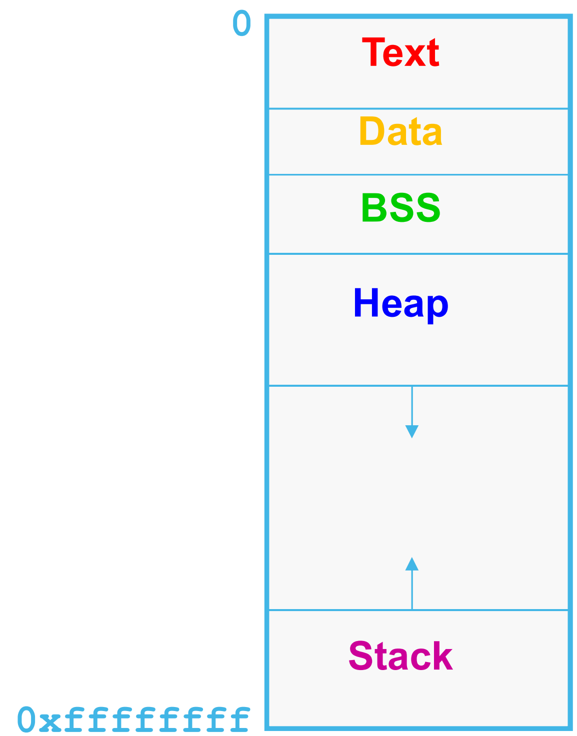
```
char* string = "hello";
int iSize;

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



Memory Allocation and De-allocation

- 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



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Memory Allocation Example

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

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

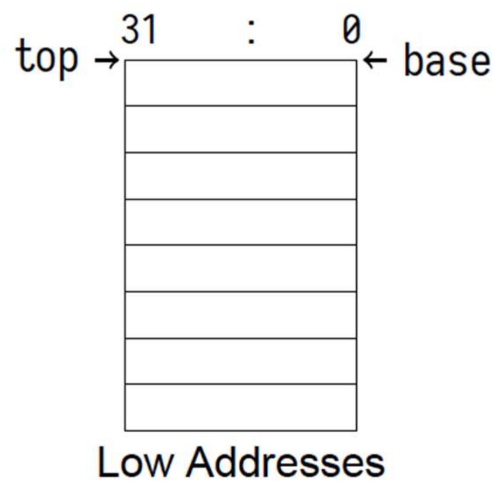
Deallocate on return from f

Deallocate on free()

Aside: Using Sections

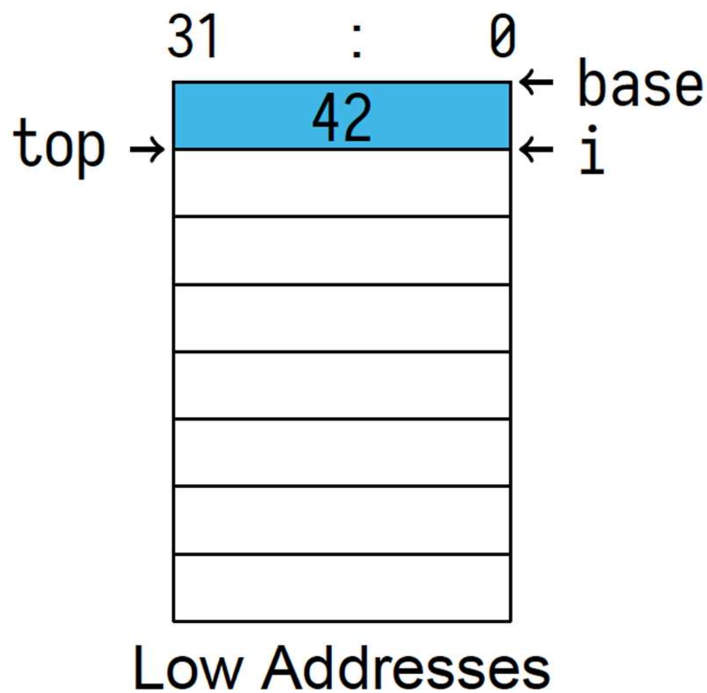
- The exact addresses of sections will vary
- However, you can usually assume certain things
- We’ll look at some of those properties later
- Learning to recognize the location of a pointer is valuable
- For example: all pointers < 4096 (0x1000) are invalid!

Stack Operations

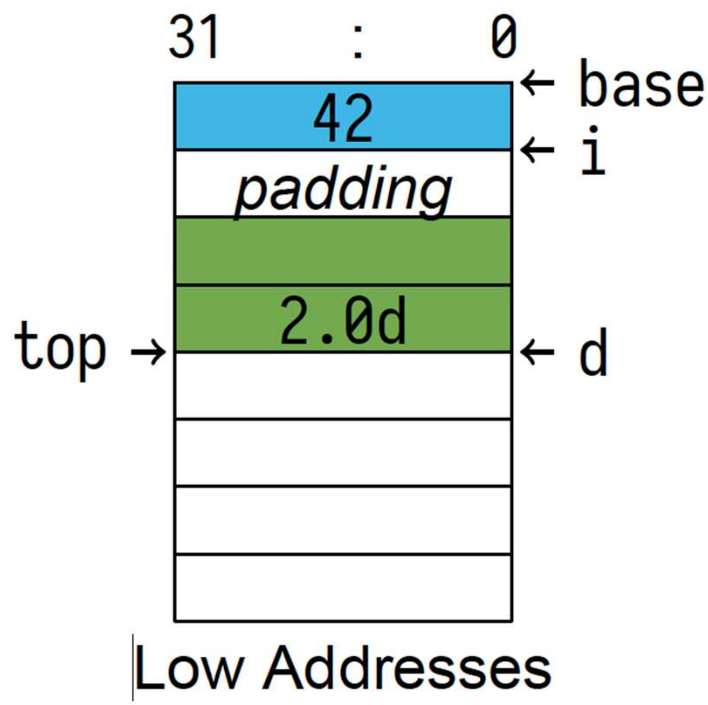


(An empty stack; each row is 32 bits.)

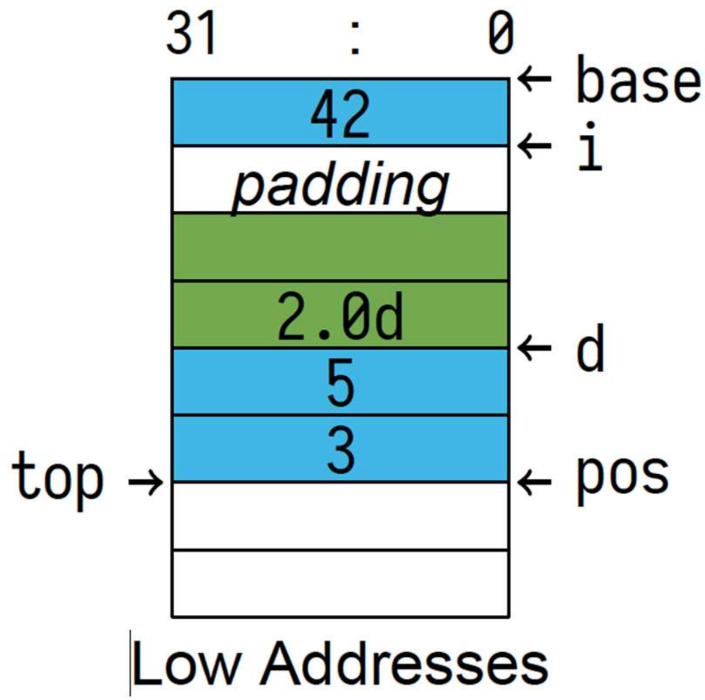
Stack Operations




```
push int i = 42;
```



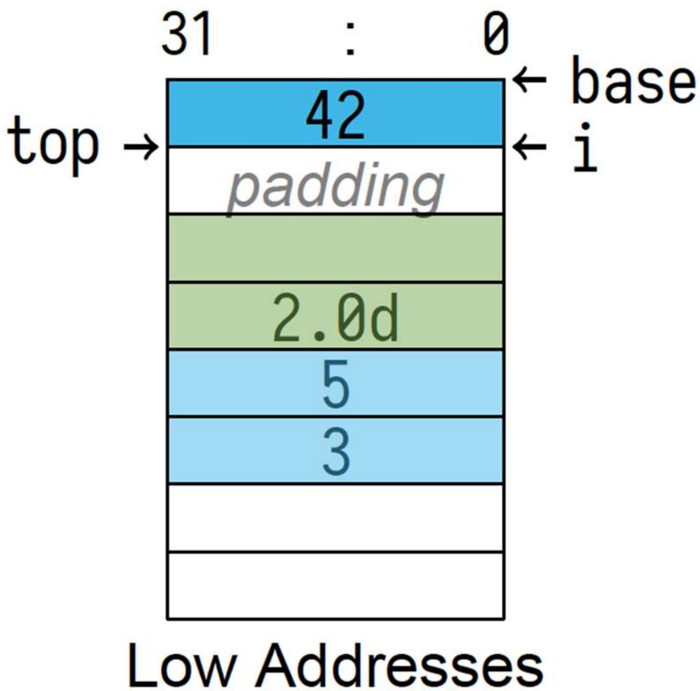
push `double d = 2.0;`
(Remember padding!)



push `struct { int x; int y; } pos = { x = 3, y = 5 };`

Stack items are typically referenced with respect to its top.

E.g., `d` is at `top + 8`



pop 20 bytes to remove pos and d
Note that the unused data remains present on the stack.

Variable Declarations

- A variable does two things
  - Ask compiler to reserve memory for data
  - Name the location of that data

```
int array[32];
```

- "Make space for 32 integers and call that space `array`
- Every non-static, local variable is an automatic variable

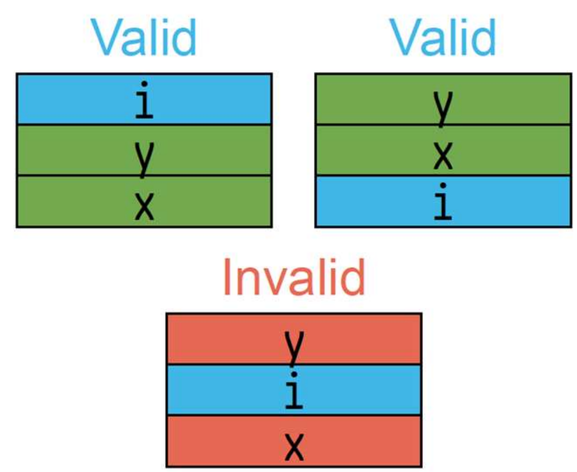
Automatic Variable Lifetime

- Automatic variables are:
  Guaranteed to be allocated before they are first referenced
  Guaranteed to be valid until their enclosing block is done
- In many cases they are created when the function is entered
- Placing automatic variables on the stack allows this

Automatic Variable Placement

- Automatic variables may be allocated anywhere
- The programmer cannot predict their order or location
- They may only be in registers!
- Their structure will be preserved

```
int i;
struct {
  int x; int y;
} pos;
```



Function Call Nesting

- Note that:
  Function calls form a tree over the life of a program
  Function calls form a stack at any point in time
- This is because:
  A function may call many functions consecutively
  A function can call only one function at a time
- These properties directly affect the program stack

Function Calls

- At its simplest, a function call consists of:
  - A jump to a new program location
  - Execution of the function code
  - A jump back to the calling location
- However, many function calls are more complicated. They may:
  - Allocate automatic variables
  - Call other functions
  - Temporarily save registers
  - …
- In these cases, functions require a stack frame.

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Stack Frames

- A stack frame holds information for a single function invocation.
- While the details vary by platform, it will include:
  - Saved processor registers
  - Local variables for the current function
  - Arguments for any called function
  - The return location for any called function
- We will discuss all of these except saved processor registers.

(Maybe we'll get to those later.)

Local Variables

- We have previously discussed automatic variables.
- Often, all local variables for a function are allocated together.
- When the function is entered, it will immediately move the top of the stack to make room for its local storage.
- This portion of the stack frame is then of fixed size.
- Its size is often not saved, but recorded in the program instructions by the compiler.
- The location of individual variables are likewise recorded.

Function Arguments

- The platform ABI will determine how arguments are passed
- Normally, it is a combination of registers and stack space
- On x86-64 Linux, the first six 64 bit values are passed in
- registers
- Any additional arguments are pushed onto the stack
- Therefore, many functions have no arguments on the stack

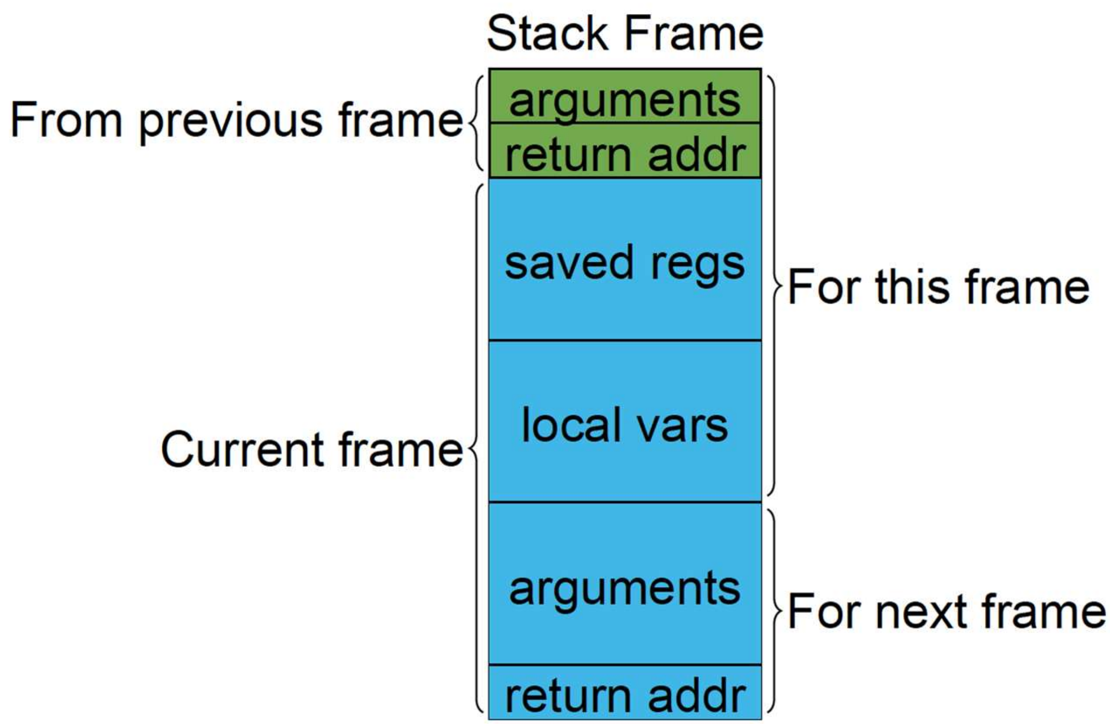
Function Arguments Layout

- If function arguments are pushed onto the stack, they are normally pushed in reverse order
- That is, the first function argument is closest to the top
- Among other reasons, this allows for a variable number of arguments
- Consider `printf`: it takes 1 or more arguments
- The first format argument tells it how many

The Program Counter

- The other major item that must be tracked for the function call stack is the program counter
- The program counter is the address of the machine instruction the processor is currently executing
- For a function call:
  - the current program counter is pushed before jumping to the called function
  - the called function pops the program counter in order to return
- On some architectures there is a dedicated instruction for this

A stack frame



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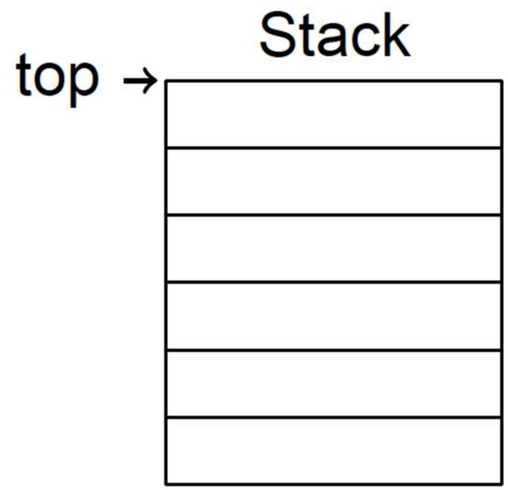
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



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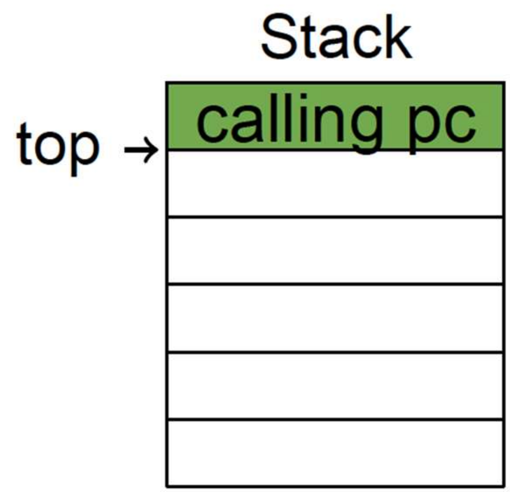


call foo()

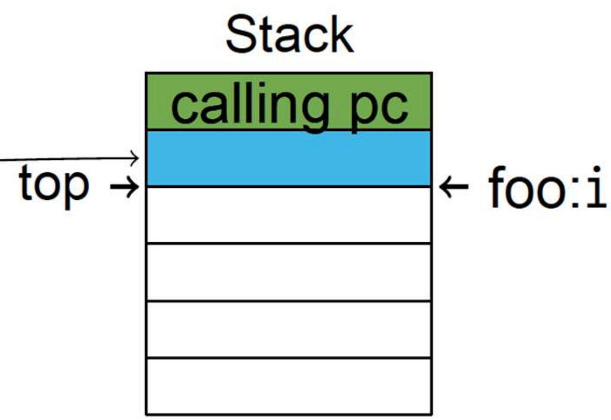
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



Reserve space for foo()'s locals

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Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
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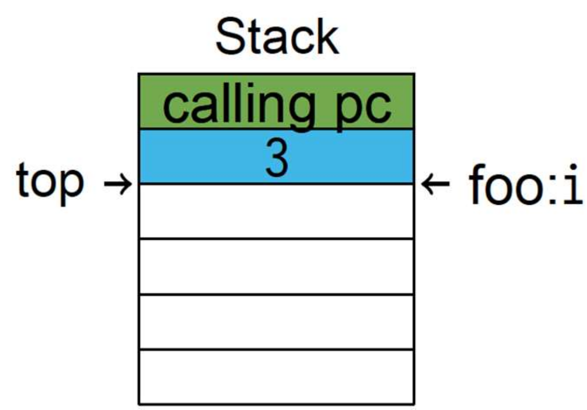
    i = 5 + j;
}
```



Execute foo()

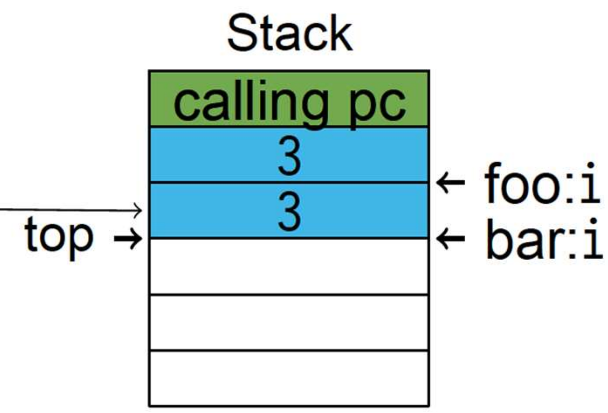
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



Execute foo();
prepare to call bar()

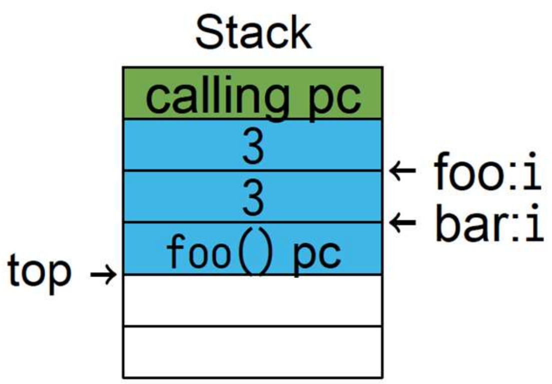
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



Push PC; call bar()

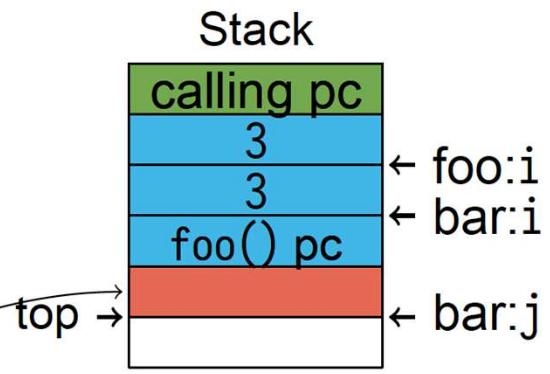
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



Reserve space for bar()'s locals

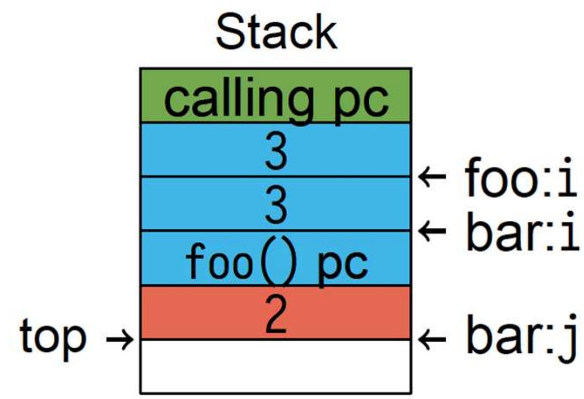
Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
    int j = 2;

    i = 5 + j;
}
```



Execute bar()

Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
    /* ... */
}

void bar(int i) {
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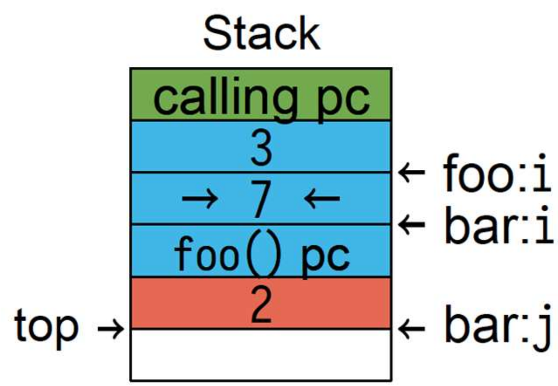
    i = 5 + j;
}
```



Execute bar()

Stack Frame: Example

```
void foo() {
    int i = 3;

    bar(i);
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}

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    i = 5 + j;
}
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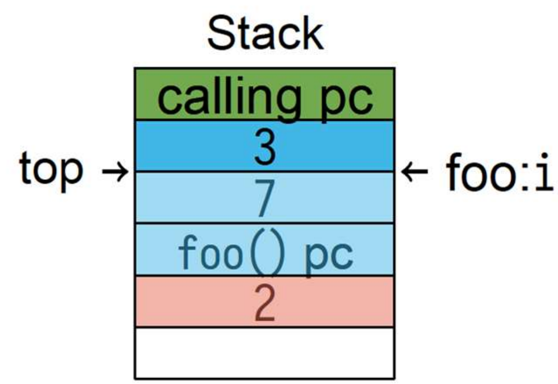

Return from bar();
Pop bar()'s stack frame;
Execute foo()

Summary

- POSIX programs are laid out in sections
  The stack is a section
- The stack grows downward
- Automatic variables are allocated on the stack
- Stack frames track function calls
- Items removed from the stack are not cleared
- Stack-allocated arguments are why C is call-by-value

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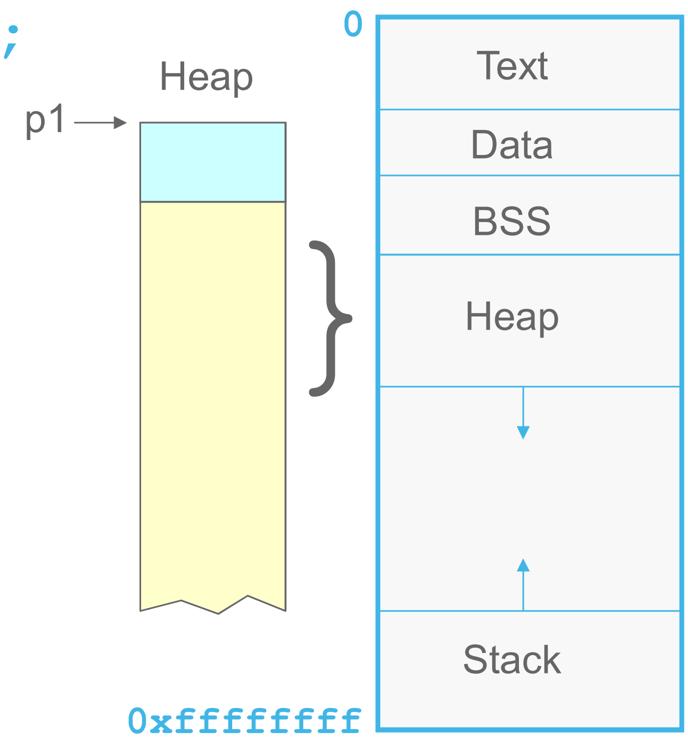
Heap: Dynamic Memory

- ```
  #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);
```


```

Heap: Dynamic Memory

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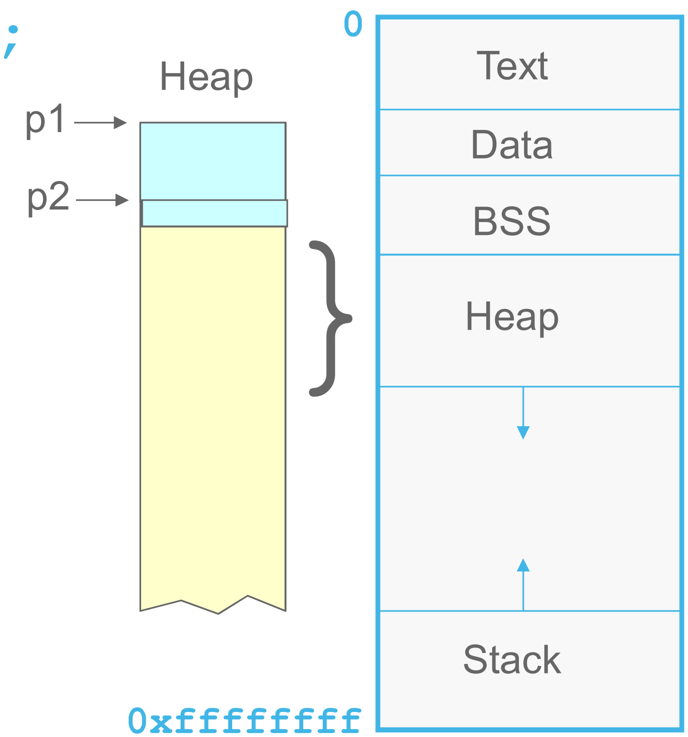
  ```

```
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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Heap: Dynamic Memory

- ```
  #include <stdlib.h>
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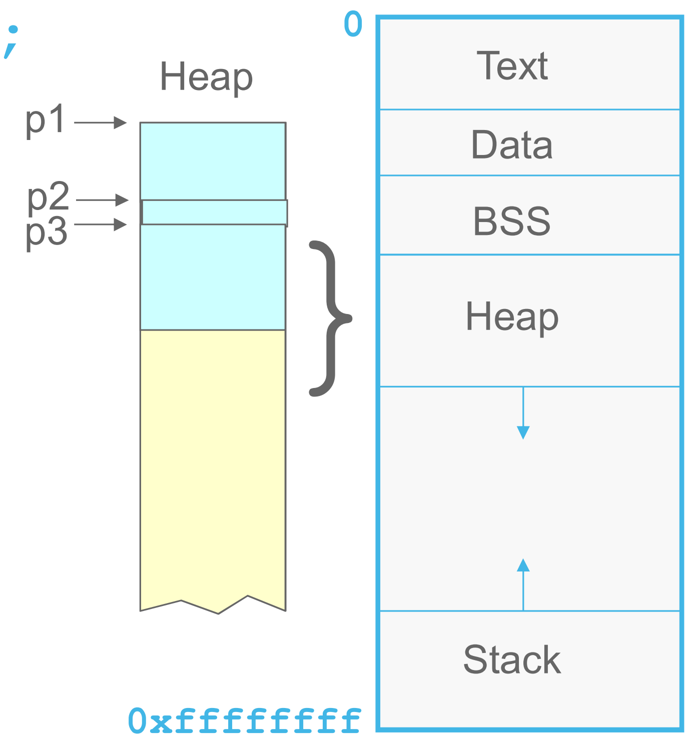
  ```

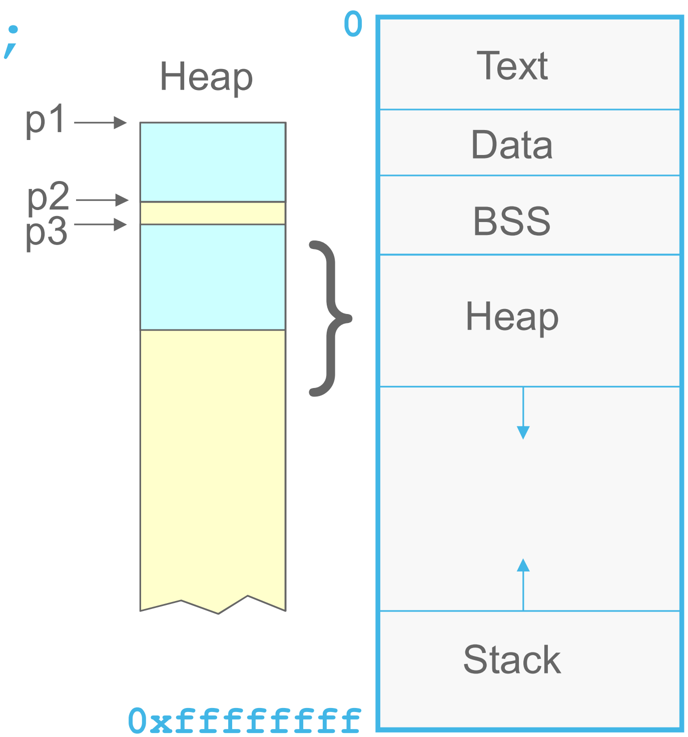
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```


```

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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Heap: Dynamic Memory

- ```
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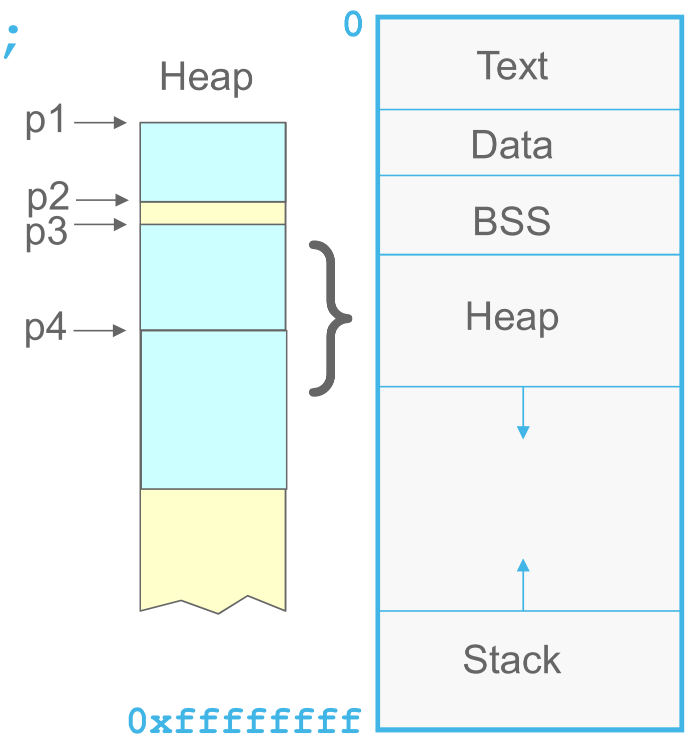
```


```

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and Engineering
School of Engineering and Applied Sciences

Heap: Dynamic Memory

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

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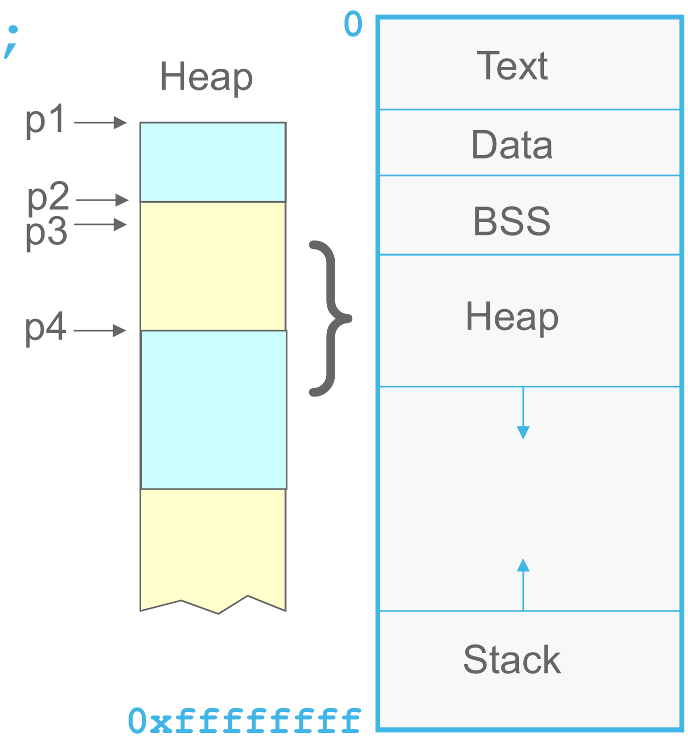
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```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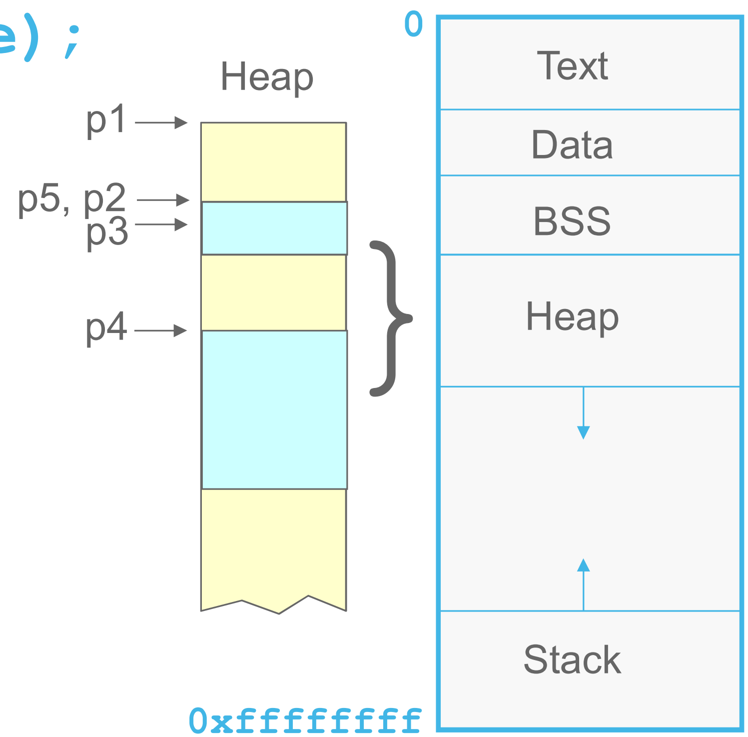

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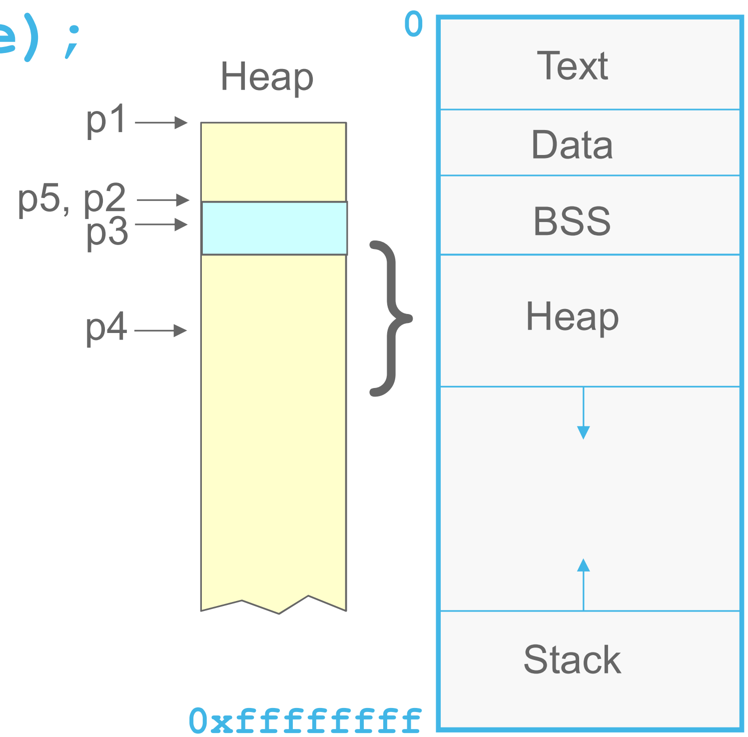

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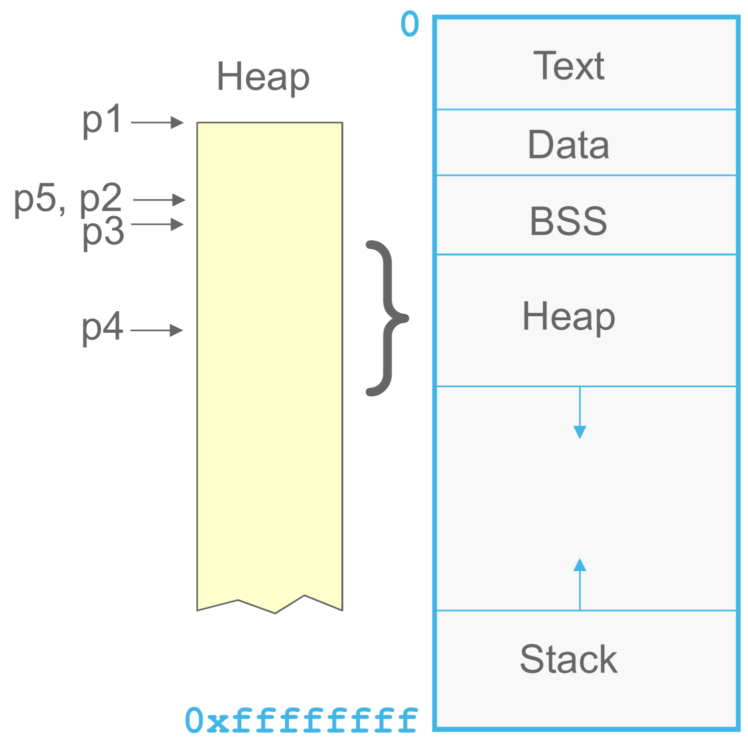
```

Readings