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The Heap and Structs
CSE 333 Spring 2021

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Teaching Assistants:

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Dylan Hartono	Elizabeth Haker	Kyrie Dowling
Leo Liao	Markus Schiffer	Neha Nagvekar
Nonthakit Chaiwong	Ramya Challa	

Administrivia

- ex1 grades:
  - We will be giving "autograder correction" points
  - Regrade requests: open 24 hr after, close 72 hr after release
- We recommend doing the extra exercises
  - Also, can Google for "C pointer exercises"
  - You MUST master pointers quickly, or you'll have trouble with the rest of the course (including hw1)
- hw0 due tonight *before* 11:59 pm (and 0 seconds)
  - Git: add/commit/push, then tag with `hw0-final`, then push tag
    - Then clone your repo somewhere totally different and do `git checkout hw0-final` and verify that all is well

Administrivia

- hw1 due Thursday, 4/15 11:59 pm
  - You ***may not*** modify interfaces (`.h` files)
  - But ***do*** read the interfaces while you're implementing them(!)
  - **New this quarter**: record bugs in bugjournal.md
  - Suggestion: Have more fun, less anxiety: pace yourself and make steady progress; don't leave it until the last minute!
- Gitlab repo usage
  - Commit things regularly (not all at once at the end)
    - Newly completed units of work / milestones / project parts
  - Provides backups – can retrieve old versions of files ☺
  - Don't push .o and executable files or other build products

Lecture Outline

- **Heap-allocated Memory**
  - **`malloc()` and `free()`**
  - **Memory leaks**
- `structs` and `typedef`
- Implementing Data Structures in C

Memory Allocation So Far

- So far, we have seen two kinds of memory allocation:

```
int counter = 0;      // global var

int main(int argc, char** argv) {
  counter++;
  printf("count = %d\n",counter);
  return 0;
}
```

```
int foo(int a) {
  int x = a + 1;      // local var
  return x;
}

int main(int argc, char** argv) {
  int y = foo(10);    // local var
  printf("y = %d\n",y);
  return 0;
}
```

- `counter` is ***statically***-allocated
  - Allocated when program is loaded
  - Deallocated when program exits
- `a`, `x`, `y` are ***automatically***-allocated
  - Allocated when function is called
  - Deallocated when function returns

Dynamic Allocation

- What we want is ***dynamically***-allocated memory
  - Your program explicitly requests a new block of memory
    - The language allocates it at runtime, perhaps with help from OS
  - Dynamically-allocated memory persists until either:
    - Your code explicitly deallocated it (*manual memory management*)
    - A garbage collector collects it (*automatic memory management*)
- C requires you to manually manage memory
  - Gives you more control, but causes headaches

Why Dynamic Allocation?

- Situations where static and automatic allocation aren't sufficient:
  - We need memory that persists across multiple function calls but not for the whole lifetime of the program
  - We need more memory than can fit on the stack
  - We need memory whose size is not known in advance

Fixed size for linux x86-64

```
// this is pseudo-C code
char* ReadFile(char* filename) {
  int size = GetFileSize(filename);
  char* buffer = AllocateMem(size);

  ReadFileIntoBuffer(filename, buffer);
  return buffer;
}
```

Aside: NULL

- NULL is a memory location that is guaranteed to be invalid
  - In C on Linux, NULL is 0x0 and an attempt to dereference NULL *causes a segmentation fault*
- Useful as an indicator of an uninitialized (or currently unused) pointer or allocation error
  - It's better to cause a segfault than to allow the corruption of memory!

segfault.c

```
int main(int argc, char** argv) {
  int* p = NULL;
  *p = 1;  // causes a segmentation fault
  return EXIT_SUCCESS;
}
```

STYLE TIP

malloc()

Returns a void*
Good practice to explicitly cast

- General usage: `var = (type*) malloc(size in bytes)`

- **malloc** allocates a block of memory of the requested size
  - Returns a pointer to the first byte of that memory
    - And returns `NULL` if the memory allocation failed!
  - You should assume that the memory initially contains garbage
  - You'll typically use `sizeof` to calculate the size you need

```
// allocate a 10-float array
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL) {
  return errcode;
}
...    // do stuff with arr
```

ALWAYS CHECK FOR NULL

`calloc()`

Different params, 2 params instead of 1!

- General usage:

```
var = (type*) calloc(num, bytes per element)
```

- Like `malloc`, but also zeros out the block of memory
  - Helpful when zero-initialization wanted (but don't use it to mask bugs – fix those)
  - Slightly slower; but useful for non-performance-critical code or if you really are planning to zero out the new block of memory
  - `malloc` and `calloc` are found in `stdlib.h`

```
// allocate a 10-double array
double* arr = (double*) calloc(10, sizeof(double));
if (arr == NULL) {
  return errcode;
}
...   // do stuff with arr
```

DEBUG TIP

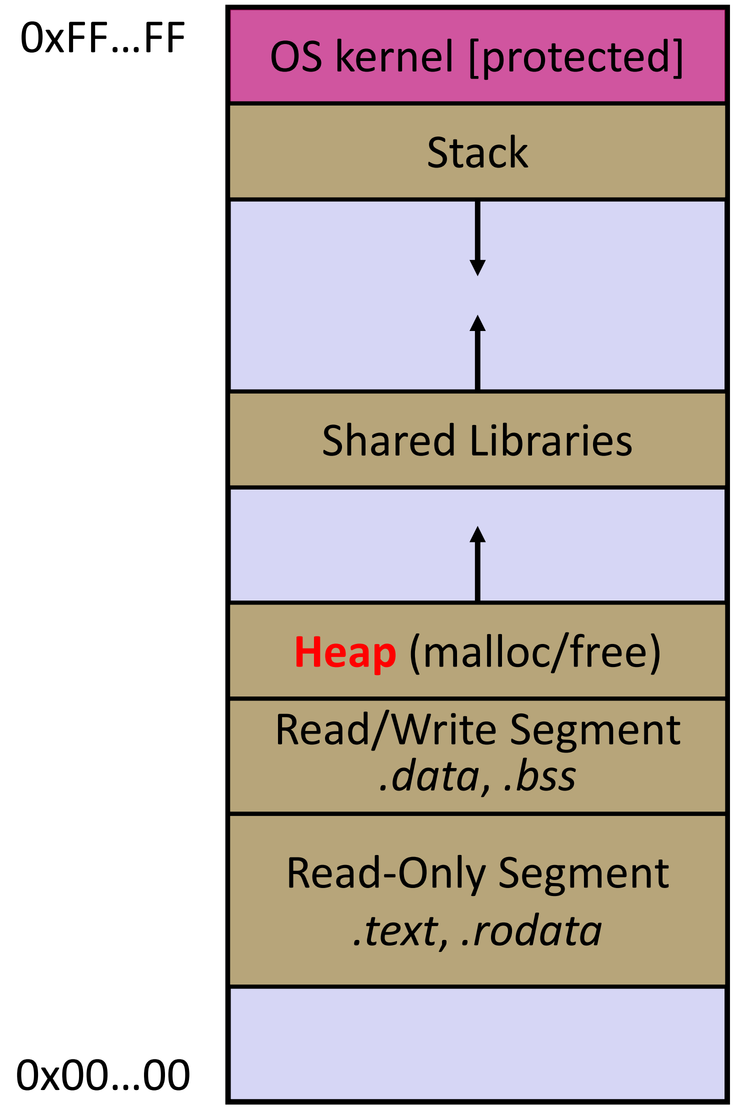
free()

- Usage: `free(pointer);`
- Deallocates the memory pointed-to by the pointer
  - Pointer *must* point to the first byte of heap-allocated memory (*i.e.* something previously returned by **`malloc`** or **`calloc`**)
  - Freed memory becomes eligible for future allocation
  - `free(NULL);` does nothing.
  - The bits in the pointer are *not changed* by calling free
    - Defensive programming: can set pointer to `NULL` after freeing it

```
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
  return errcode;
...              // do stuff with arr
free(arr);
arr = NULL;      // OPTIONAL
```

The Heap

- The Heap is a large pool of available memory used to hold dynamically-allocated data
  - **`malloc`** allocates chunks of data in the Heap; **`free`** deallocates those chunks
  - **`malloc`** maintains bookkeeping data in the Heap to track allocated blocks
    - Lab 5 from 351!

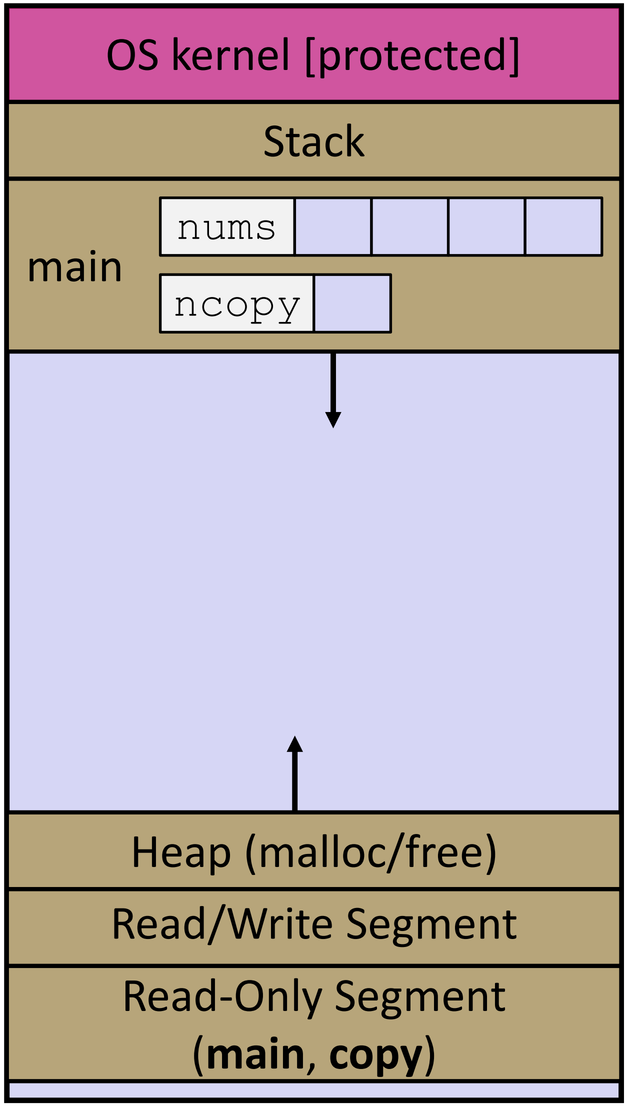


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

```c
#include <stdlib.h>

int* copy(int a[], int size) {
  int i, *a2;

  a2 = (int*)malloc(size*sizeof(int));
  if (a2 == NULL)
    return NULL;

  for (i = 0; i < size; i++)
    a2[i] = a[i];

  return a2;
}

int main(int argc, char** argv) {
  int nums[4] = {1, 2, 3, 4};
  int* ncopy = copy(nums, 4);
  // .. do stuff with the array ..
  free(ncopy);
  return 0;
}
```



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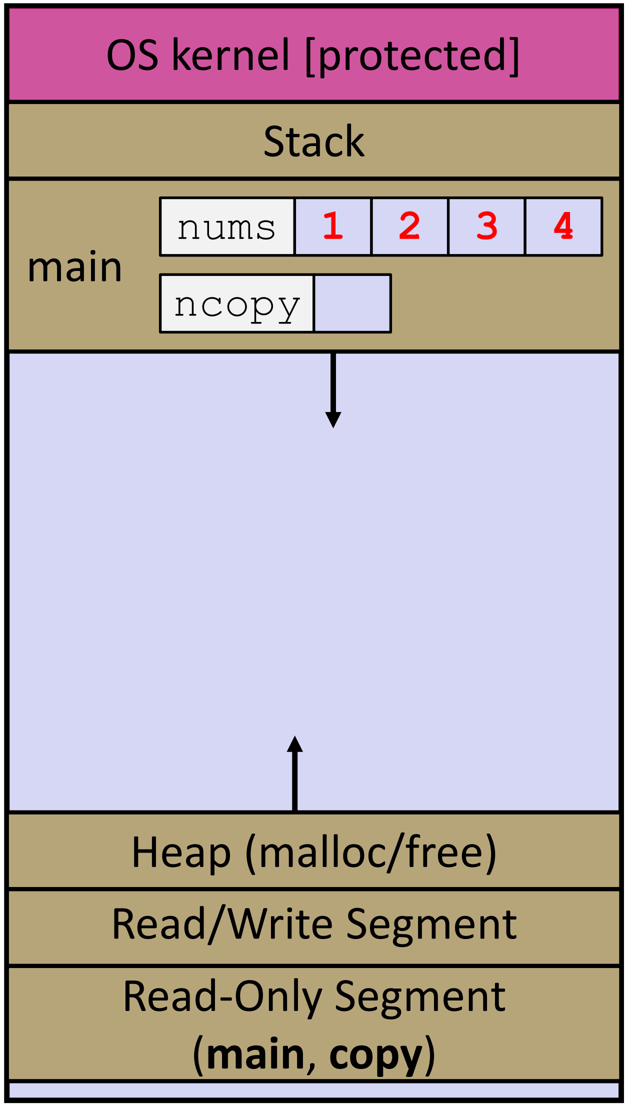

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                'Promoted' to int*
int* copy(int a[], int size) {
  int i, *a2;
                4        4
  a2 = malloc(size*sizeof(int));
  if (a2 == NULL)
    return NULL;

  for (i = 0; i < size; i++)
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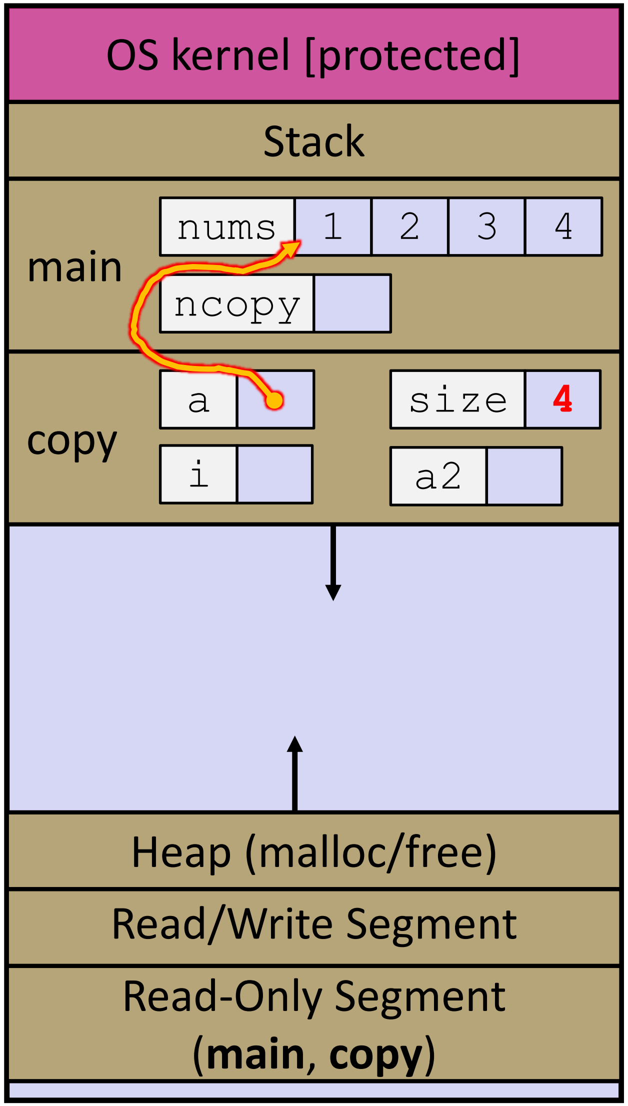

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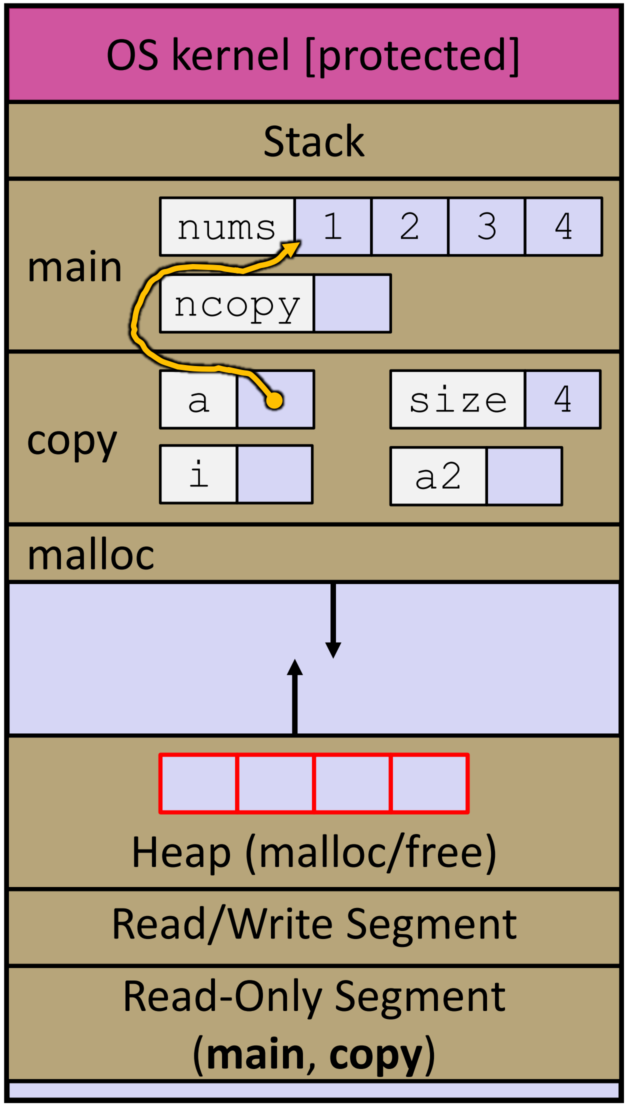

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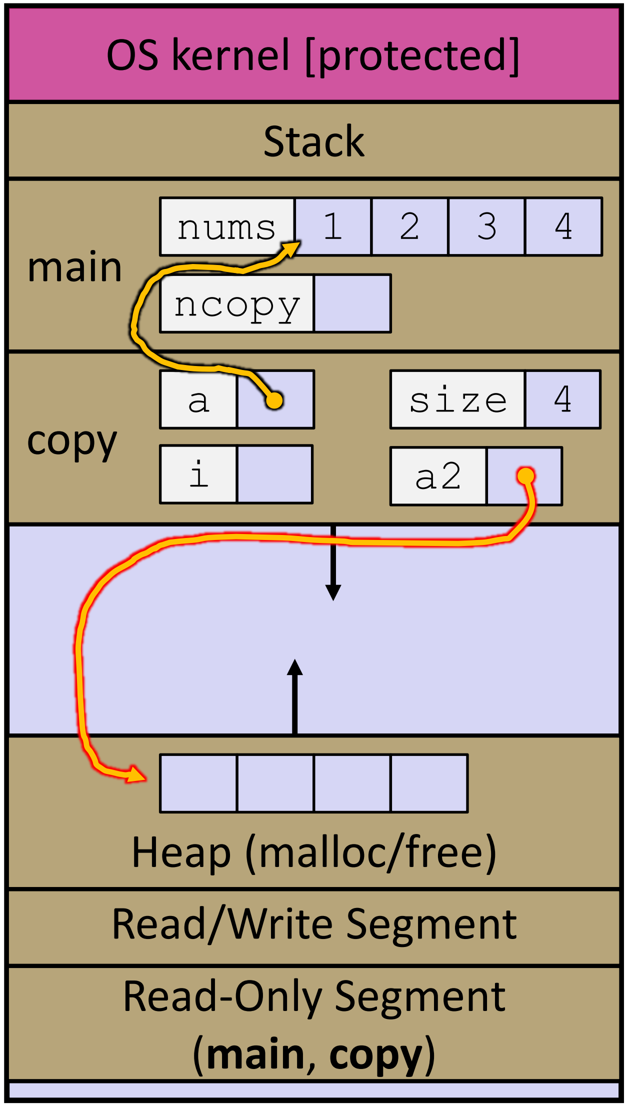
```

Error checking, NULL returned on error



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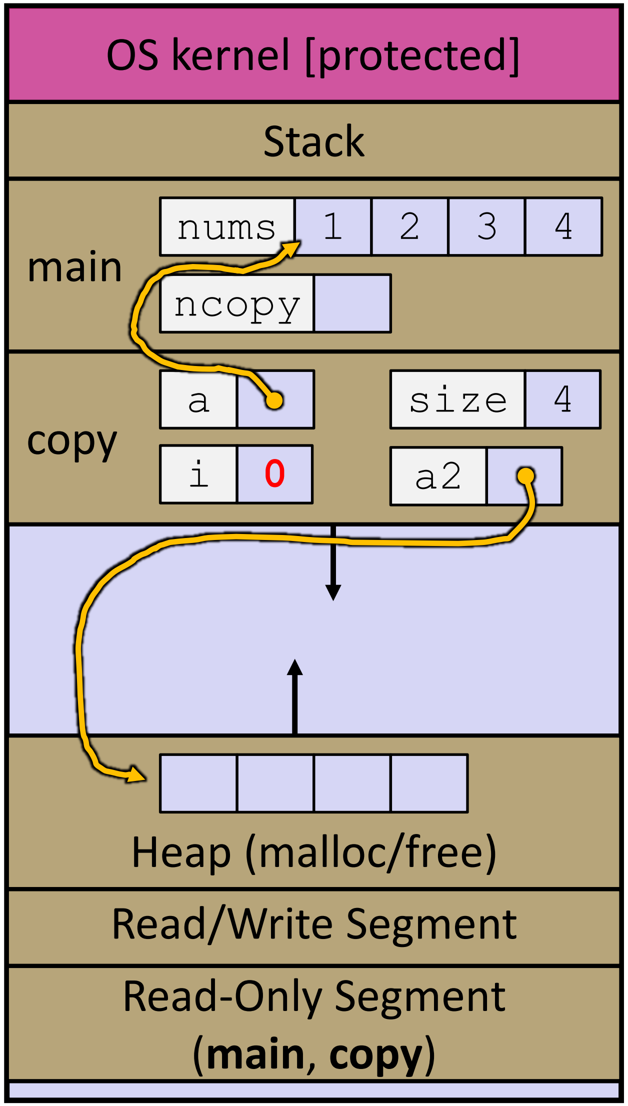

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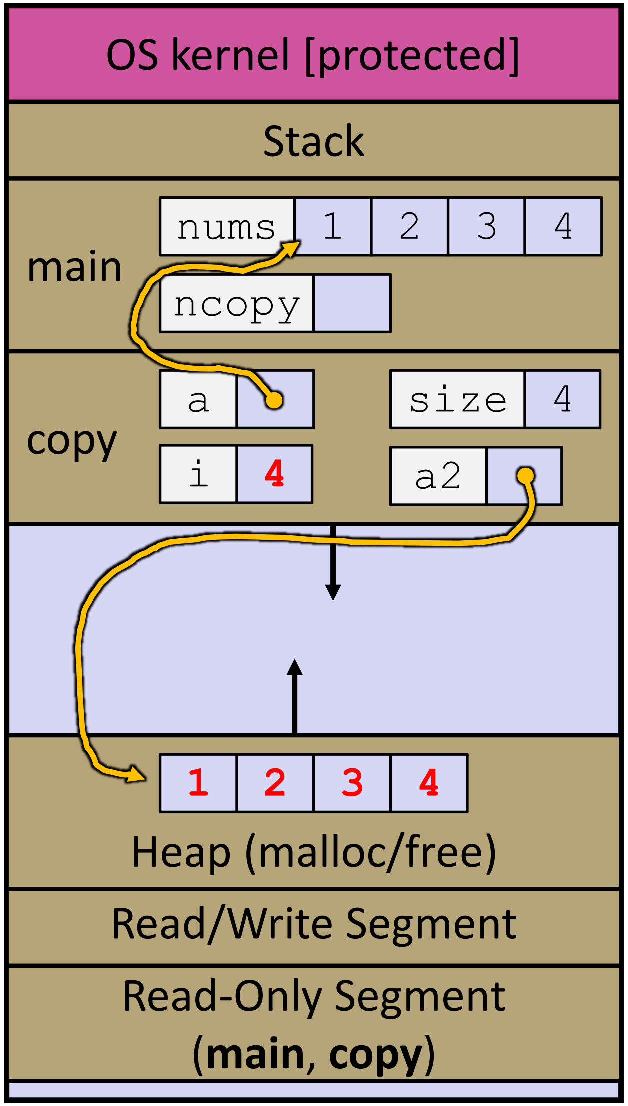

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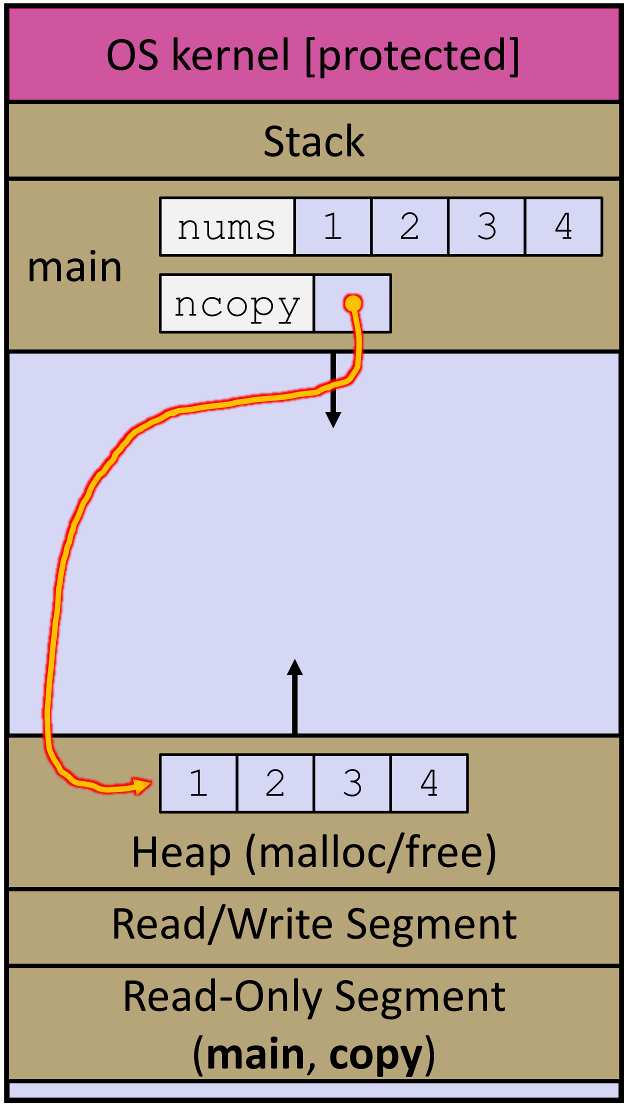

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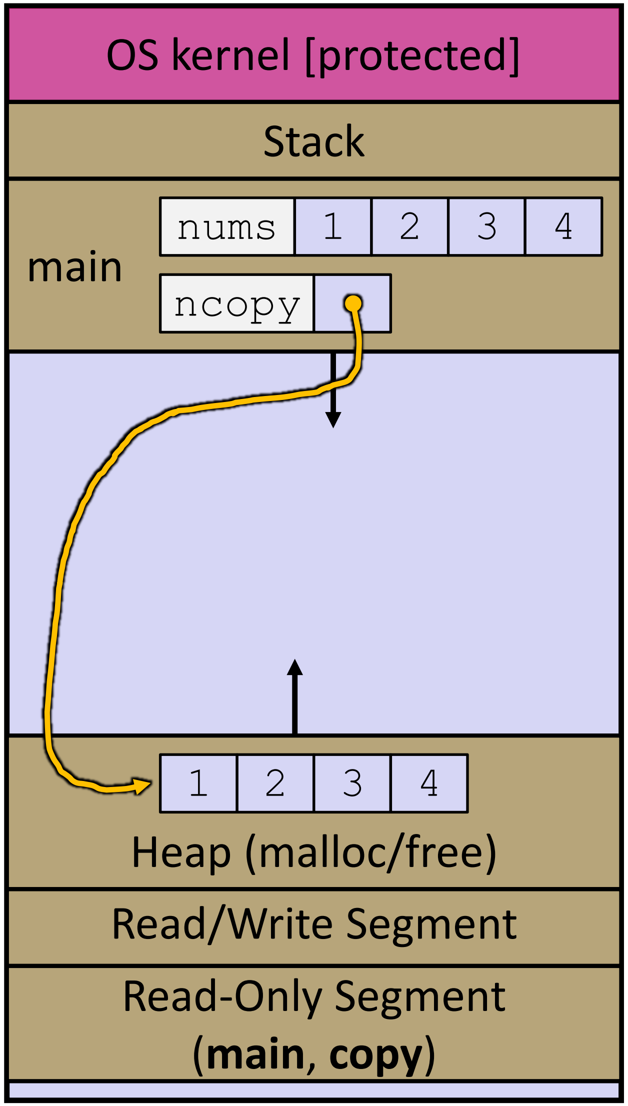

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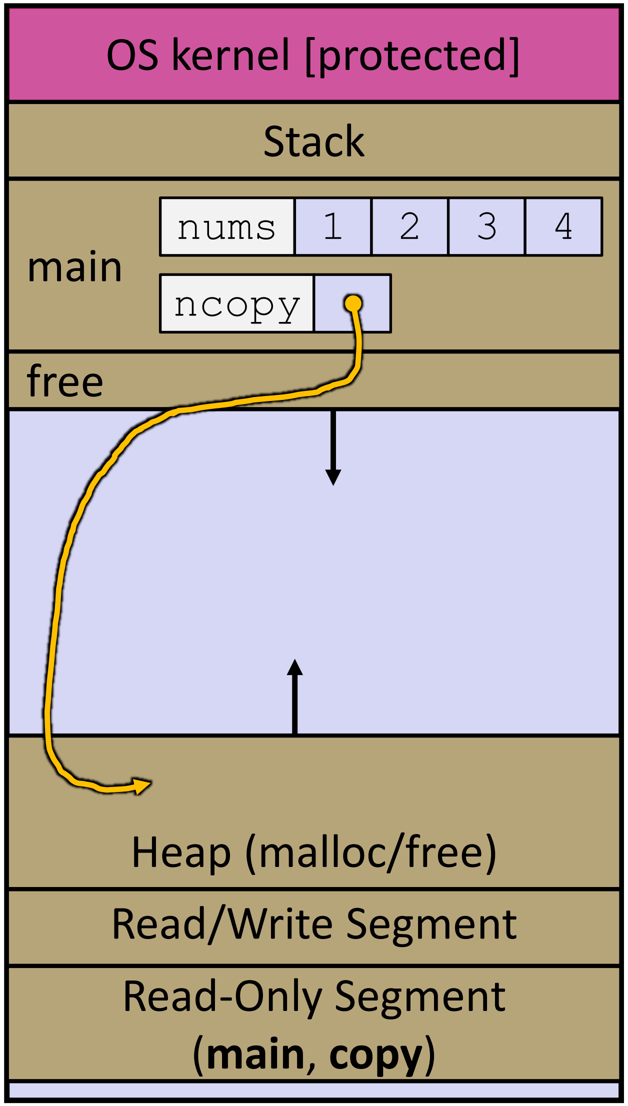

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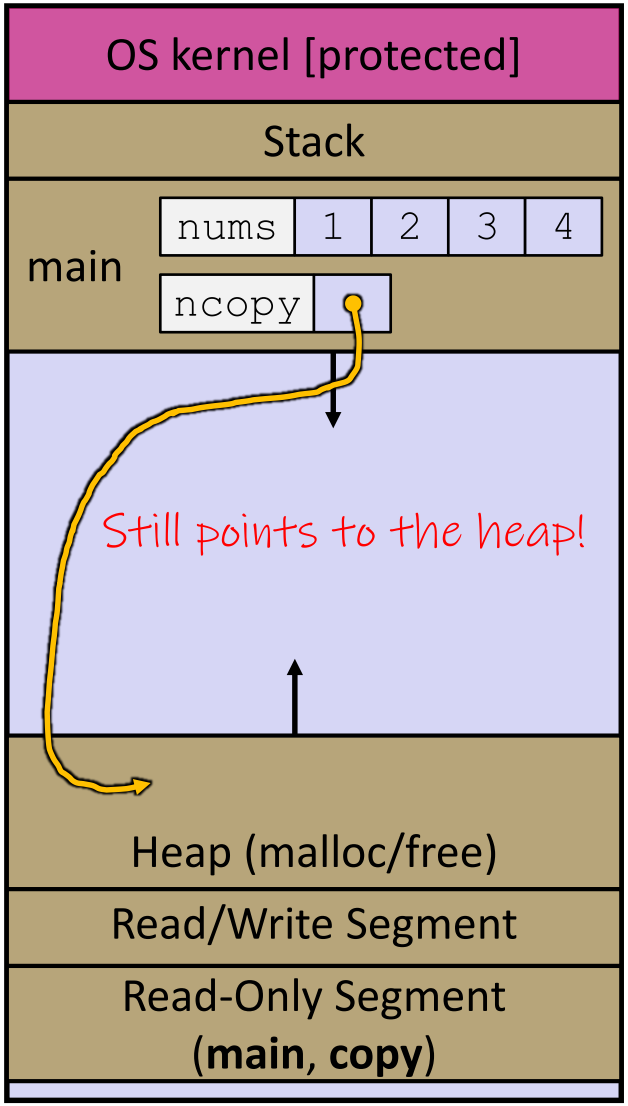

Poll Everywhere

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- Which line below is first *guaranteed* to cause an error?

A. Line 1

B. Line 4

C. Line 6

D. Line 7

E. We're lost...

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

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

1  a[2] = 5;
2  b[0] += 2;
3  c = b+3;
4  free(&(a[0]));
5  free(b);
6  free(b);
7  b[0] = 5;

  return 0;
}
```

Memory Corruption

- There are all sorts of ways to corrupt memory in C

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

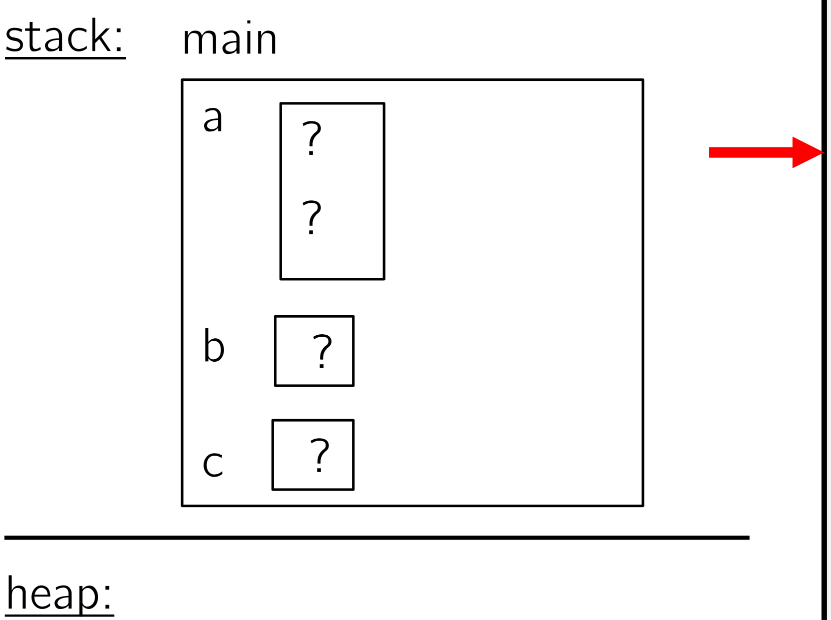
int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

memcorrupt.c

Memory Corruption - What Happens?

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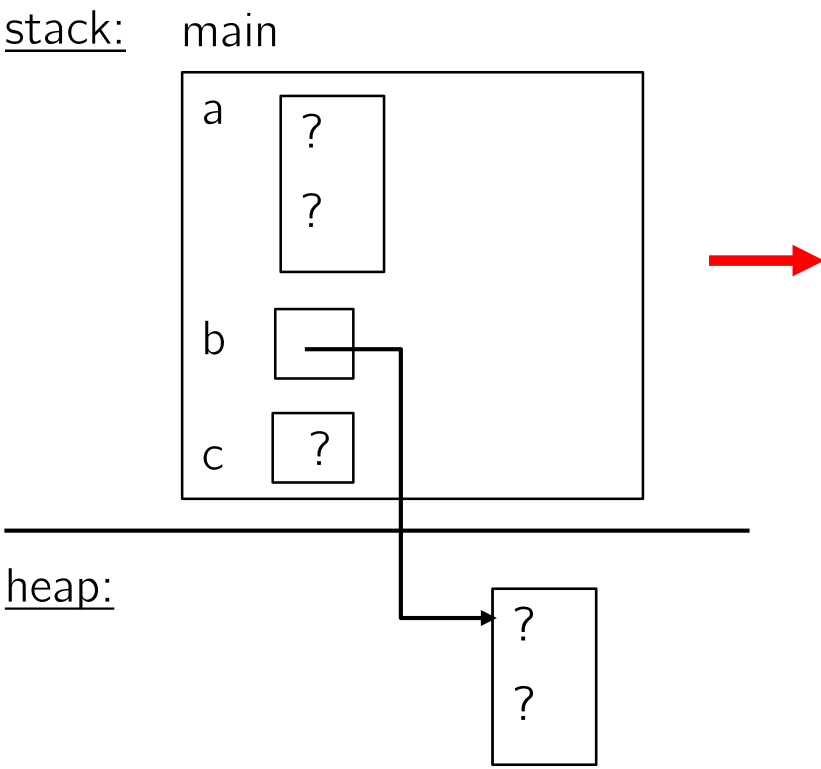


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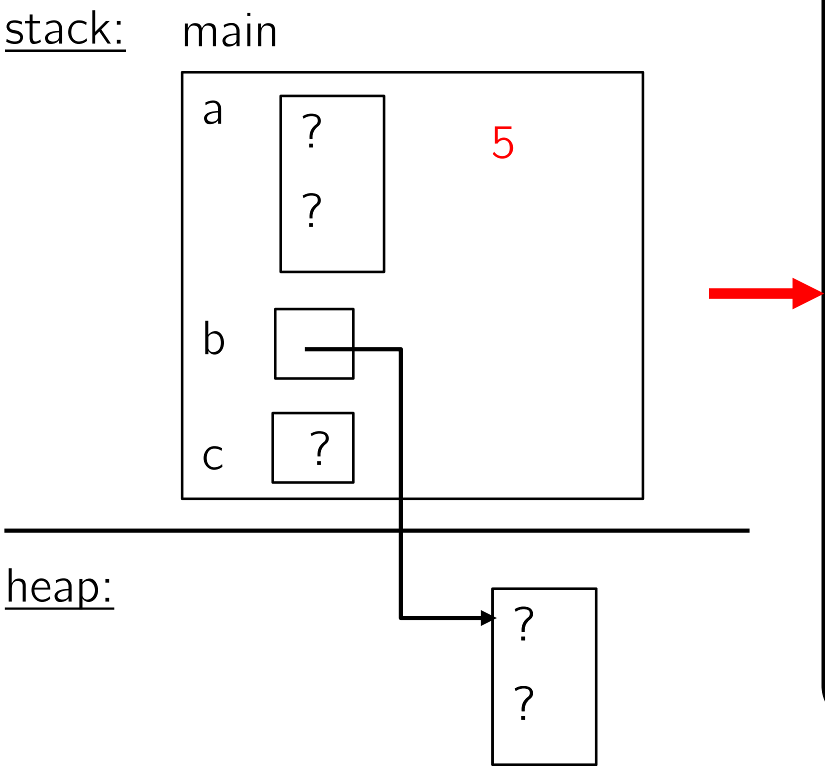


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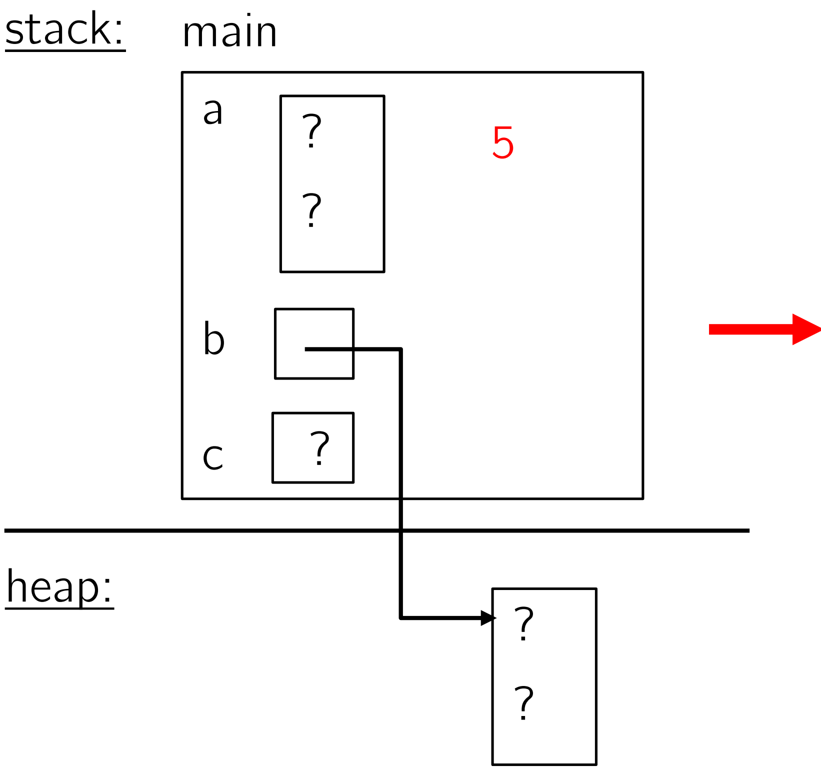


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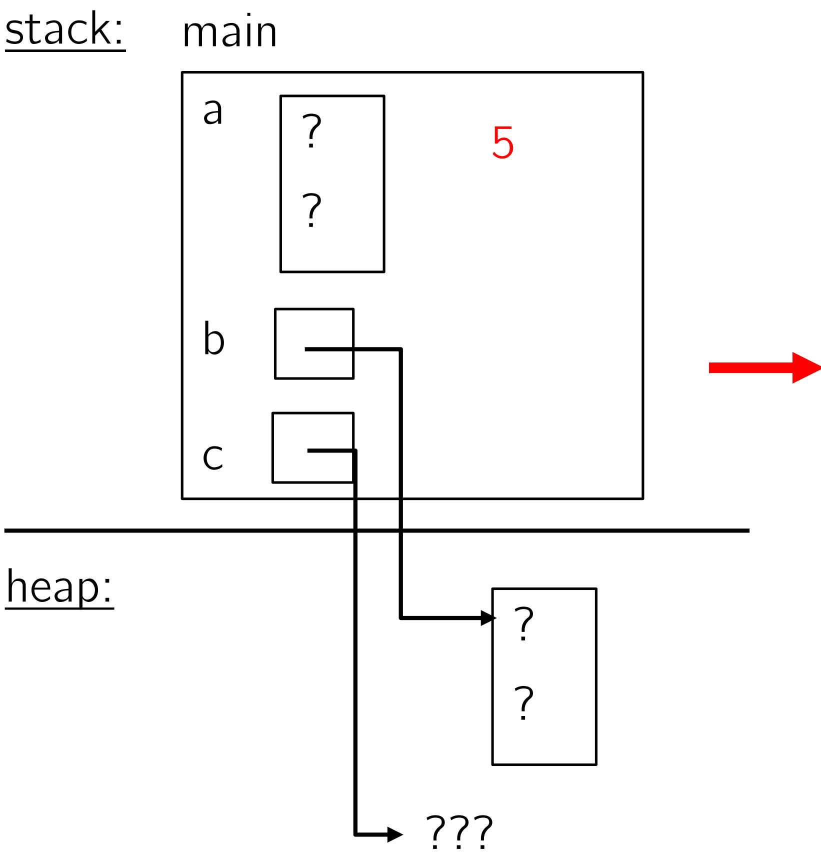


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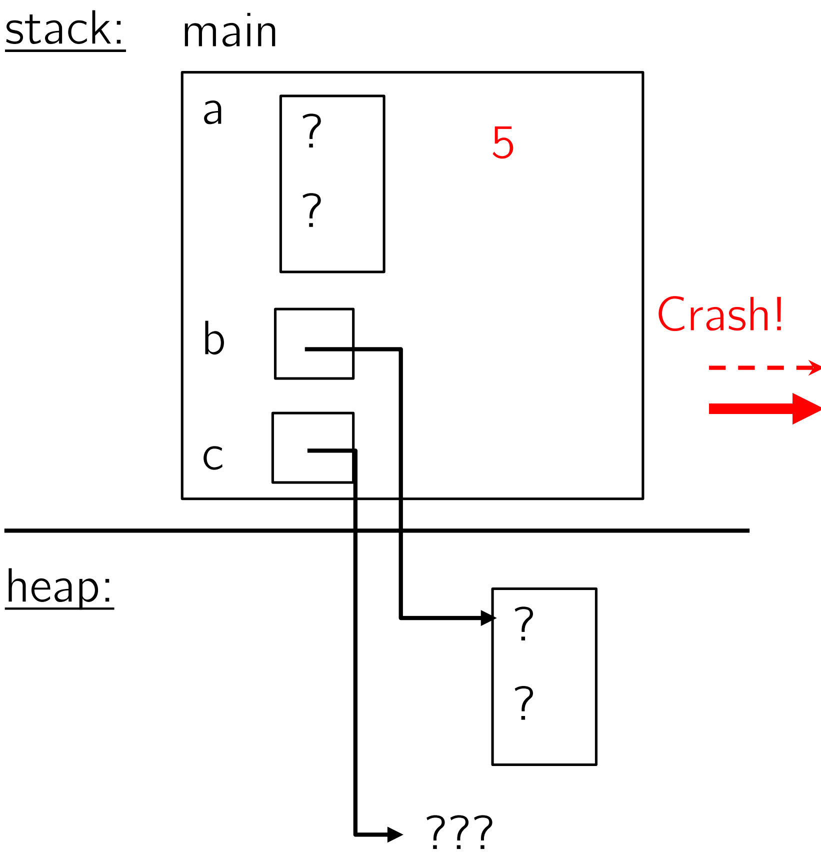


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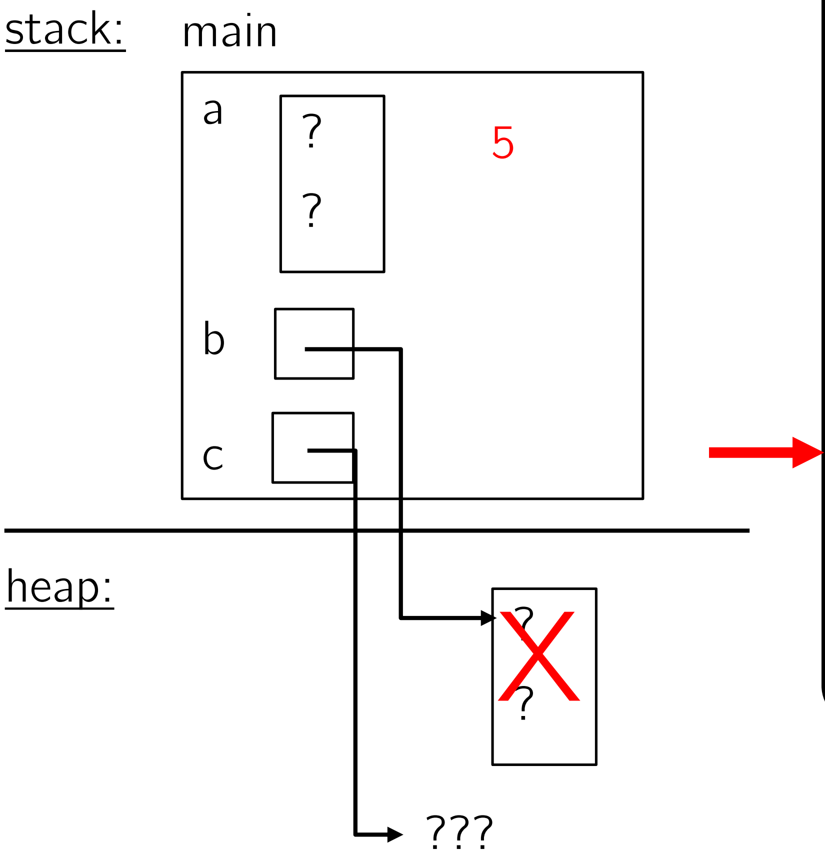


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  return 0;
}
```
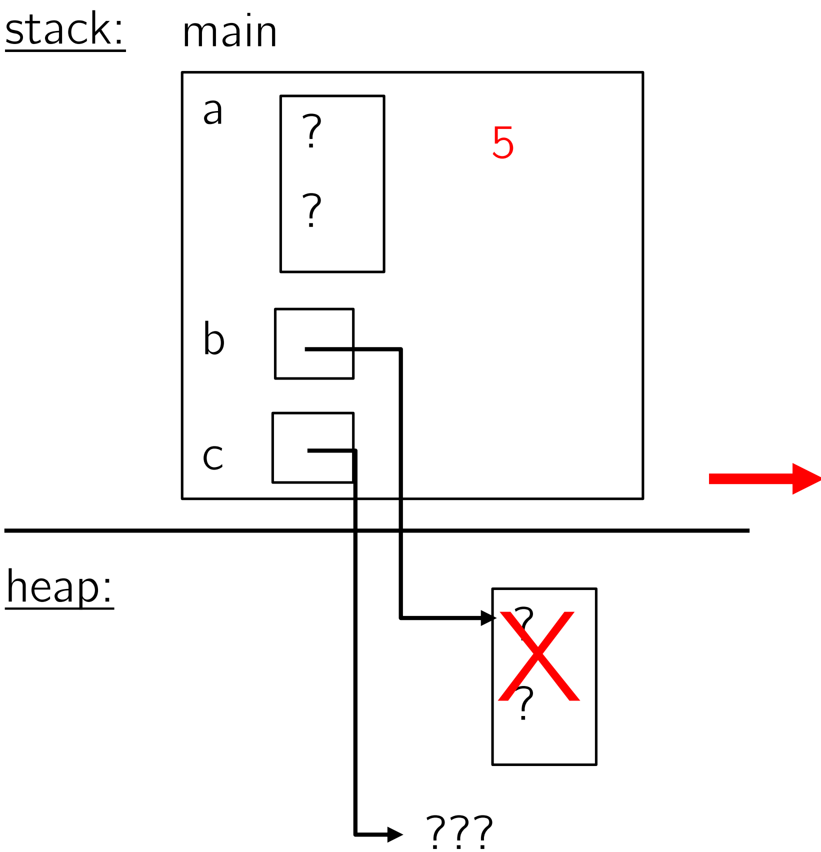

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?

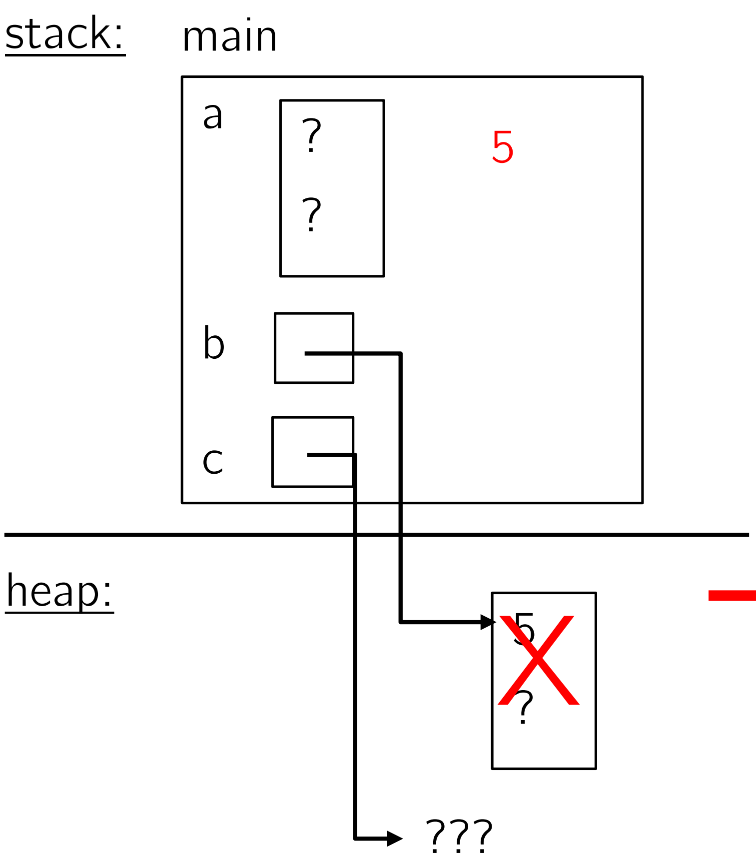



```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?




```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;     // assigns past the end of an array
  b[0] += 2;    // assumes malloc zeros out memory
  c = b+3;      // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);      // double-free the same block
  b[0] = 5;     // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Leak

- A memory leak occurs when code fails to deallocate dynamically-allocated memory that is no longer used
  - *e.g.* forget to `free` malloc-ed block, lose/change pointer to malloc-ed block

- What happens: program's VM footprint will keep growing
  - This might be OK for *short-lived* program, since all memory is deallocated when program ends
  - Usually has bad repercussions for *long-lived* programs
    - Might slow down over time (*e.g.* lead to VM thrashing)
    - Might exhaust all available memory and crash
    - Other programs might get starved of memory

Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks
- **`structs` and `typedef`**
- Implementing Data Structures in C

Structured Data

- A `struct` is a C datatype that contains a set of fields
  - Similar to a Java class, but with no methods or constructors
  - Useful for defining new structured types of data
  - Act similarly to primitive variables
  - A struct *tagname* is a *tag*; *not* a full first-class type name
- Generic declaration:

```
struct tagname {
  type1 name1;
  ...
  typeN nameN;
};
```

```
// the following defines a new
// structured datatype called
// a "struct Point"
struct Point {
  float x, y;
};

// declare and initialize a
// struct Point variable
struct Point origin = {0.0,0.0};
```

Using structs

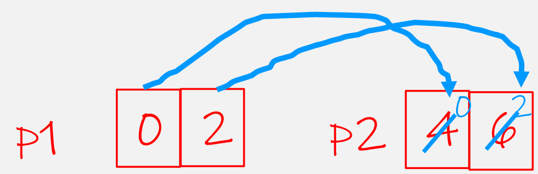
- Use " . " to refer to a field in a struct
- Use "->" to refer to a field from a struct pointer
  - Dereferences pointer first, then accesses field

```
struct Point {
  float x, y;
};

int main(int argc, char** argv) {
  struct Point p1 = {0.0, 0.0};  // p1 is stack allocated
  struct Point* p1_ptr = &p1;

  p1.x = 1.0;
  p1_ptr->y = 2.0;  // equivalent to (*p1_ptr).y = 2.0;
  return 0;
}
```

simplestruct.c

Copy by Assignment

- You can assign the value of a struct from a struct of the same type – *this copies the entire contents!*




```c
#include <stdio.h>

struct Point {
  float x, y;
};

int main(int argc, char** argv) {
  struct Point p1 = {0.0, 2.0};
  struct Point p2 = {4.0, 6.0};

  printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
  p2 = p1;
  printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
  return 0;
}
```

structassign.c

typedef

- Generic format: `typedef type name;`
- Allows you to define new data type *names/synonyms*
  - Both `type` and `name` are usable and refer to the same type
  - Be careful with pointers – `*` before `name` is part of `type`!

```
// make "superlong" a synonym for "unsigned long long"
typedef unsigned long long superlong;

// make "str" a synonym for "char*"
typedef char *str;

// make "Point" a synonym for "struct point_st { ... }"
// make "PointPtr" a synonym for "struct point_st*"
typedef struct point_st {
  superlong x;
  superlong y;
} Point, *PointPtr;  // similar syntax to "int n, *p;"

Point origin = {0, 0};
```

type
name
type name
struct point_st == Point
struct point_st* == Point* == PointPtr

Dynamically-allocated Structs

- You can **`malloc`** and **`free`** structs, just like other data type
  - `sizeof` is particularly helpful here

equivalent

```
// a complex number is a + bi
typedef struct complex_st {
  double real;    // real component
  double imag;    // imaginary component
} Complex, *ComplexPtr;

// note that ComplexPtr is equivalent to Complex*
ComplexPtr AllocComplex(double real, double imag) {
  Complex* retval = (Complex*) malloc(sizeof(Complex));
  if (retval != NULL) {
    retval->real = real;
    retval->imag = imag;
  }
  return retval;
}
```

complexstruct.c

Structs as Arguments

- Structs are passed by value, like everything else in C
  - Entire struct is copied – where? Register if small enough, stack otherwise
  - To manipulate a struct argument, pass a pointer instead

```
typedef struct point_st {
  int x, y;
} Point, *PointPtr;

void DoubleXBroken(Point p)    {  p.x *= 2; }

void DoubleXWorks(PointPtr p) { p->x *= 2; }

int main(int argc, char** argv) {
  Point a = {1,1};
  DoubleXBroken(a);
  printf("(%d,%d)\n", a.x, a.y);   // prints: ( 1 ,1 )
  DoubleXWorks(&a);
  printf("(%d,%d)\n", a.x, a.y);   // prints: ( 2, 1 )
  return 0;
}
```

Only modifies local copy (DoubleXBroken)

Modifies caller's data (DoubleXWorks)

Returning Structs

- Exact method of return depends on calling conventions
  - Often in `%rax` and `%rdx` for small structs
  - Often returned in memory for larger structs

```
// a complex number is a + bi
typedef struct complex_st {
  double real;     // real component
  double imag;     // imaginary component
} Complex, *ComplexPtr;

Complex MultiplyComplex(Complex x, Complex y) {
  Complex retval;

  retval.real = (x.real * y.real) - (x.imag * y.imag);
  retval.imag = (x.imag * y.real) - (x.real * y.imag);
  return retval;  // returns a copy of retval
}
```

values copied out

complexstruct.c

Pass Copy of Struct or Pointer?

- Value passed: passing a pointer is cheaper and takes less space unless struct is small

- Field access: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize

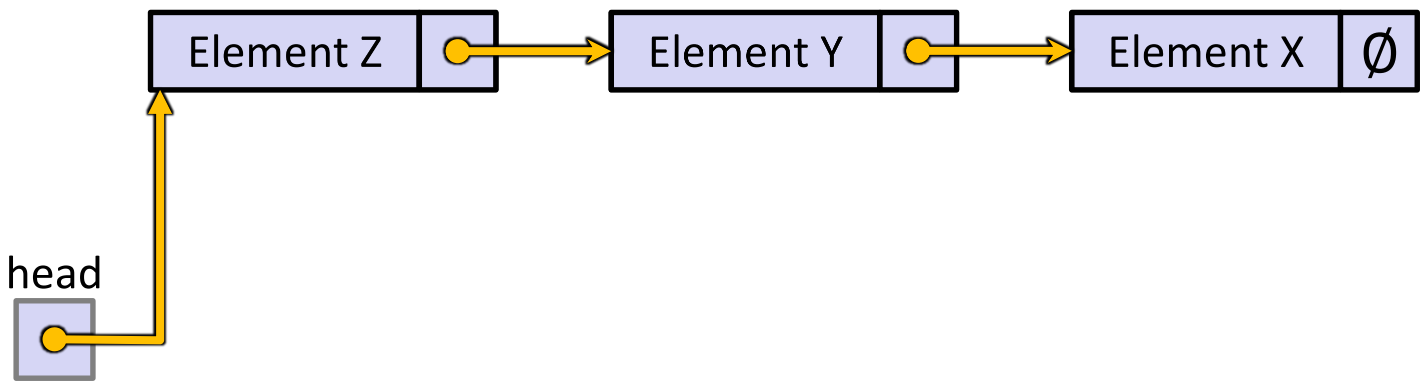
- For small stucts (like `struct complex_st`), passing a copy of the struct can be faster and often preferred if function only reads data; for large structs use pointers

Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks
- `struct`s and `typedef`
- **Implementing Data Structures in C**

Simple Linked List in C

- Each node in a linear, singly-linked list contains:
  - Some element as its payload
  - A pointer to the next node in the linked list
    - This pointer is NULL (or some other indicator) in the last node in the list



Linked List Node

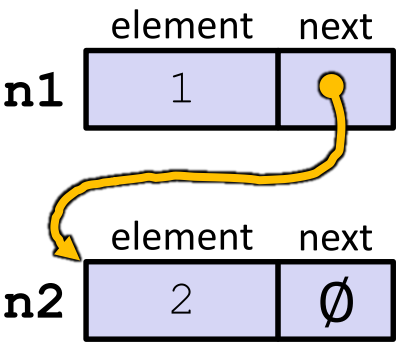
- Let's represent a linked list node with a struct
  - For now, assume each element is an int

```
#include <stdio.h>

typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

int main(int argc, char** argv) {
  Node n1, n2;

  n1.element = 1;
  n1.next = &n2;
  n2.element = 2;
  n2.next = NULL;
  return 0;
}
```



manual_list.c

Push Onto List

Arrow points to *next* instruction.

```
typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c

Push Onto List

Arrow points to *next* instruction.

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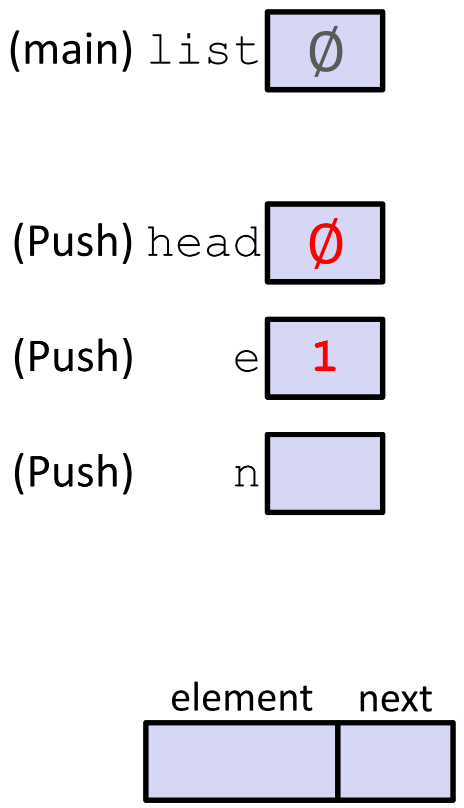
typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```



push_list.c

Push Onto List

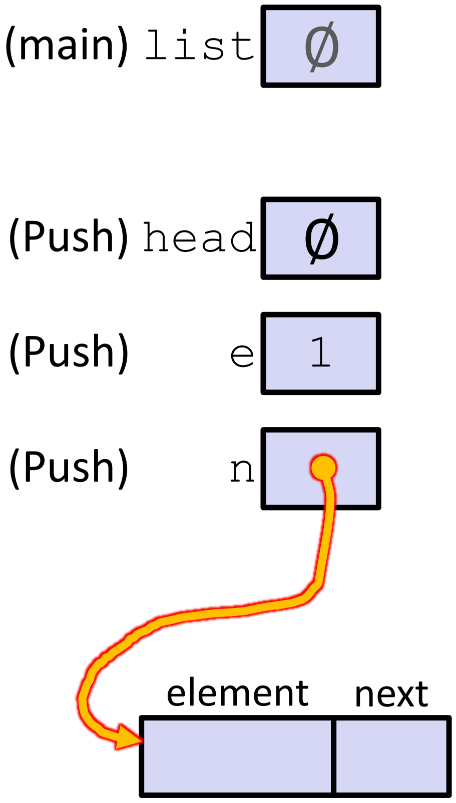
Arrow points to *next* instruction.

```
typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c



Push Onto List

Arrow points to *next* instruction.

```
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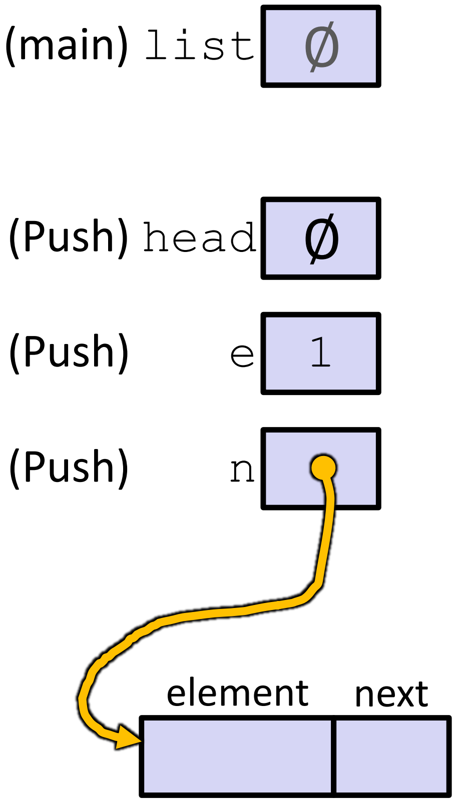
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```



push_list.c

Push Onto List

Arrow points to *next* instruction.

```
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  int element;
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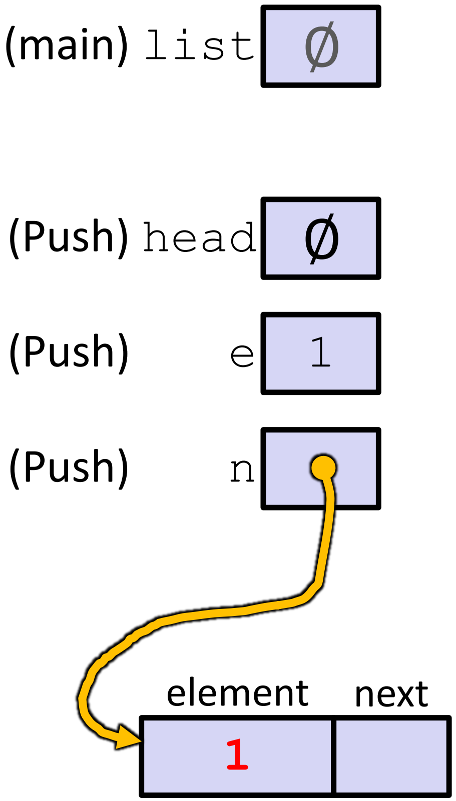
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```



push_list.c

Push Onto List

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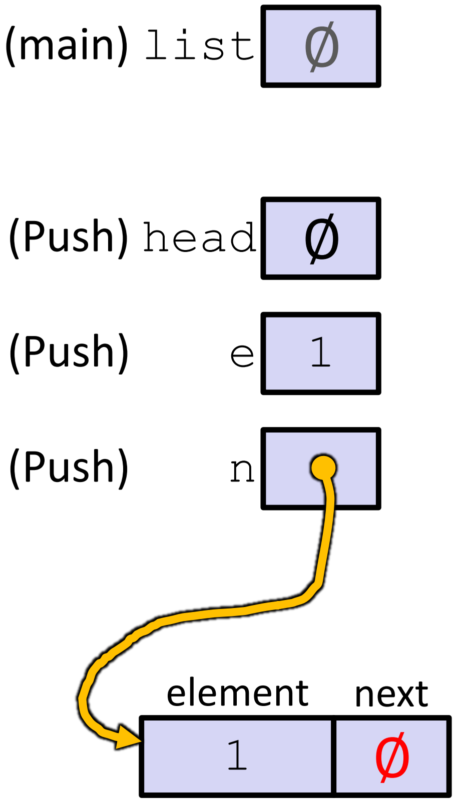
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c



Push Onto List

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  int element;
  struct node_st* next;
} Node;

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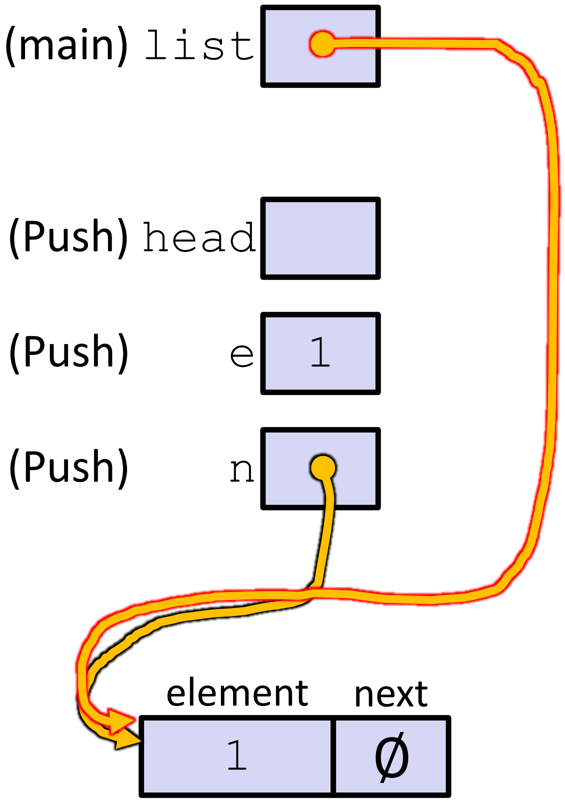
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```



push_list.c

Push Onto List

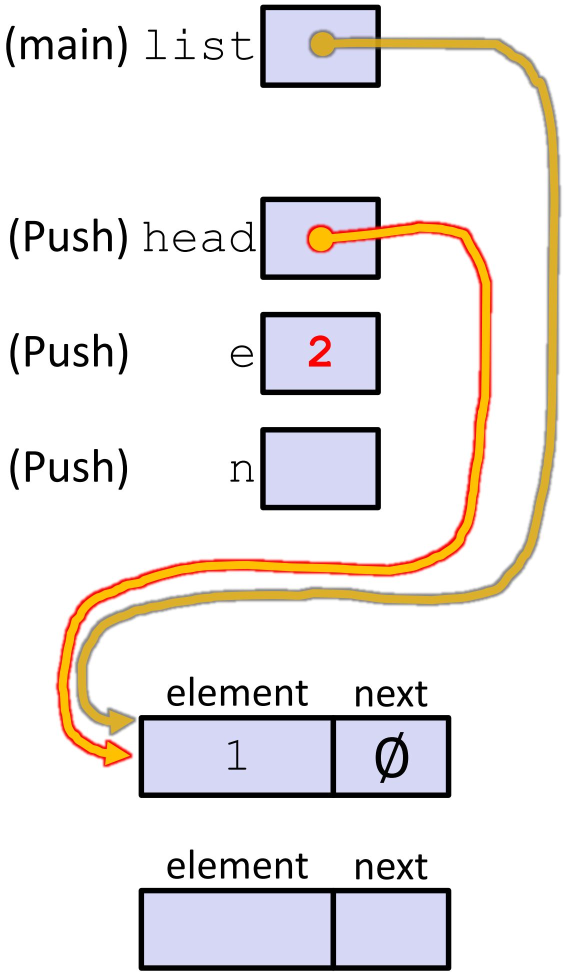
Arrow points to *next* instruction.

```c
typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));   // <- arrow
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c



Push Onto List

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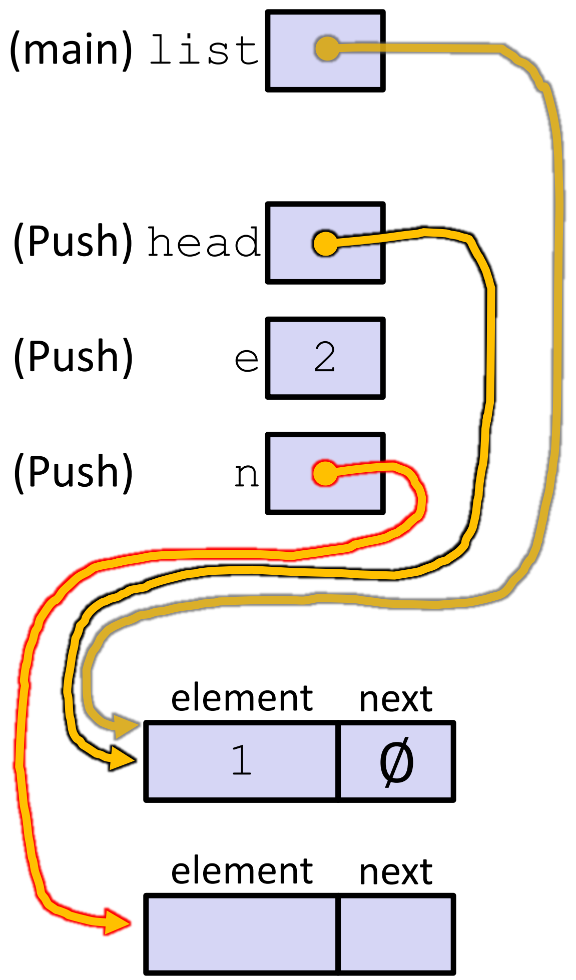
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```



push_list.c

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  Node* n = (Node*) malloc(sizeof(Node));
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  n->next = head;
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}

int main(int argc, char** argv) {
  Node* list = NULL;
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  return 0;
}
```
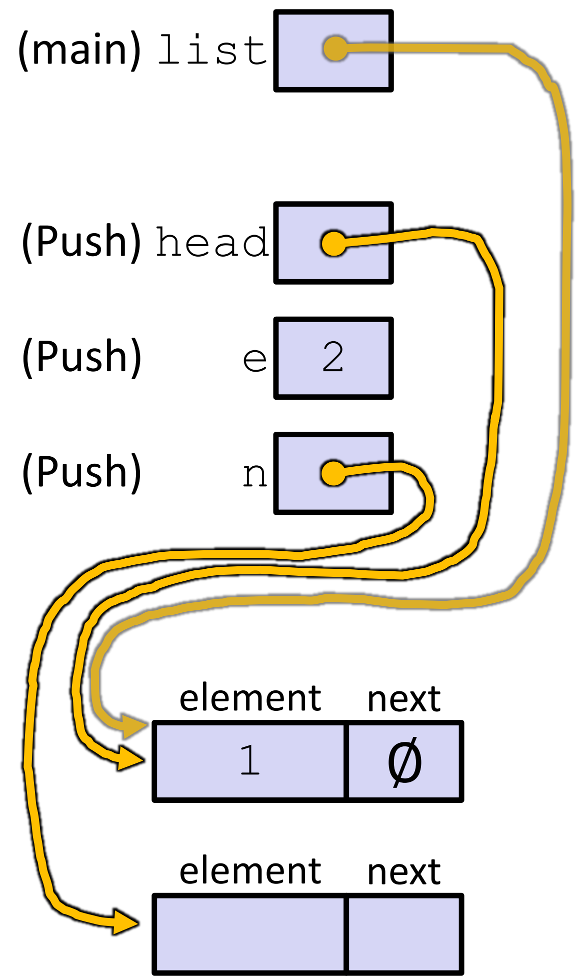

push_list.c



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  Node* n = (Node*) malloc(sizeof(Node));
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  n->next = head;
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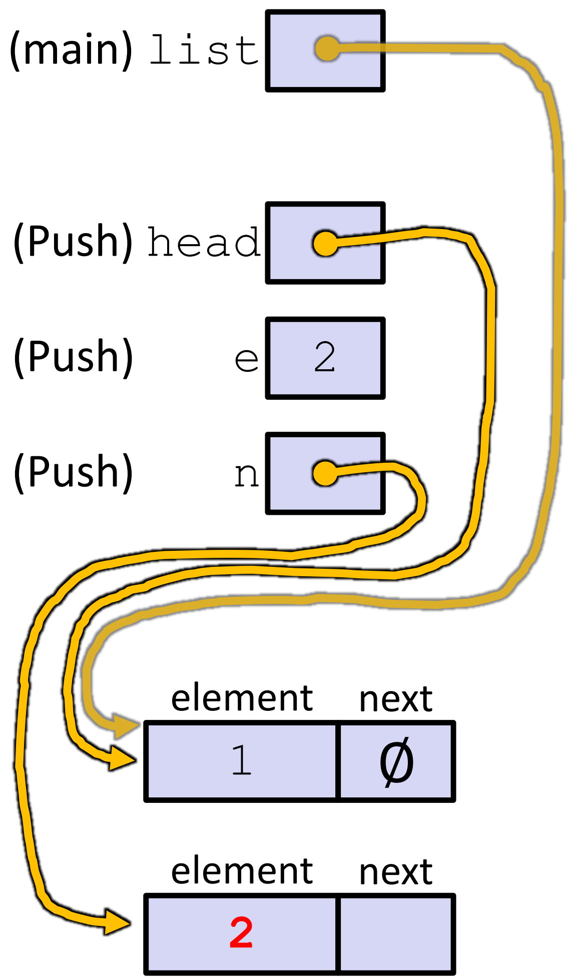
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c



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  struct node_st* next;
} Node;

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  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

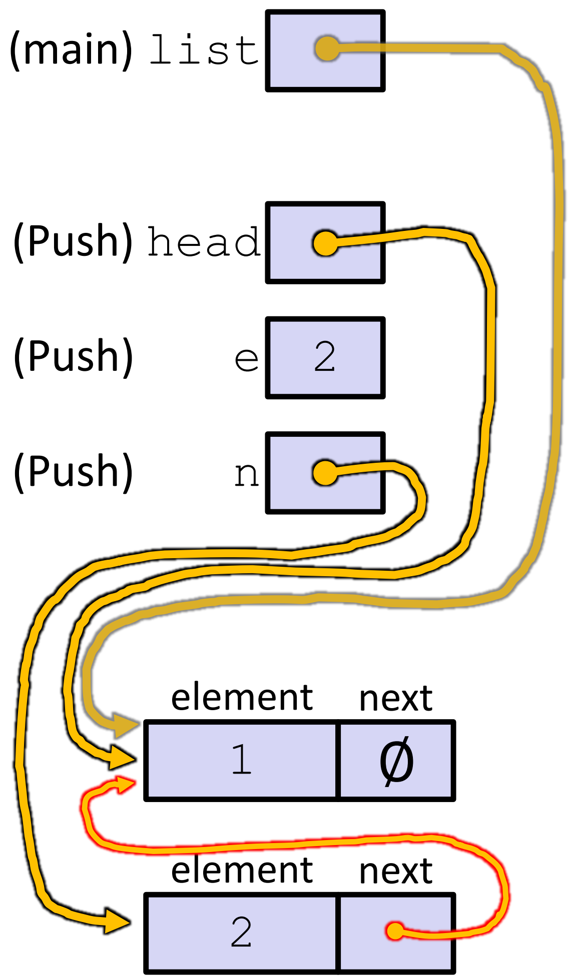

push_list.c

Push Onto List

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  n->element = e;
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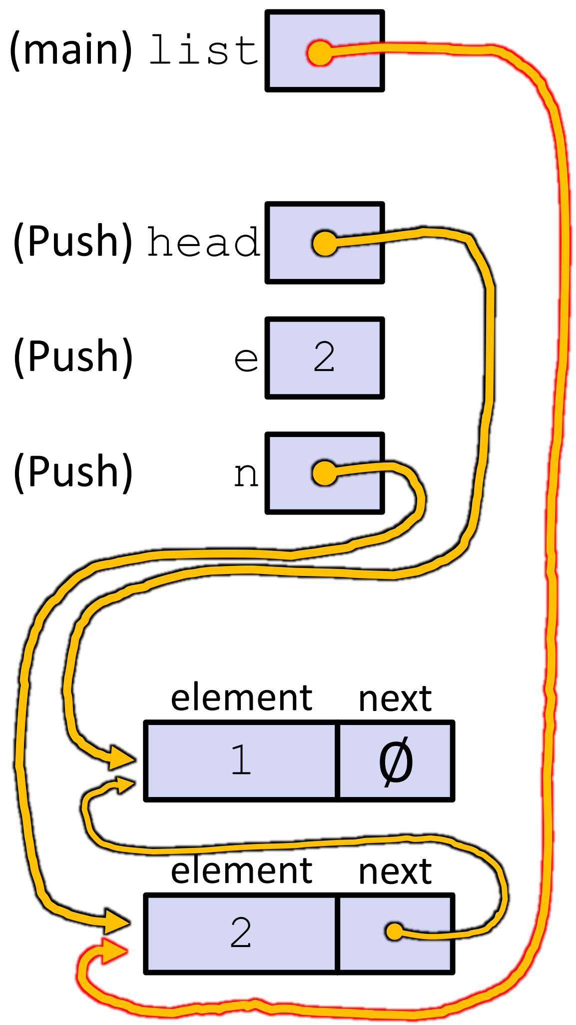
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

push_list.c



Push Onto List

Arrow points to *next* instruction.

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} Node;

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  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```
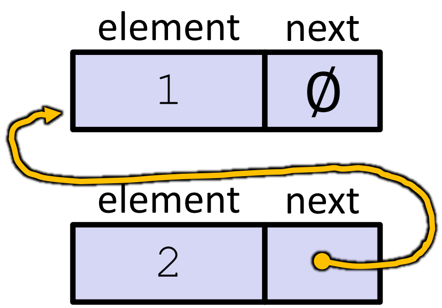

push_list.c

A (benign) memory leak!
Try running with Valgrind:

```
bash$ gcc -Wall -g -o
push_list push_list.c

bash$ valgrind --leak-
check=full ./push_list
```



Extra Exercise #1

- Write a program that defines:
  - A new structured type Point
    - Represent it with `float`s for the x and y coordinates
  - A new structured type Rectangle
    - Assume its sides are parallel to the x-axis and y-axis
    - Represent it with the bottom-left and top-right Points
  - A function that computes and returns the area of a Rectangle
  - A function that tests whether a Point is inside of a Rectangle

Extra Exercise #2

- Implement `AllocSet()` and `FreeSet()`
  - AllocSet() needs to use malloc twice: once to allocate a new ComplexSet and once to allocate the "points" field inside it
  - FreeSet() needs to use free twice

```
typedef struct complex_st {
  double real;     // real component
  double imag;     // imaginary component
} Complex;

typedef struct complex_set_st {
  double   num_points_in_set;
  Complex* points;          // an array of Complex
} ComplexSet;

ComplexSet* AllocSet(Complex c_arr[], int size);
void FreeSet(ComplexSet* set);
```