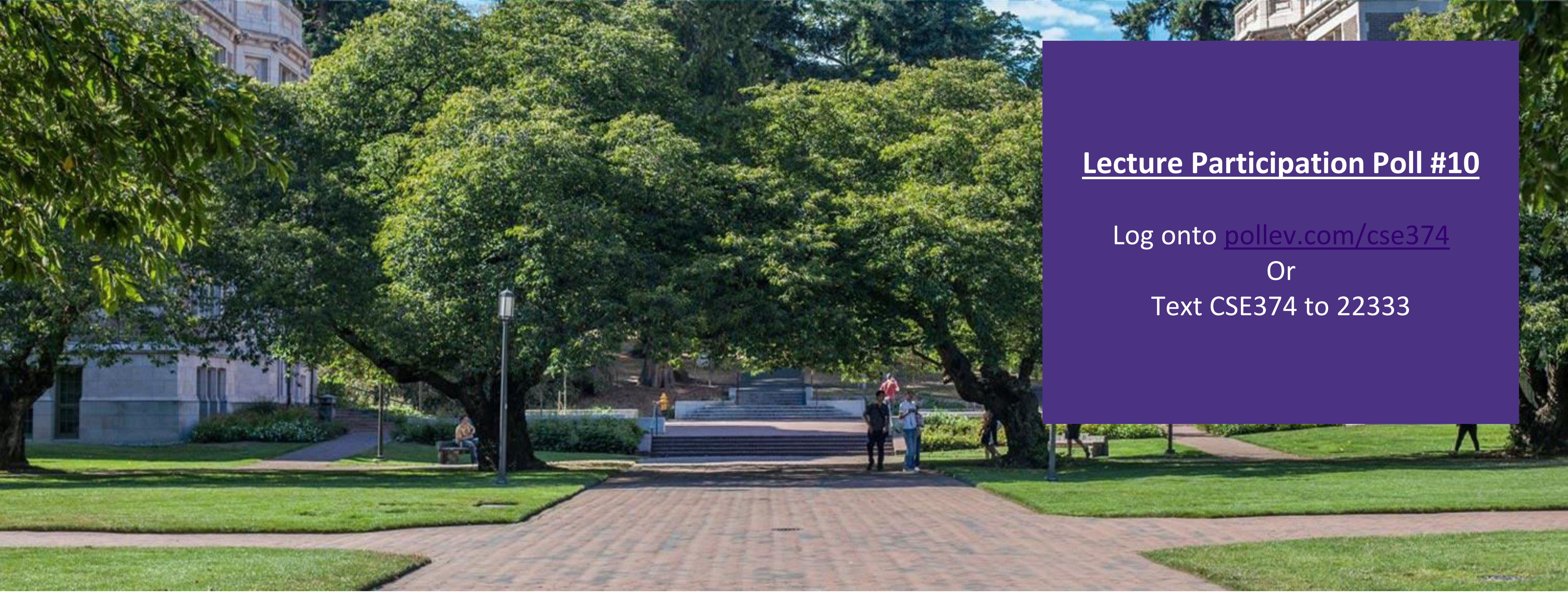


Lecture Participation Poll #10

Log onto pollev.com/cse374
Or
Text CSE374 to 22333

Lecture 10: Dynamic Memory Allocation

CSE 374: Intermediate Programming Concepts and Tools

Administrivia

Assignments

- HW3 live – due next Thursday
- HW2 due Thursday
- HW1 deadline pushed out

Array Syntax with Pointers

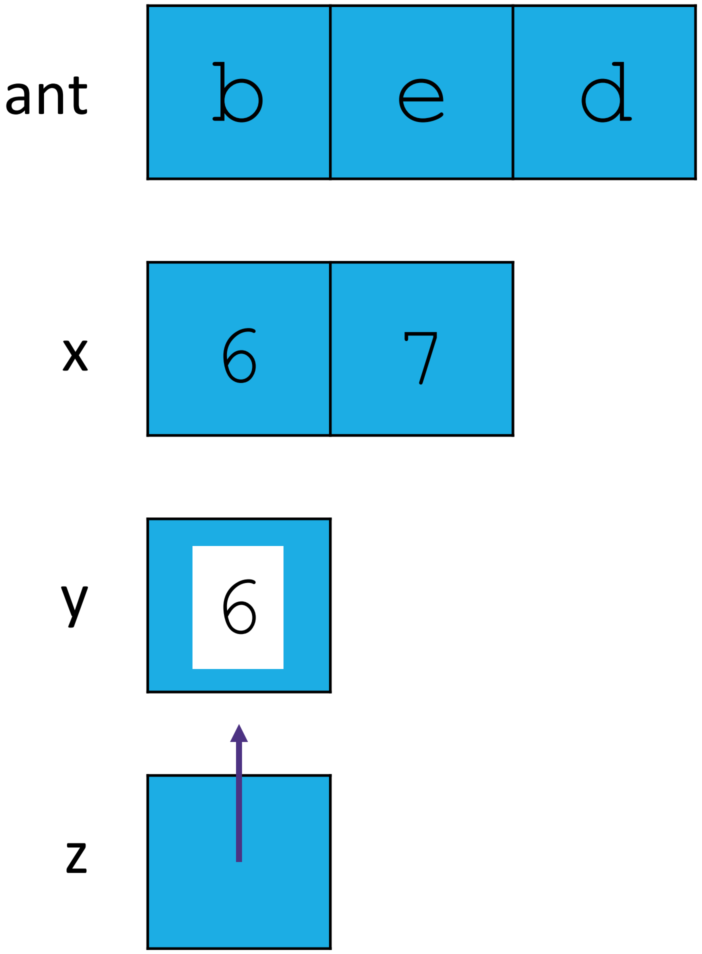
- You can use the bracket notation to index pointers
  - `char arr[] = "cse";`
  - `char* ptr = arr;`
  - `char letter_c = *ptr; // equivalent to ptr[0]`
  - `char letter_e = ptr[2];`
- The bracket syntax is just another way of saying this:
  - `letter_e = *(ptr + 2);`
- "Pointer arithmetic" works with other types like int, long

Pointer Mystery

```
#include <stdio.h>
// What does the program print?

void mystery(char *a, int *b, int c)
{
   int *d = b - 1;
   c = *b + c;
   *b = c - *d;
   *d = *b - *d;
   a[2] = a[b - d];
}

int main(int argc, char **argv)
{
   char ant[4] = "bed";
   int x[2];
   *x = 6;
   x[1] = 7;
   int y = 4;
   int *z = &y;
   *z = *x;
   printf("%d %d %d %s\n", *x, x[1], y, ant);
   mystery(ant, x + 1, y);
   printf("%d %d %d %s\n", *x, x[1], y, ant);
}
```



ant

b e d

x

6 7

y

6

z

Output:

6 7 6 bed

1 7 6 bee

Memory Allocation

- **Allocation** refers to any way of asking for the operating system to set aside space in memory
- How much space? Based on variable type & your system
  - to get specific sizes for your system use “sizeof(<datatype>)” function in stdlib.h
- Global Variables – **static** memory allocation
  - space for global variables is set aside at compile time, stored in RAM next to program data, not stack
  - space set aside for global variables is determined by C based on data type
  - space is preserved for entire lifetime of program, never freed
- Local variables – **automatic** memory allocation
  - space for local variables is set aside at start of function, stored in stack
  - space set aside for local variables is determined by C based on data type
  - space is deallocated on return

Type	Storage Size	Value Range
char	1 byte	-128 to 127 or 0 to 255
unsigned char	1 byte	0 to 255
signed char	1 byte	-128 to 127
int	2 or 4 bytes	-32,786 to 32,767 or -2,147,483,648 to 2,147,483,647
unsigned int	2 or 4 bytes	0 to 65,535 or 0 to 4,294,967,295
short	2 bytes	-32,768 to 32,767
unsigned short	2 bytes	0 to 65,535
long	8 bytes	-9223372036854775808 to 9223372036854775807
unsigned long	8 bytes	0 to 18446744073709551615
float	4 bytes	1.2E-38 to 3.4E+38
double	8 bytes	2.3E-308 to 1.7E+308
long double	10 bytes	3.4E-4932 to 1.1E+4932

* pointers require space needed for an address – dependent on your system – 4 bytes for 32-bit, 8 bytes for 64-bit

https://www.gnu.org/software/libc/manual/html_node/Memory-Allocation-and-C.html

Does this always work?

- Static and automatic memory allocation – memory set aside is known at runtime
  - Fast and easy to use
  - partitions the maximum size per data type – not efficient
  - life of data is automatically determined – not efficient
- What if we don't know how much memory we need until program starts running?

```
char* ReadFile(char* filename)
{
   int size = GetFileSize(filename);
   char* buffer = AllocateMem(size);

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

You don't know how big the filesize is

Dynamic Allocation

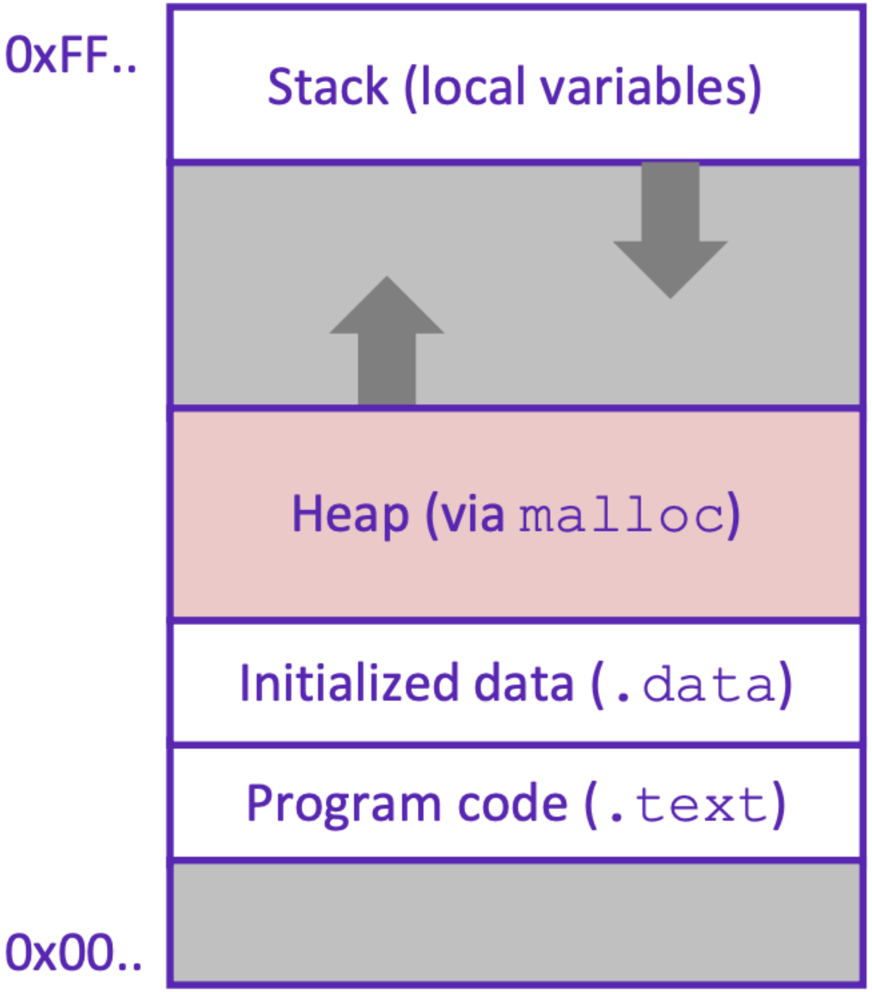
- Situations where static and automatic allocation aren't sufficient
  - Need memory that persists across multiple function calls
    - Lifetime is known only at runtime (long-lived data structures)
  - Memory size is not known in advance to the caller
    - Size is known only at runtime (ie based on user input)
- Dynamically allocated memory persists until:
  - A garbage collector releases it (automatic memory management)
    - Implicit memory allocator, programmer only allocates space, doesn't free it
    - "new" in Java, memory is cleaned up after program finishes <HOW DOES THIS WORK?
  - Your code explicitly deallocates it (manual memory management)
    - C requires you manually manage memory
    - Explicit memory allocation requires the programmer to both allocate space and free it up when finished
    - "malloc" and "free" in C
- Memory is allocated from the heap, not the stack
  - Dynamic memory allocators acquire memory at runtime

Storing Program Data in the RAM

- When you trigger a new program the operating system starts to allocate space in the RAM
  - Operating System will default to keeping all memory for a program as close together within the ram addresses as possible
  - Operating system manages where exactly in the RAM your data is stored
    - Space is first set aside for program code (lowest available addresses)
    - Then space is set side for initialized data (global variables, constants, string literals)
    - As program runs…
      - When the programmer manually allocates memory for data it is stored in the next available addresses on top of the initialized data, building upwards as space is needed
      - When the program requires local variables they are stored in the empty space at top of RAM, leaving space between stack and heap
      - When the space between the stack and heap is full – crash (out of memory)

The heap is a large pool of available memory set aside specifically for dynamically allocated data

Address Space Visualization



Allocating Memory in C with malloc()

- `void* malloc(size_t size)`
  - allocates a continuous block of “`size`” bytes of **uninitialized** memory
  - Returns `null` if allocation fails or if `size == 0`
    - Allocation fails if out of memory, very rare but always check allocation was successful before using pointer
  - `void*` means a pointer to any type (int, char, float)
    - `malloc` returns a pointer to the beginning of the allocated block
- `var = (type*) malloc(sizeInBytes)`
  - Cast void* pointer to known type
  - Use `sizeof(type)` to make code portable to different machines
- `free` deallocates data allocated by `malloc`
- Must add `#include <stdlib.h>`
- Variables in C are uninitialized by default
  - No default “0” values like Java
  - Invalid read – reading from memory before you have written to it

```
//allocate an array to store 10 floats
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
{
   return ERROR;
}
printf(“%f\n”, *arr) // Invalid read!
<add something to array>
<print f again, now it’s ok>
```

calloc()

`var = (type*) calloc(numOfElements, bytesPerElement);`

- Like malloc, but also initializes the memory by filling it with 0 values
- Slightly slower, but useful for non-performance critical code
- Also in stdlib.h

```
//allocate an array to store 10 doubles
double* arr = (double*) calloc(10, sizeof(double));
if (arr == NULL)
{
   return ERROR;
}
printf(“%f\n”, arr[0]) // Prints 0.00000
```

realloc()

- void* realloc(void* p, size_t size)
  - creates a new allocation with given size, copies the contents of p into it and then frees p
  - saves a few lines of code
  - can sometimes be faster due to allocator optimizations
  - part of stdlib.h

Freeing Memory in C with free()

- `void free(void* ptr)`
  - Released whole block of memory stored at location ptr to pool of available memory
  - ptr must be the address originally returned by malloc (the beginning of the block) otherwise system exception raised
  - ptr is unaffected by free
    - Set pointer to NULL after freeing it to deallocate that space too
  - Calling free on an already released block (double free) is undefined behavior – best case program crashes
  - Rule of thumb: for every runtime call to malloc there should be one runtime call to free
  - if you lose all pointers to an object you can no longer free it – memory leak!
    - be careful when reassigning pointers
    - this is usually the cause of running out of memory– unreachable data that cannot be freed
  - if you attempt to use an object that has been freed you hit a dangling pointer
  - all memory is freed once a process exits, and it is ok to rely on this in many cases

```
//allocate an array to store 10 floats
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
{
   return ERROR;
}
for (int i = 0; i < size*num; i++)
{
   arr[i] = 0;
}
free(arr);
arr = NULL; // Optional
```

Example

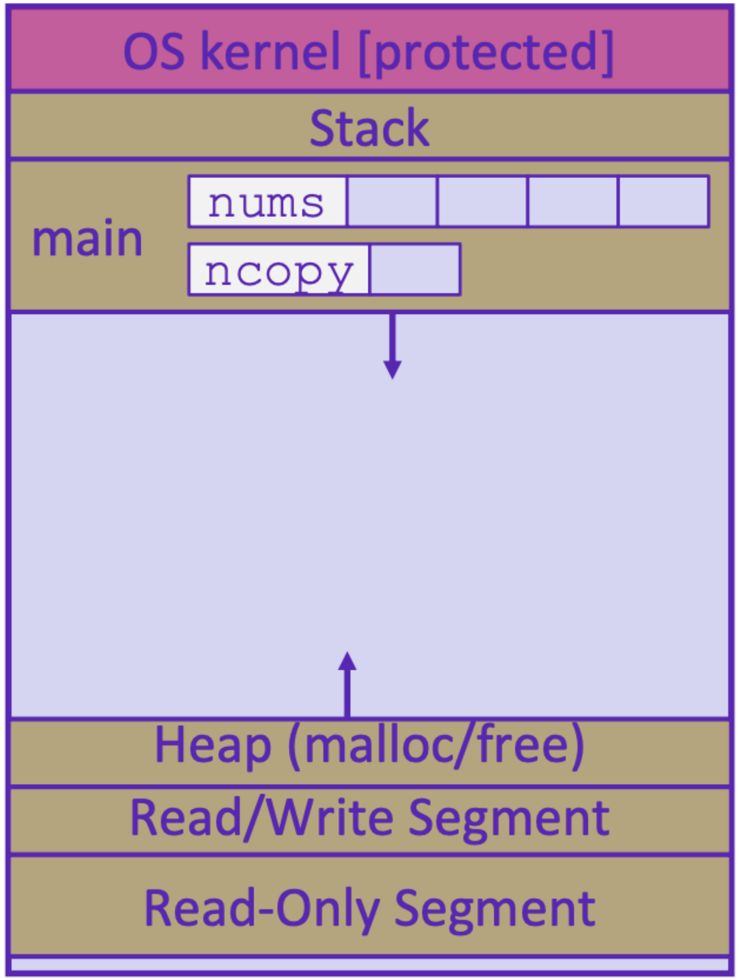
```
void foo(int n, int m)
{
   int i, *p; // declare local variables
   p = (int*) malloc(n*sizeof(int)); //allocate block of n ints
   if (p == NULL) // check for allocation error
   {
      perror(“malloc”); //prints error message to stderr
      exit(0);
   }
   for (i=0; i<n; i++) // initialize int array
      p[i] = i;
   p = (int*) realloc(p, (n+m)*sizeof(int)); // add space for m at end of p block
   if (p == NULL) // check for allocation error
   {
      perror(“realloc”);
      exit(0);
   }
   for (i=n; i<n+m; i++) // initialize new space at back of array
      p[i] = i;
   for (i=0; i<n+m; i++) // print out array
      printf(“%d\n”, p[i]);
   free(p); // free p, pointer will be freed at end of function
}
```

Example: 1 – initialized data

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```



OS kernel [protected]

Stack

main

nums

ncopy

Heap (malloc/free)

Read/Write Segment

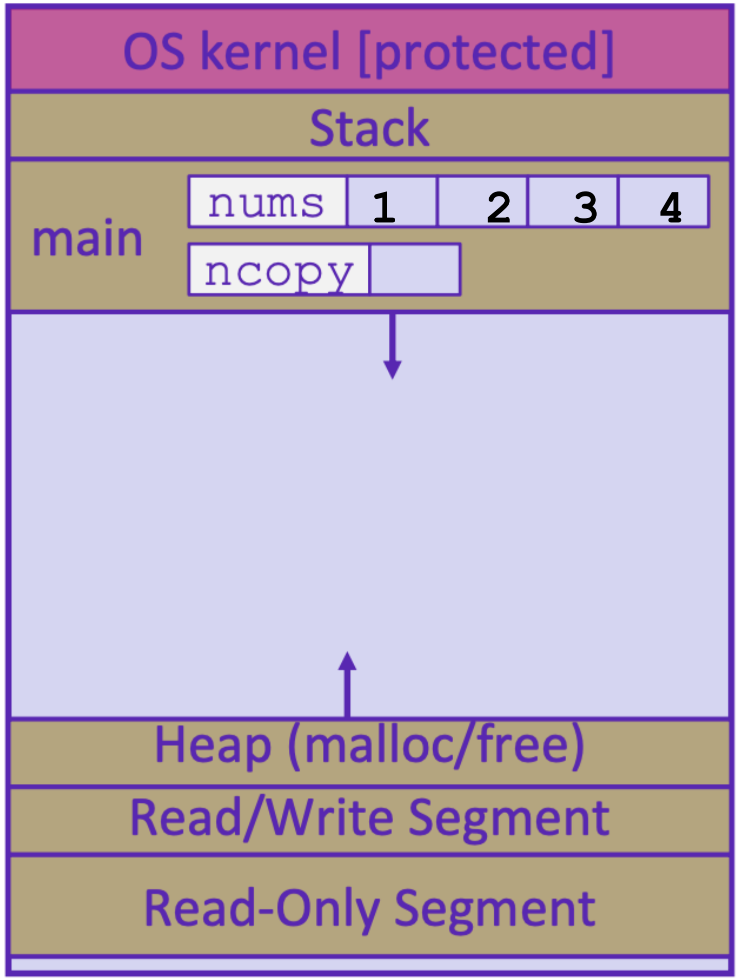
Read-Only Segment

Example: 2 – main local variable in stack

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```

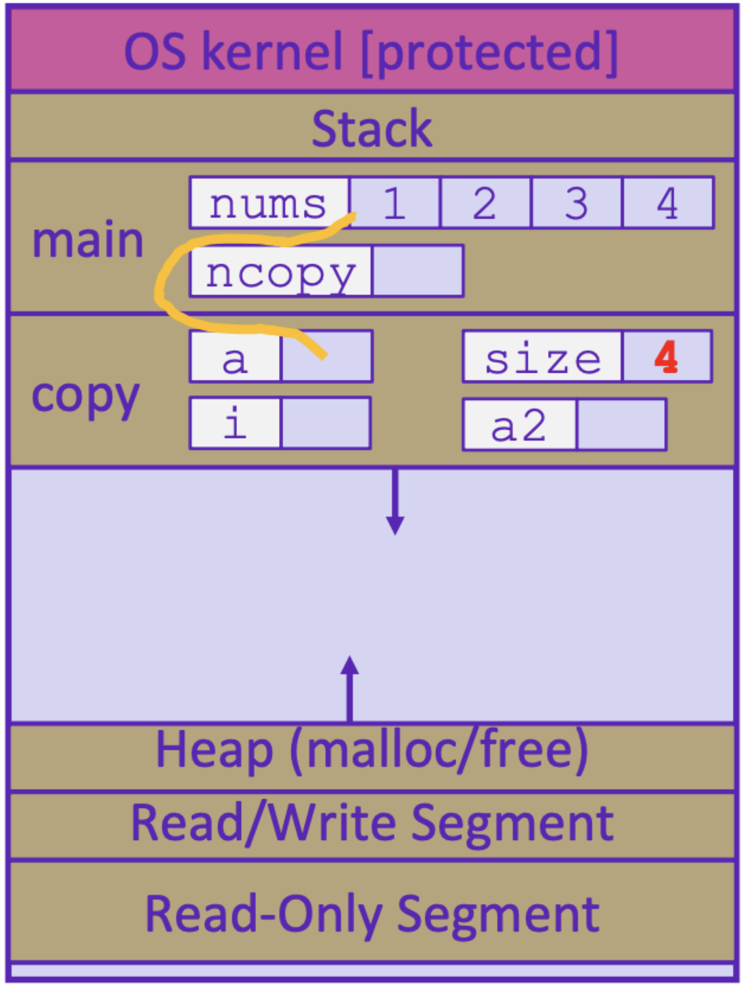


Example: 3 – copy local variables in stack

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```

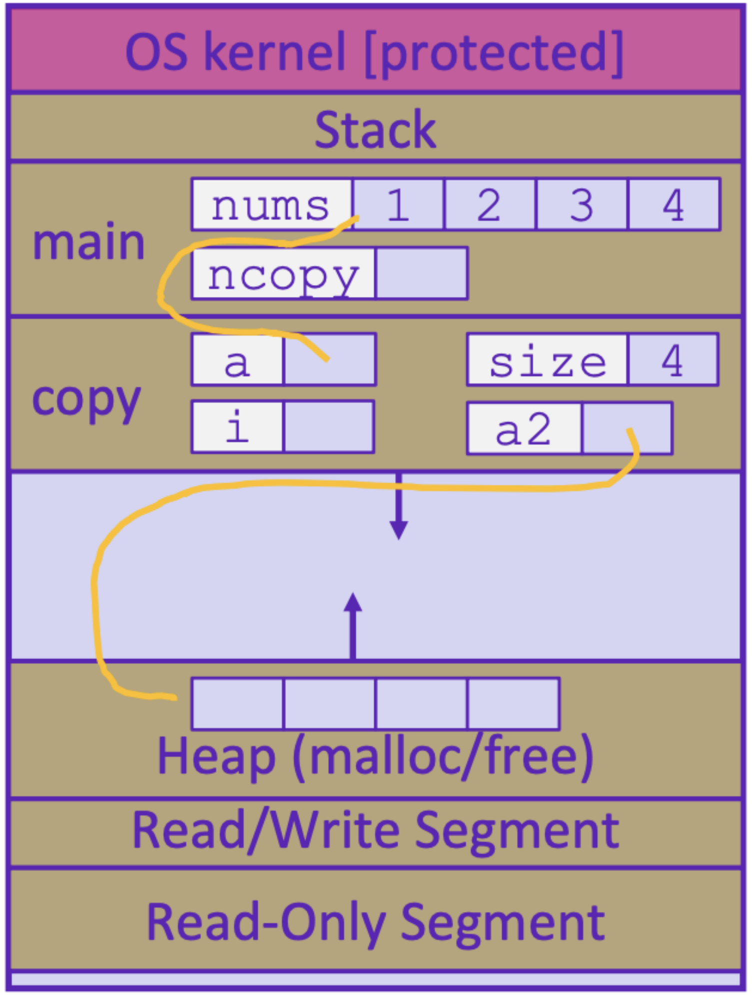


Example: 4 – malloc space for int array

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```

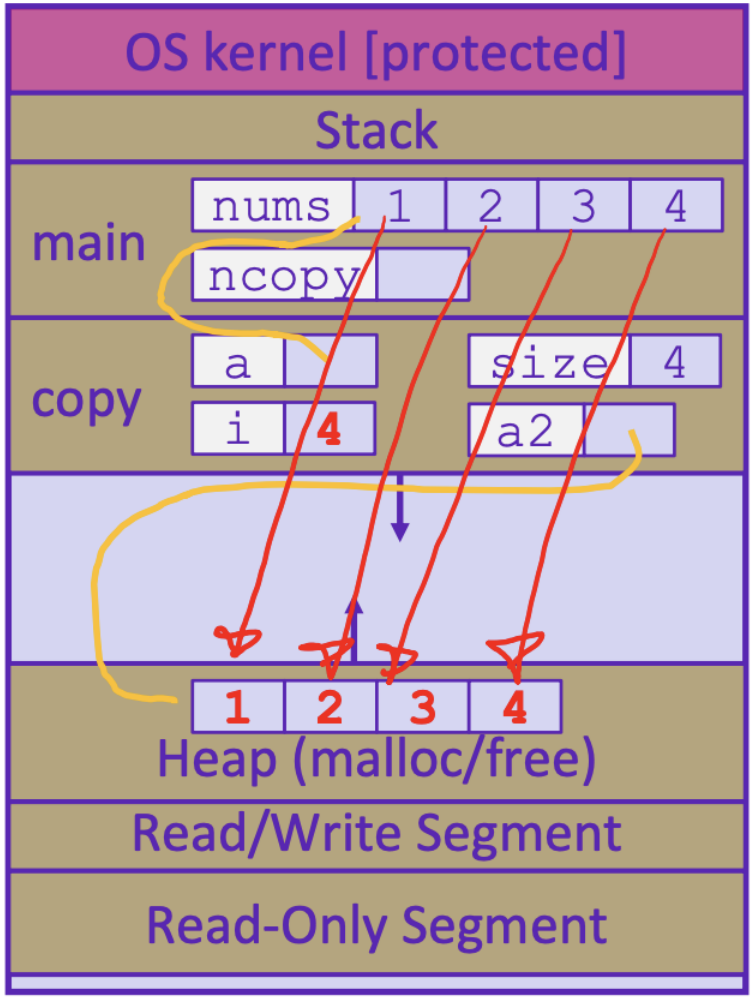


Example: 5 – fill available space from local var

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```

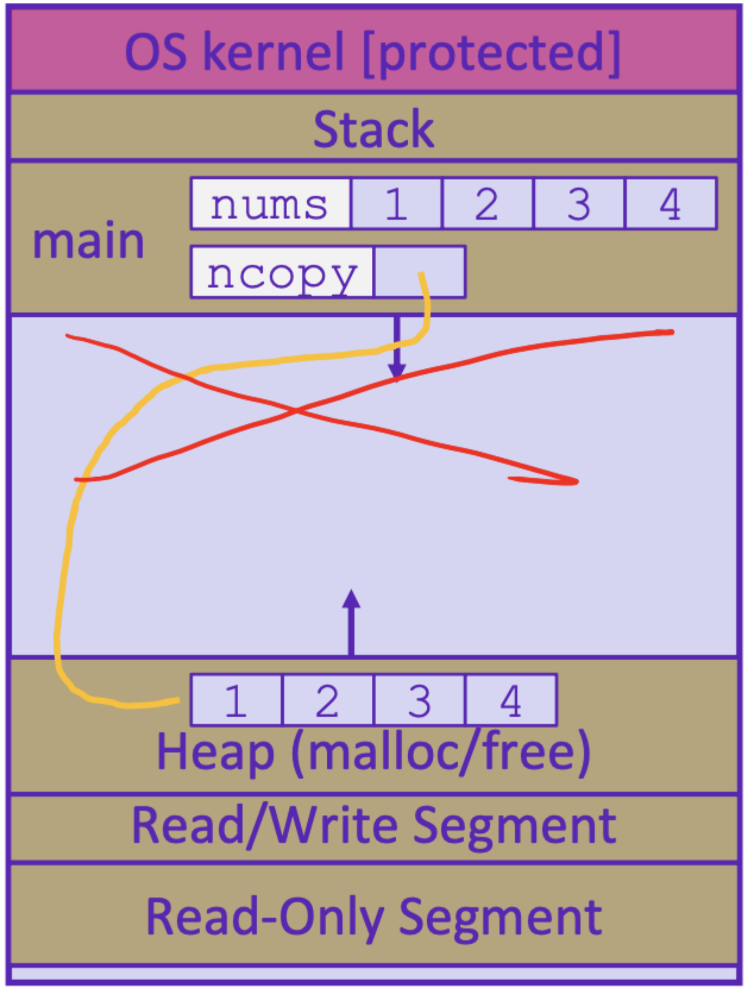


Example: 6 – finish copy and free stack space

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```

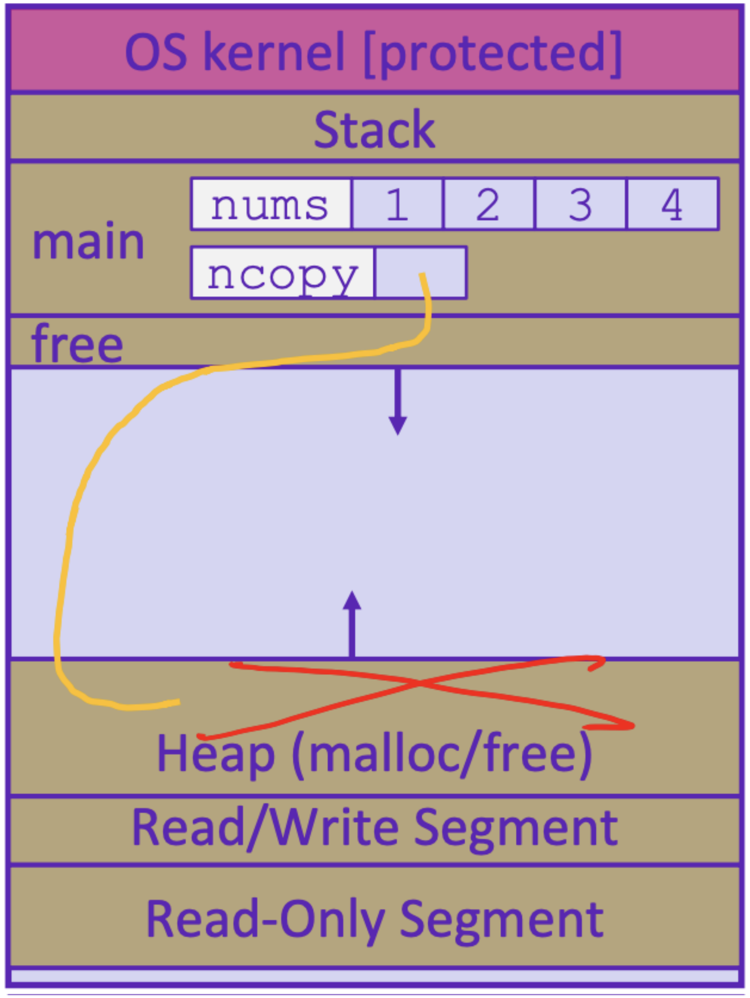


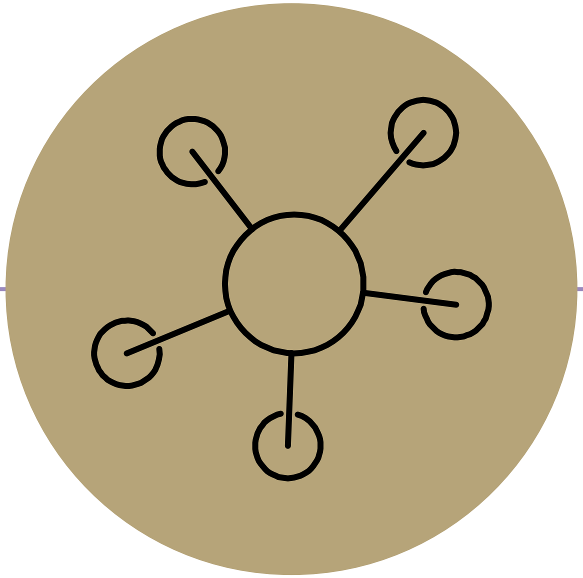
Example: 7 – free ncopy from heap

```
#include <stdlib.h>

int* copy(int a[], int size)
{
   int i, *a2;
   a2 = 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 your copy!
   free(ncopy);
   return EXIT_SUCCESS;
}
```





Appendix

Pointers to pointers

Levels of pointers make sense:

I.e.: `argv, *argv, **argv`

Or: `argv, argv[0], argv[0][0]`

But

`&(&p)` doesn't make sense

```
void f(int x) {
    int*p = &x;
    int**q = &p;
    // x, p, *p, q, *q, **q
}
```

Integer, pointer to integer, pointer to pointer to integer

`&p` is the address of '`p`',

`&(&p)` would be the address of the address of `p`, but that value isn't stored separately anywhere and doesn't have an address

Try using `printf ("The address of x is %p\n", &x);`

Arrays again

"A reference to an object of type array-of-T which appears in an expression decays (with three exceptions) into a pointer to its first element; the type of the resultant pointer is pointer-to-T."

http://c-faq.com/aryptr/aryptrequiv.html

Right: x is the array, which decays to a pointer to an int and &x returns a pointer to the entire array.

```c
void f1(int* p) {  // takes a pointer
  *p = 5;
}
int* f2() {
    int x[3];     // x on stack, is pointer
    x[0] = 5;
    (&x)[0] = 5; // address of x, points to
                 // same place but different T
    *x = 5;      // put value at location x
    *(x+0) = 5;  // Also put value at x
    f1(x);
    f1(&x);     // wrong - watch types!
    x = &x[2]; // No!  X isn't really a pointer
    int *p = &x[2];
    return x; // correct type, but is a
              // dangling pointer
}
```

errno

- How do you know if an error has occurred in C?
  - no exceptions like Java
- usually return a special error value (NULL, -1)
- stdlib functions set a global variable called errno
  - check errno for specific error types
  - if (errno == ENOMEM) // allocation failure
  - perror("error message") prints to stderr

C Garbage Collector

- garbage collection is the automatic reclamation of heap-allocated memory that is never explicitly freed by application
  - used in many modern languages: Java, C#, Ruby, Python, Javascript etc…
  - "conservative" garbage collectors do exist for C and C++ but cannot collect all garbage
- Data is considered "garbage" if it is no longer reachable
  - lost pointers to data (Like a dropped link list node in Java)
  - memory allocator can sometimes get help from the compiler to know what data is a pointer and what is not