CSE 333

Lecture 4 - malloc, free, struct, typedef

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Administrivia 1

New exercise out today, due before class Wednesday

Exercise grading: 3 means almost absolutely perfect; 2 means good but some small flaws. We expect 2's to be (much?) more common than 3's, particularly at first.

- We cut a fair amount of slack on ex0, ex1 for picky style things, but use clint.py to check from now on & ask if something seems off base

HW0 due tonight, 11 pm

- Be sure to add/commit/push, then tag with hw0-final, then push tag
- Then clone the repo into somewhere completely different, do git checkout hw0-final, and verify that all is well

Administrivia 2

HW1 pushed to GitLab repos on Fri., due Thur. 7/7. Reminders:

- You might get a "merge conflict" when pushing HW0. Do a pull, accept the merge (ok to use the default message), then do git add/commit/push
- Suggestion: look at example_program_{ll|ht}.c for typical usage of lists & hash tables

HW1 (and all future): you ***may not*** modify interfaces (.h files)

- Often true in "real life" — or at least assume that is the rule unless told otherwise

Problems? Questions? Use the discussion board so all can benefit

Administrivia 3

We *highly* recommend doing the exercises that are at the end of each lecture

- also, Google for “C pointer exercises” and do as many as you can get your hands on
- you MUST master pointers quickly, or you’ll have problems for the rest of the course (not to mention HW1)

Double pointers

what's the difference between a (char *) and a (char **)?

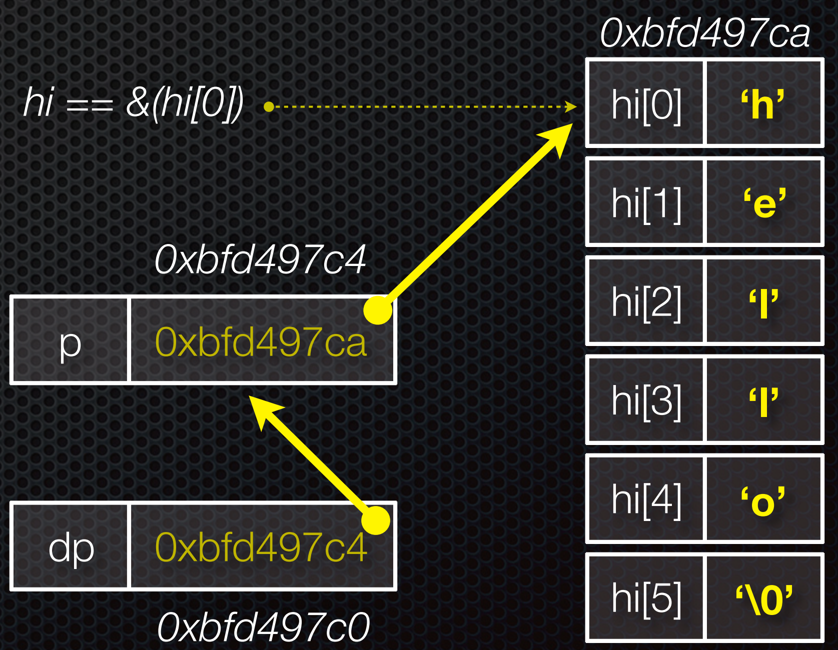
```
int main(int argc, char **argv) {
  char hi[6] = {'h', 'e', 'l',
                'l', 'o', '\0'};
  char *p, **dp;

  p = &(hi[0]);
  dp = &p;

  printf("%c %c\n", *p, **dp);
  printf("%p %p %p\n", p, *dp, hi);
  p += 1;
  printf("%c %c\n", *p, **dp);
  printf("%p %p %p\n", p, *dp, hi);
  *dp += 2;
  printf("%c %c\n", *p, **dp);
  printf("%p %p %p\n", p, *dp, hi);
  return 0;
}
```

exercise0.c

Exercise 0: draw / update the box-and-arrow diagram for this program as it executes



Today's goals:

- understand heap-allocated memory
    - malloc( ), free( )
    - memory leaks
- quick intro to structs and typedef

Memory allocation

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

```
// a global variable
int counter = 0;

int main(int argc, char **argv) {
  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
  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

We need more flexibility

Sometimes we want to allocate memory that:

- persists across multiple function calls but for less than the lifetime of the program
- is too big to fit on the stack
- is allocated and returned by a function and its size is not known in advance to the caller

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

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

Dynamic allocation

What we want is ***dynamically*** **allocated memory**

- your program explicitly requests a new block of memory
  - the language runtime allocates it, perhaps with help from OS
- dynamically allocated memory persists until:
  - your code explicitly deallocates 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

C and malloc

*variable = (type *) malloc(size in bytes);*

malloc allocates a block of memory of the given size

- returns a pointer to the first byte of that memory
  - malloc returns **NULL** if the memory could not be allocated
- you should assume 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;
arr[0] = 5.1;  // etc.
```

C and calloc

*variable = (type *) calloc(howmany, #bytes for each);*

Like malloc, but also zeroes out the block of memory

- helpful for shaking out bugs
- slightly slower; preferred for non-performance-critical code
- malloc and calloc are found in *stdlib.h*

```
// allocate a 10 long-int array
long *arr = (long *) calloc(10, sizeof(long));
if (arr == NULL)
  return errcode;
arr[0] = 5L;  // etc.
```

Deallocation

free(pointer);

Releases the memory pointed-to by the pointer

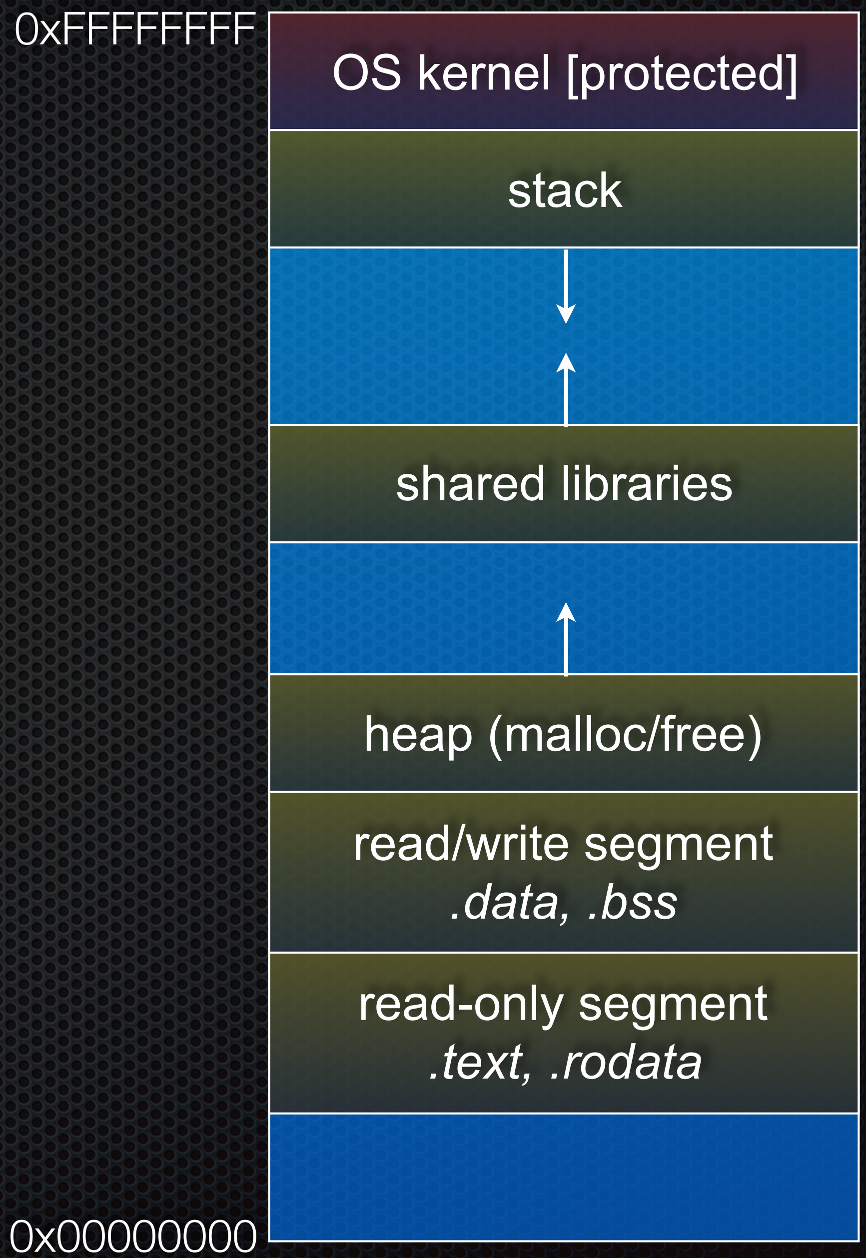
- pointer *must* point to the first byte of heap-allocated memory
    - i.e., something previously returned by malloc( ) or calloc( )
- after free( )'ing a block of memory, that block of memory might be returned in some future malloc( ) / calloc( )
- Some guidelines say you should set a pointer to NULL after freeing it
    - Useful defensive programming; required if variable definition comment says so

```
long *arr = (long *) calloc(sizeof(long),10);
if (arr == NULL)
  return errcode;
// .. do something ..
free(arr);
arr = NULL;
```

Heap

The heap (aka "free store")

- is a large pool of unused memory that is used for dynamically allocated data
- malloc allocates chunks of data in the heap, free deallocates data
- malloc maintains book-keeping data in the heap to track allocated blocks



Heap + stack

```c
#include <stdlib.h>

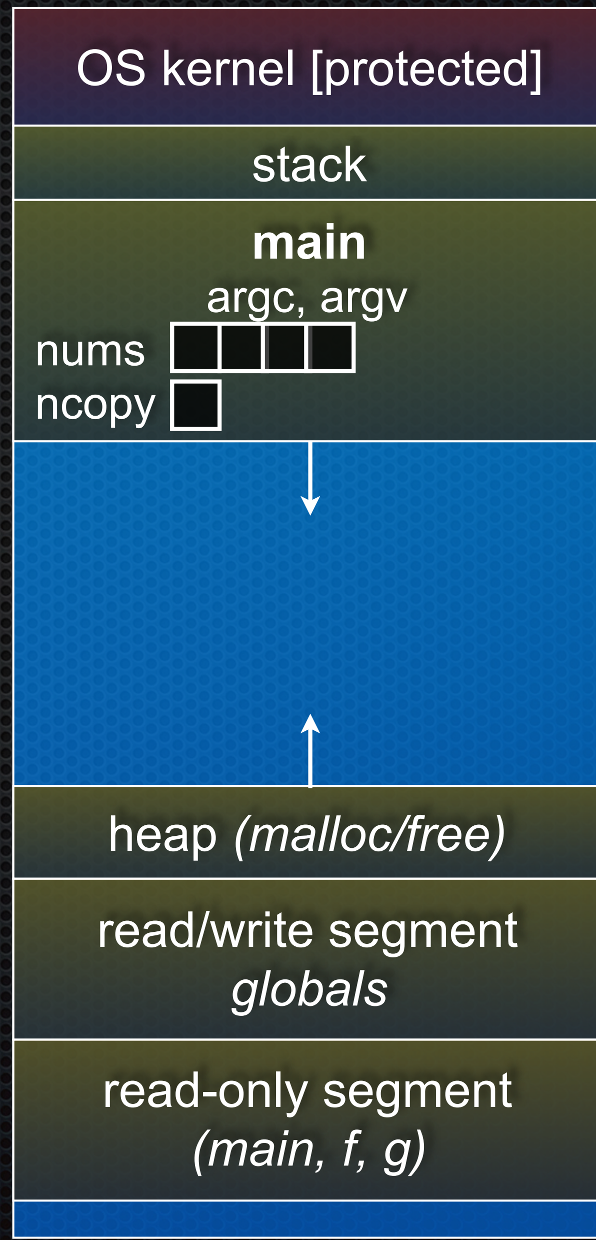
int *copy(int a[], int size) {
  int i, *a2;

  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 nums[4] = {2,4,6,8};
  int *ncopy = copy(nums, 4);
    // ... do stuff ...
  free(ncopy);
  return 0;
}
```

arraycopy.c



Heap + stack

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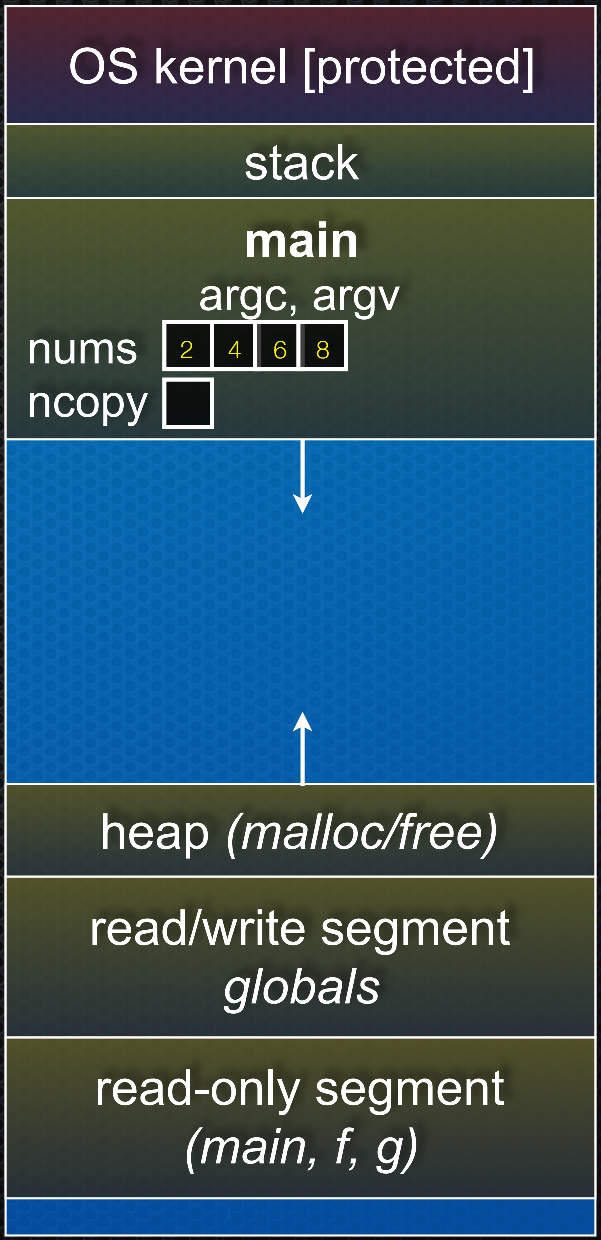

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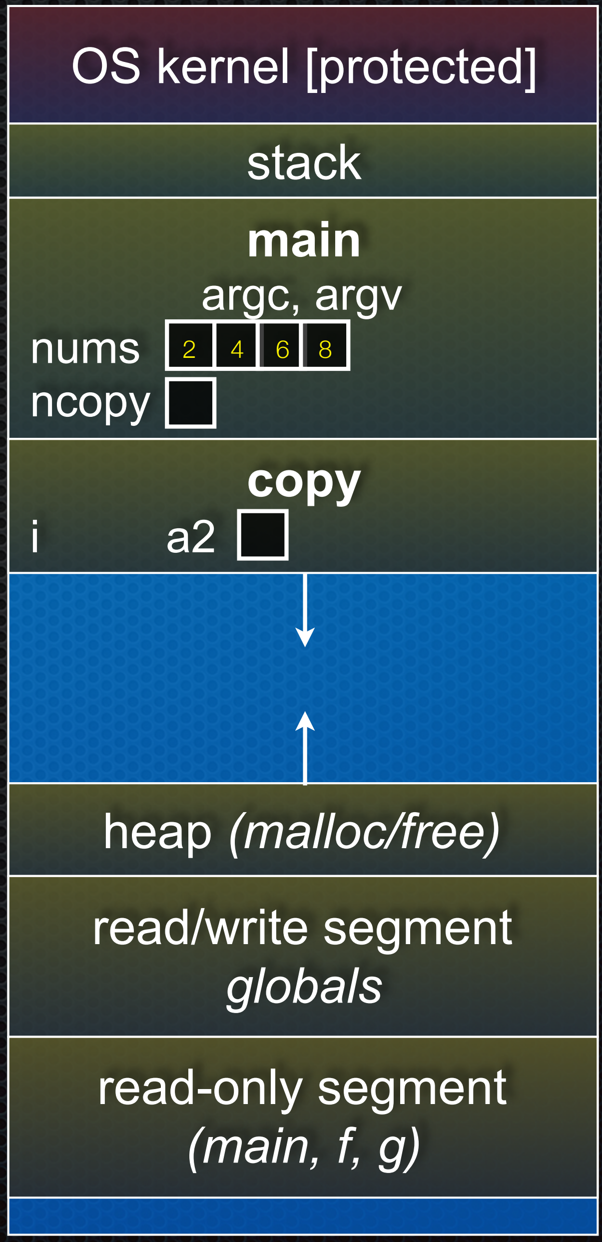

Heap + stack

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  int i, *a2;

  a2 = malloc(
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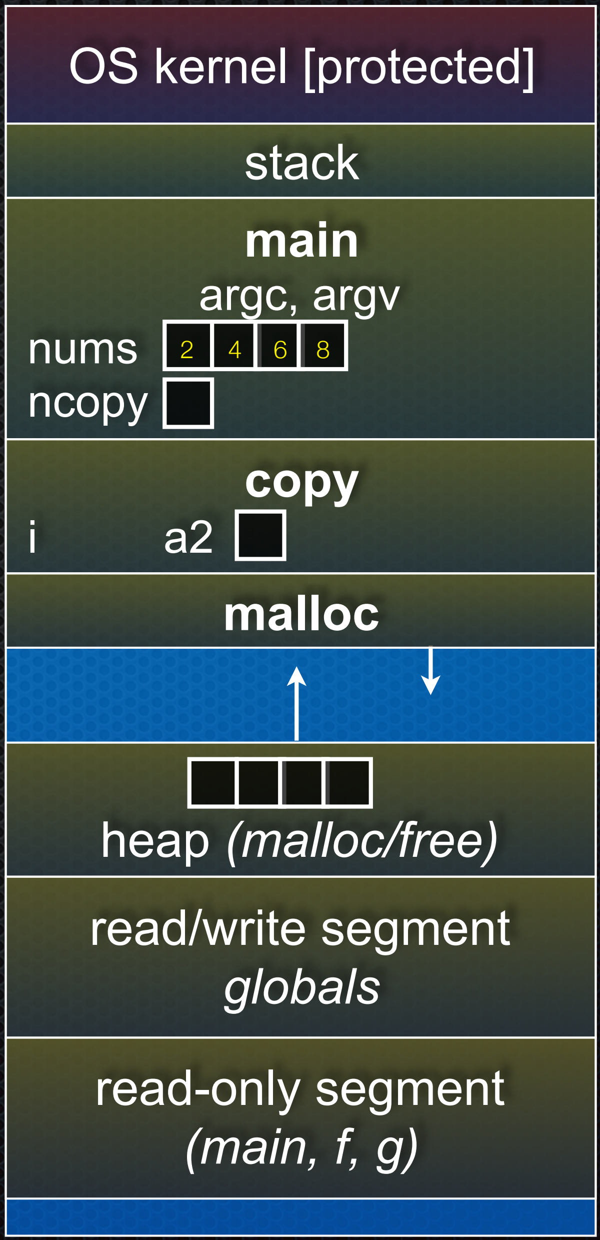
  if (a2 == NULL)
    return NULL;

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

int main(...) {
  int nums[4] = {2,4,6,8};
  int *ncopy = copy(nums, 4);
    // ... do stuff ...
  free(ncopy);
  return 0;
}
```

arraycopy.c



Heap + stack

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}
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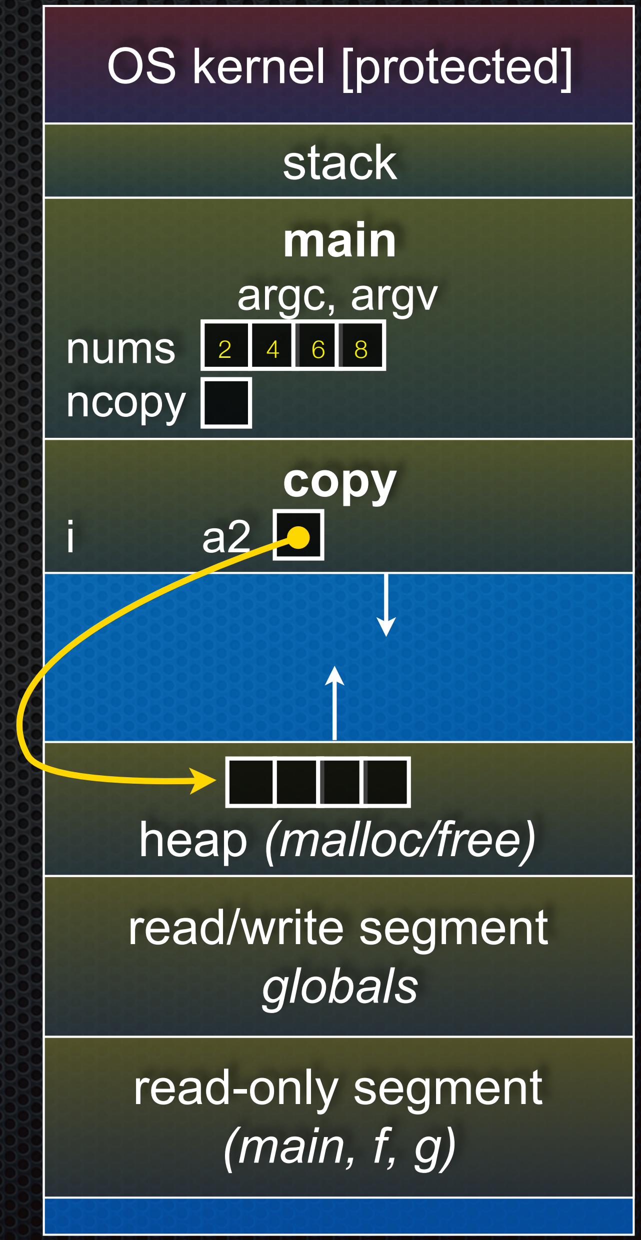
arraycopy.c



Heap + stack

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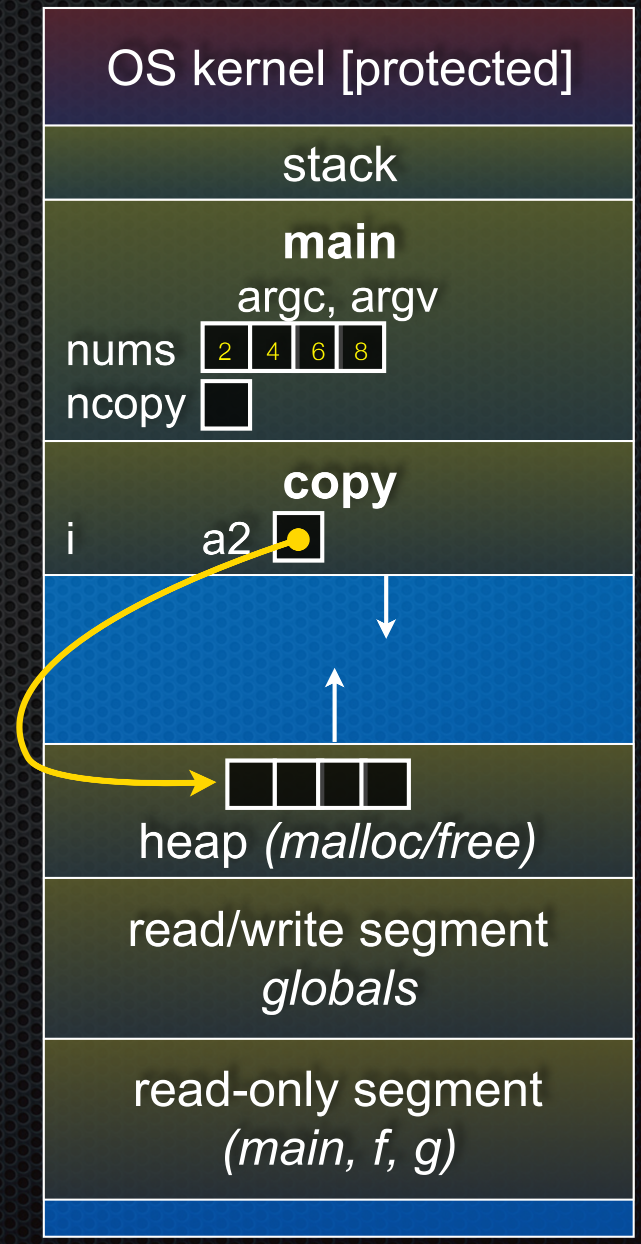
arraycopy.c



Heap + stack

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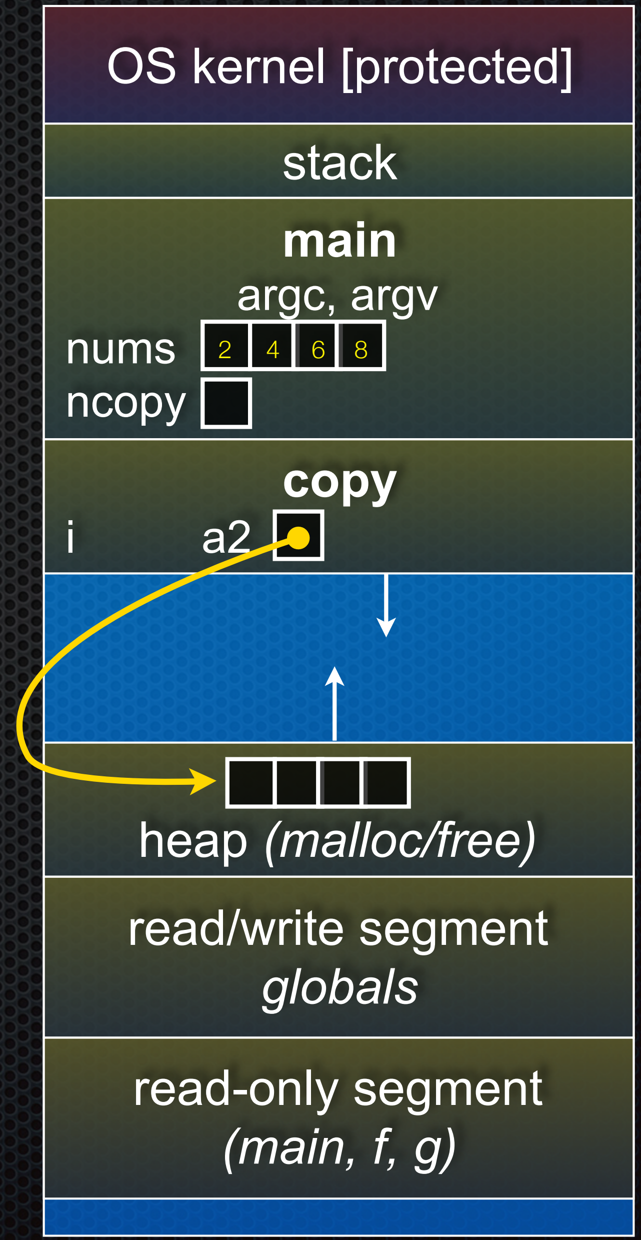
arraycopy.c



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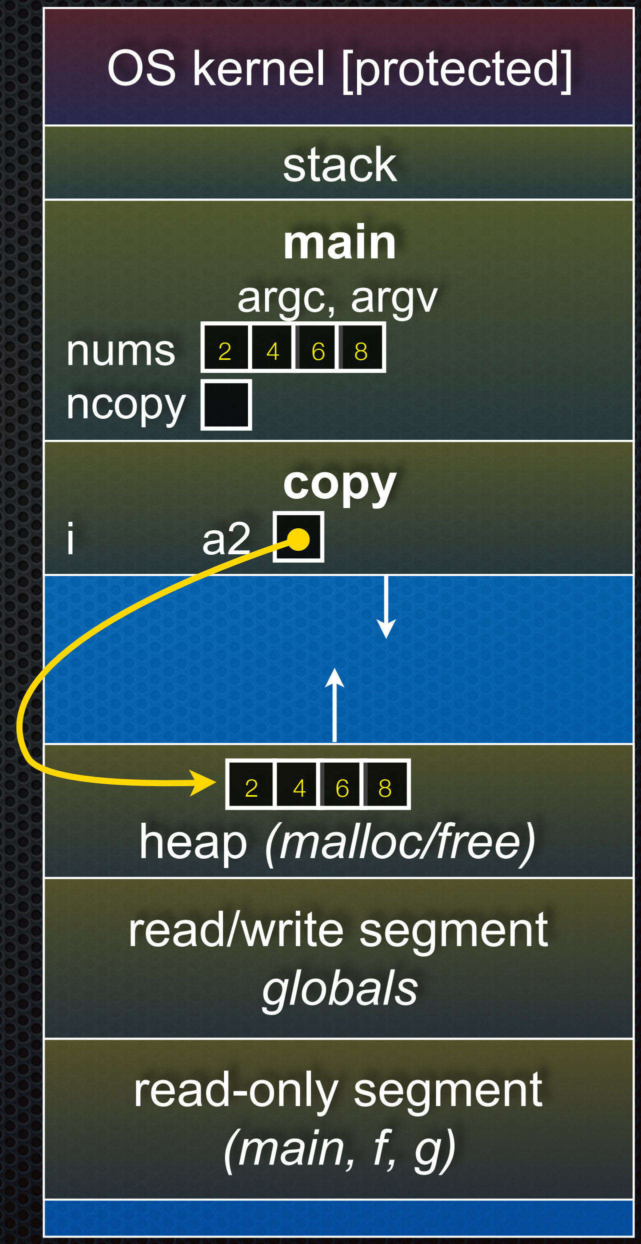
arraycopy.c



Heap + stack

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  int i, *a2;

  a2 = malloc(
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  if (a2 == NULL)
    return NULL;

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

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  free(ncopy);
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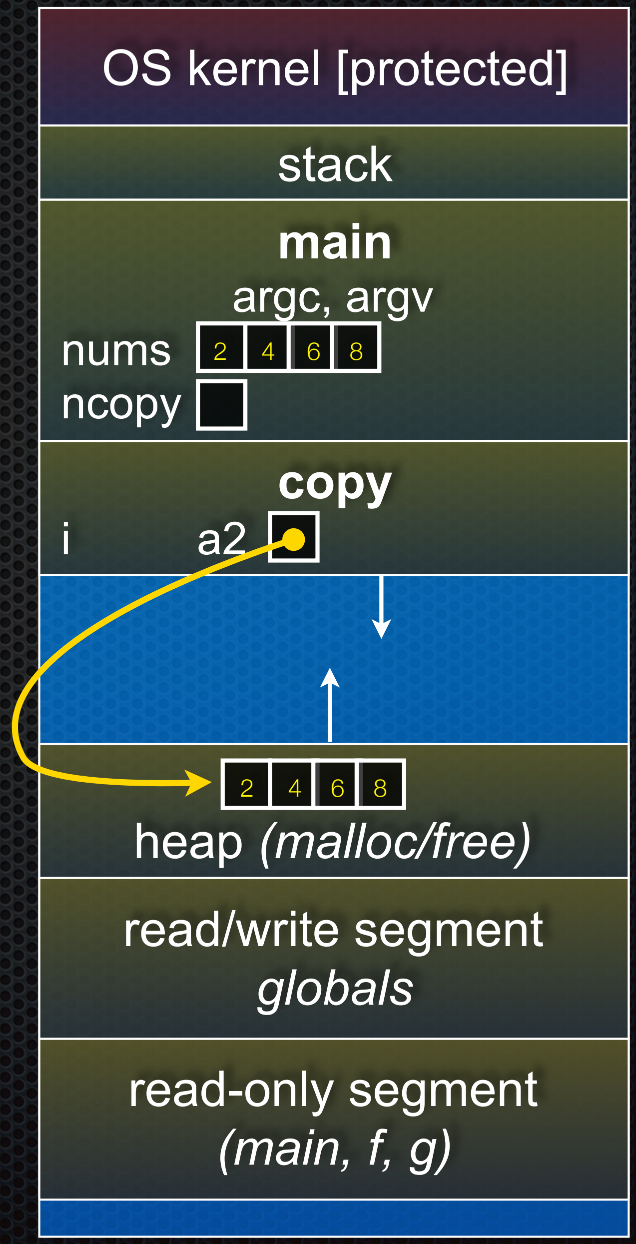
```

arraycopy.c



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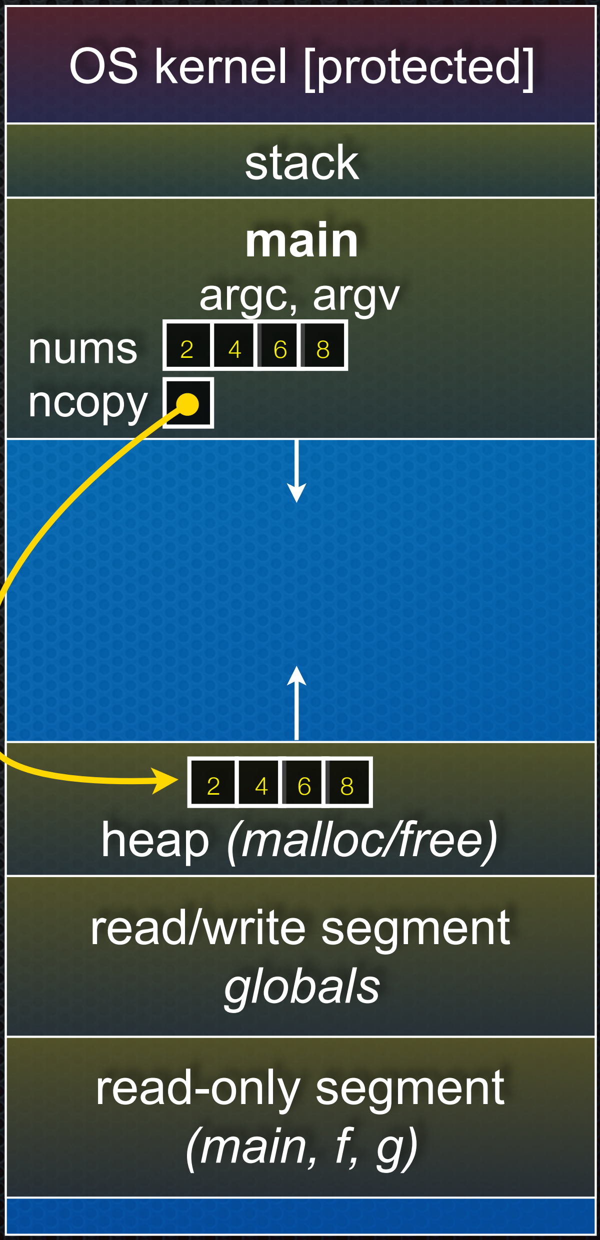
arraycopy.c



Heap + stack

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    a2[i] = a[i];
  return a2;
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int main(...) {
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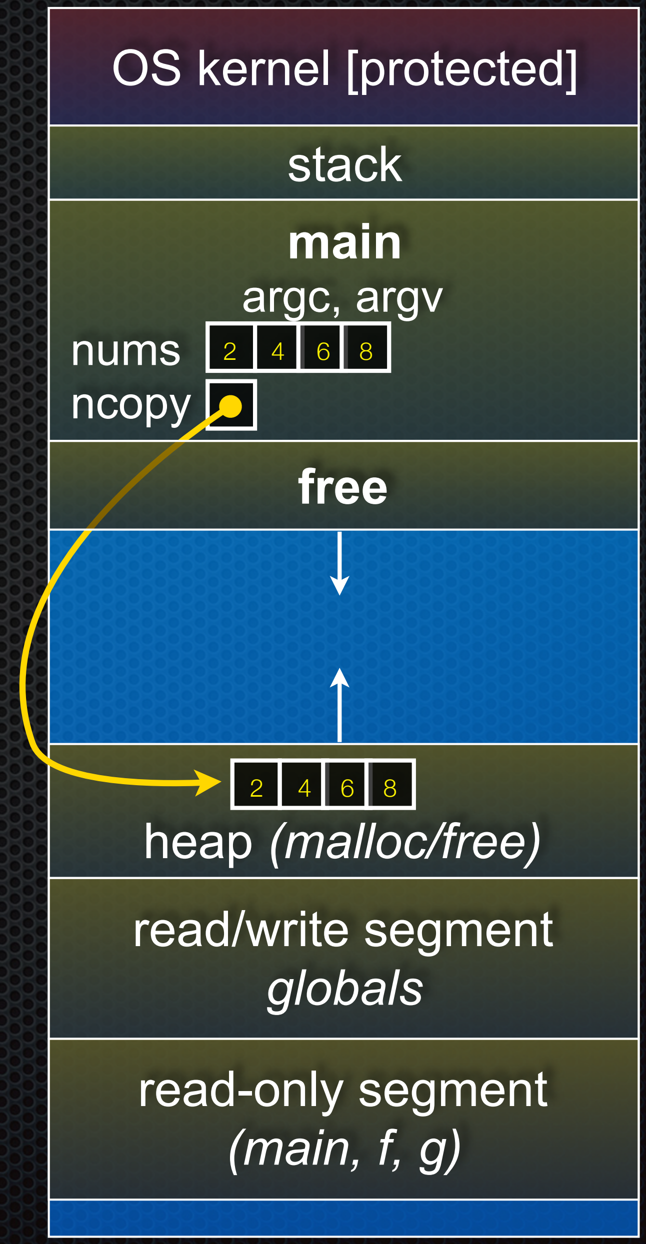
  free(ncopy);
  return 0;
}
```

arraycopy.c



Heap + stack

```c
#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(...) {
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  int *ncopy = copy(nums, 4);
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  free(ncopy);
  return 0;
}
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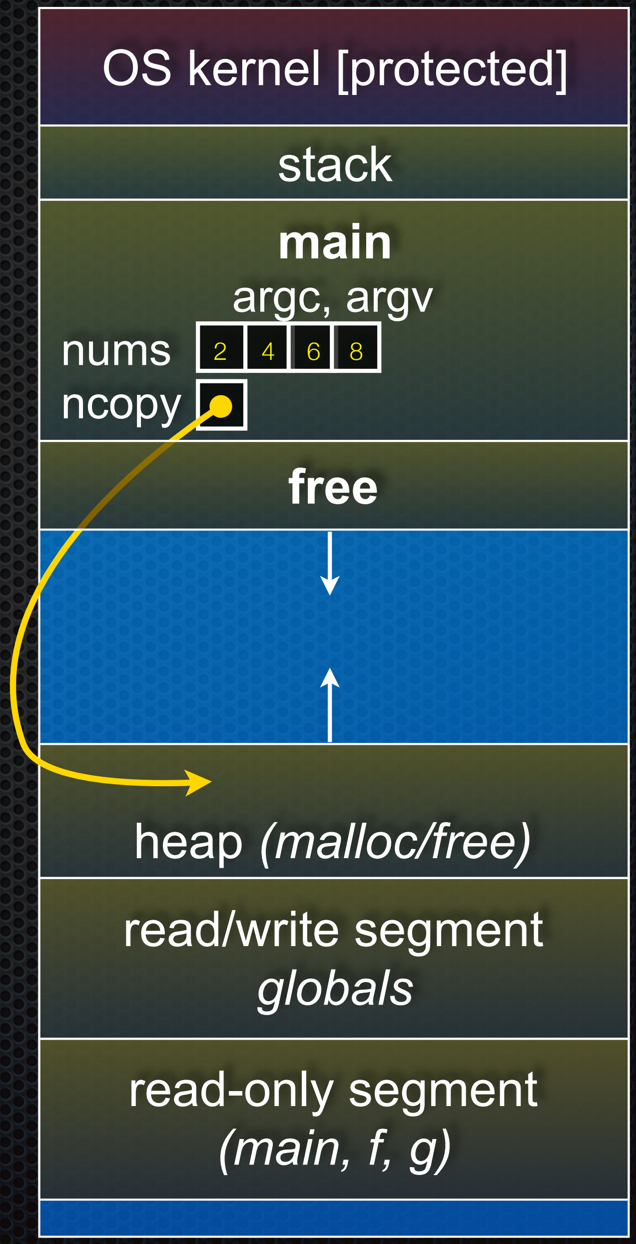
arraycopy.c



Heap + stack

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  int i, *a2;

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  for (i = 0; i < size; i++)
    a2[i] = a[i];
  return a2;
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    // ... do stuff ...
  free(ncopy);
  return 0;
}
```
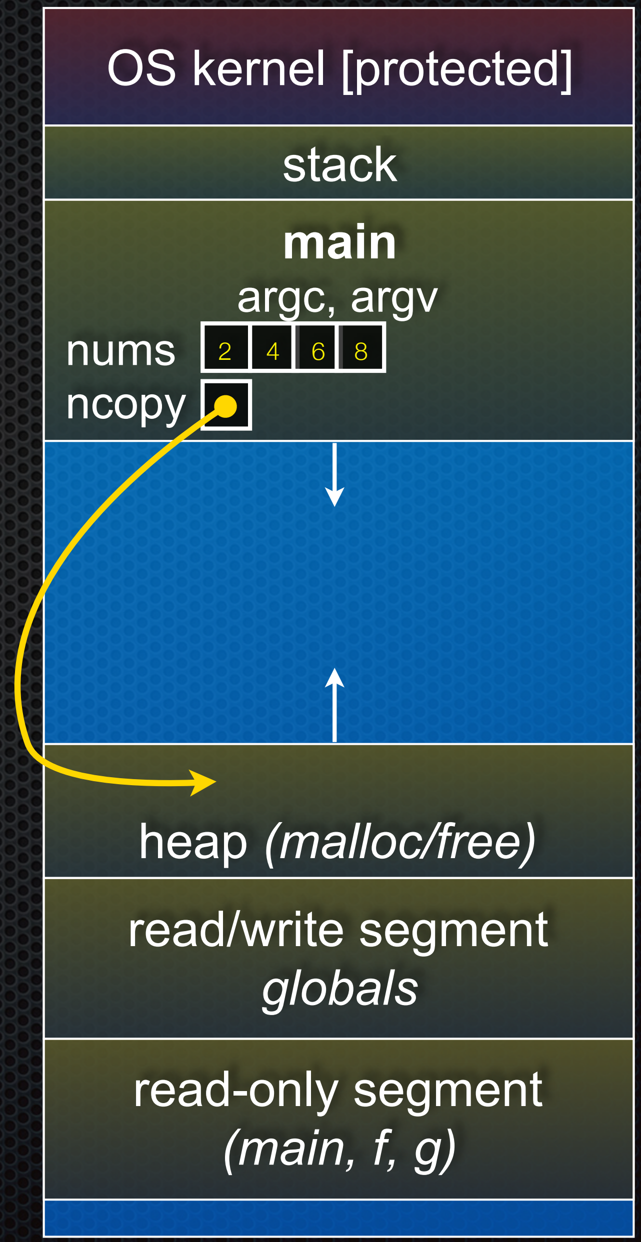

arraycopy.c



NULL

NULL: a guaranteed-to-be-invalid memory location

- in C on Linux:
  - NULL is 0x00000000
  - an attempt to deference NULL causes a segmentation fault
- that's why setting a pointer NULL after you have free( )'d it is useful defense (particularly if the pointer sticks around for a while)
  - it's better to have a segfault than to corrupt memory!

segfault.c

```c
#include <stdio.h>

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

  a[2] = 5;    // assign past the end of an array
  b[0] += 2;   // assume malloc zeroes out memory
  c = b+3;     // mess up your pointer arithmetic
  free(&(a[0]));  // free() something not malloc()'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a free()'d pointer

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

memcorrupt.c

Memory leak

A memory leak happens when code fails to deallocate dynamically allocated memory that will no longer be used

```
// assume we have access to functions FileLen,
// ReadFileIntoBuffer, and NumWordsInString.

int NumWordsInFile(char *filename) {
  char *filebuf = (char *) malloc(FileLen(filename)+1);
  if (filebuf == NULL)
    return -1;

  ReadFileIntoBuffer(filename, filebuf);

  // leak! we never free(filebuf)
  return NumWordsInString(filebuf);
}
```

Implications of a leak?

Your program's *virtual memory* footprint will keep growing

- for short-lived programs, this might be OK
- for long-lived programs, this usually has bad repercussions
  - might slow down over time (VM thrashing – see cse451)
    - *potential "DoS attack" if a server leaks memory*
  - might exhaust all available memory and crash
  - other programs might get starved of memory
- in some cases, you might prefer to leak memory than to corrupt memory with a buggy free( )

Structured data

struct tagname {
type name;
type name;
...
type name;
};

```c
// The following defines a new structured
// data type called a "struct Point".
struct Point {
  float x, y;
};

struct Point origin = {0.0, 0.0};
```

struct: a C type that contains a set of fields

- similar to a Java class, but without methods / constructors
- instances can be allocated on the stack or heap
- useful for defining new structured types of data

Using structs

Use "." to refer to fields in a struct

Use "->" to refer to fields through a pointer to a struct

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

int main(int argc, char **argv) {
  int i = 1;
  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;    // means same as (*p1_ptr).y = 2.0;
  return 0;           // but better (i.e., expected) style
```

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

```
#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

typedef type name;

Allows you to define a new type whose name is *name*

- especially useful when dealing with structs

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

// make "Point" be a synonym for "struct point_st { ... }"
typedef struct point_st {
  superlong x;
  superlong y;
} Point;

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

Dynamically allocated structs

You can malloc and free structs, as with other types

- sizeof is particularly helpful here

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

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

```c
// Point is a (struct point_st)
// PointPtr is a (struct point_st *)
typedef struct point_st {
  int x, y;
} Point, *PointPtr, **PointPtrPtr;

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);
  DoubleXWorks(&a);
  printf("(%d,%d)\n", a.x, a.y);
  return 0;
}
```

structarg.c

structs are passed by value

- like everything else in C (except arrays)
    - entire structure is copied
- to pass-by-reference, pass a pointer to a struct
    - Very common

You can return structs

```c
// a complex number is a + bi
typedef struct complex_st {
  double real;  // real component (i.e., a)
  double imag;  // imaginary component (i.e., b)
} Complex, *ComplexPtr;

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

  retval.real = x.real + y.real;
  retval.imag = x.imag + y.imag;
  return retval;  // returns a copy of retval
}

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;
}
```

complexstruct.c

Call by value or reference?

What if a function only needs to read a struct?

- Call-by-value copies a struct, call-by reference copies a pointer
  - Pointer copy is cheaper and takes less space unless struct is small
  - Indirect field references through pointers are a bit more expensive, also can be harder for compiler to optimize because of pointer aliasing
- For small things like complex numbers, call by value can be faster and is often preferred; for large structs use pointers

Similar issues for functions that return struct values

- But be sure not to return dangling pointers!!!

Exercise 1

Write and test a program that defines:

- a new structured type Point
  - represent it with floats for the x, y coordinate
- 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/returns the area of a Rectangle
- a function that tests whether a Point is in a Rectangle

Exercise 2

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

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

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

Implement AllocSet( ), 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

See you on Wednesday!