CS 241: Systems Programming
Lecture 14. Pointers and Arrays

Fall 2019

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Announcements

HW2 is due this Sunday at 23:59

HW3 is now up. Its due Sunday, October 13 at 23:59

Arrays in Java

Arrays in Java are normal `Objects` created with new

```
int[] arr = new int[100];
```

They're indexed from `0` to `arr.length-1`

Attempts to access out of bounds elements leads to `ArrayIndexOutOfBoundsExceptions`

They can be passed to functions or returned from function

Arrays in C

```
int arr1[100];                    // Fixed-size array
double arr2[x];                   // Variable-sized array
unsigned char arr3[x][y][z];      // Multi-dimensional array
```

Arrays are indexed from 0 to one less than their bound

- Arrays don't keep track of their length
- Accessing an array outside its bound is undefined behavior:

> — An array subscript is out of range, even if an object is apparently accessible with the given subscript (as in the lvalue expression **`a[1][7]`** given the declaration **`int a[4][5]`**) (6.5.6).

Arrays cannot be returned from functions (but can sort of be passed to them)

Initializing arrays

Like all other variables in C, arrays need to be initialized

- Exception: global variables are initialized to all zeros

Fixed-sized arrays can be initialized with an **initializer**

- `int a[5] = { 0 };` // same as { 0, 0, 0, 0, 0 }
- `int b[5] = { 1, 2, 3 };` // same as { 1, 2, 3, 0, 0 }
- `int c[] = { 1, 2, 3 };` // b has length 3
- `int d[5] = { [3] = 1, [4] = 2, [0] = 3 };`
  // same as { 3, 0, 0, 1, 2 }
- `int e[] = { [3] = 1, [0] = 3 };` // same as { 3, 0, 0, 1 }

Variable-sized arrays cannot be initialized with an initializer

Which of the following defines an array of four integers with the 0th element set to 5?

A.
```
int arr[4] = { 5, 4, 3, 2, 1 };
```

B.
```
int arr[] = { 5 };
```

C.
```
int arr[4] = { [5] = 0 };
```

D.
```
int arr[4] = { [0] = 5, [4] = 3 };
```

E.
```
int arr[4] = { [0] = 5, [3] = 2 };
```

Aside about style

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Using multiple lines can improve readability

- But do it only when it does (it probably doesn't here)

```
int a[] = {
  37,
  42, // Trailing commas are fine
};
```

Aside about style

Using multiple lines can improve readability

- But do it only when it does (it probably doesn't here)

```
int a[] = {
  37,
  42, // Trailing commas are fine
};
```

Explicit indices in the initializer, like [3] = 5, can help

- Use them when readability is improved

```
int a[] = {
  [0] = 37,
  [1] = 42,
};
```

Initializing a variable sized array

```
// Option 1. Loop over each element and assign it a value
void foo(size_t count) {
  int arr[count];
  for (size_t idx = 0; idx < count; ++idx)
    arr[idx] = 0;
  // ...
}

// Option 2. Use memset() from string.h
#include <string.h>
void bar(size_t count) {
  int arr[count];
  memset(arr, 0, sizeof arr);
  // ...
}
```

Function parameters

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

void make_identity(size_t n, double arr[n][n]) {
  for (size_t row = 0; row < n; ++row) {
    for (size_t col = 0; col < n; ++col) {
      arr[row][col] = (row == col ? 1.0 : 0.0);
    }
  }
}
int main(int argc, char *argv[argc]) {
  size_t dim = (argc > 1 ? atoi(argv[1]) : 2);
  double ident[dim][dim]; // Danger of crashing with large dim!

  make_identity(dim, ident);
  for (size_t row = 0; row < dim; ++row) {
    for (size_t col = 0; col < dim; ++col) {
      printf("%.1f ", ident[row][col]);
    }
    putchar('\n');
  }
  return 0;
}
```

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  make_identity(dim, ident);
  for (size_t row = 0; row < dim; ++row) {
    for (size_t col = 0; col < dim; ++col) {
      printf("%.1f ", ident[row][col]);
    }
    putchar('\n');
  }
  return 0;
}
```

Array syntax for main

Function parameters

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  }
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  for (size_t row = 0; row < dim; ++row) {
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      printf("%.1f ", ident[row][col]);
    }
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  }
  return 0;
}
```

Array syntax for main

Not passed by value!
There are no array *values* in C

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int main(int argc, char *argv[argc]) {
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  for (size_t row = 0; row < dim; ++row) {
    for (size_t col = 0; col < dim; ++col) {
      printf("%.1f ", ident[row][col]);
    }
    putchar('\n');
  }
  return 0;
}
```

Array syntax for main

Not passed by value!
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```
$ ./matrix 3
1.0 0.0 0.0
0.0 1.0 0.0
0.0 0.0 1.0
```

Size and length of an array

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For arrays that are **not** function parameters, e.g.,

```
int a[5];
int b[x];
```

we can use `sizeof` to get the size and length

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- Size

```
size_t size1 = sizeof a; // 5 * sizeof(int)
size_t size2 = sizeof b; // x * sizeof(int)
```

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int a[5];
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we can use `sizeof` to get the size and length

- Size

```
size_t size1 = sizeof a; // 5 * sizeof(int)
size_t size2 = sizeof b; // x * sizeof(int)
```

- Length

```
size_t len1 = sizeof a / sizeof a[0];
  // size1 / sizeof(int) = 5
size_t len2 = sizeof b / sizeof b[0];
  // size2 / sizeof(int) = x
```

C's memory model: Objects

C has a bunch of "objects" (not at all like the Java notion of an object!)

- Every variable definition creates a new, distinct object
- Literals (e.g., the string literal "foo") are objects
- Each object is a collection of bytes
- `sizeof object` — gives the size of an object
- `sizeof(type)` — gives the size of an object with type type

```
int x;
assert(sizeof x == sizeof(int));
```

Object lifetimes

Objects have a lifetime

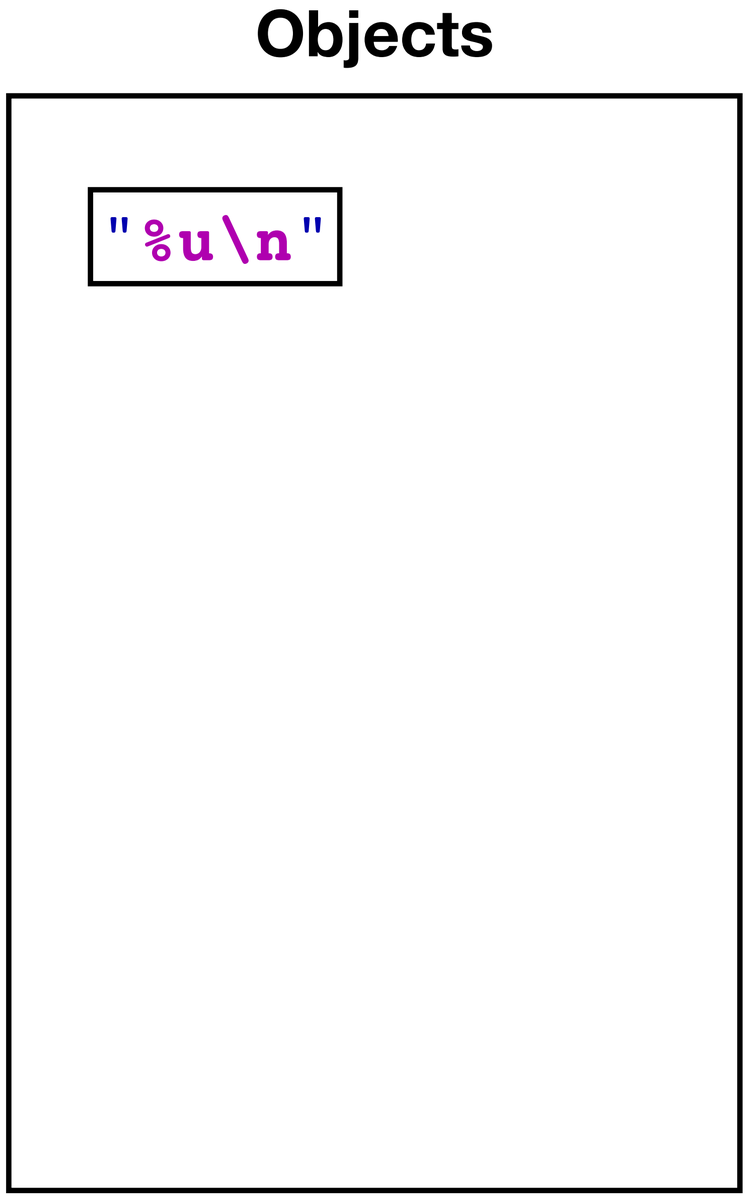
- Local variables live as long as they are in scope
- Global variables (including file and function static) live the whole program
- Temporary objects (returned from functions) live only until the end of the expression with the function call (we can mostly ignore these)
- We can dynamically create objects and manage their lifetimes (later)
- **Accessing an object outside its lifetime is undefined behavior**

Object example

```c
#include <stdio.h>

unsigned int slow_fib(unsigned int n) {
  if (n <= 1)
    return n;
  return slow_fib(n-1) + slow_fib(n-2);
}

int main(void) {
  unsigned int x = 2;
  unsigned int fx = slow_fib(x);
  printf("%u\n", fx);
  return 0;
}
```



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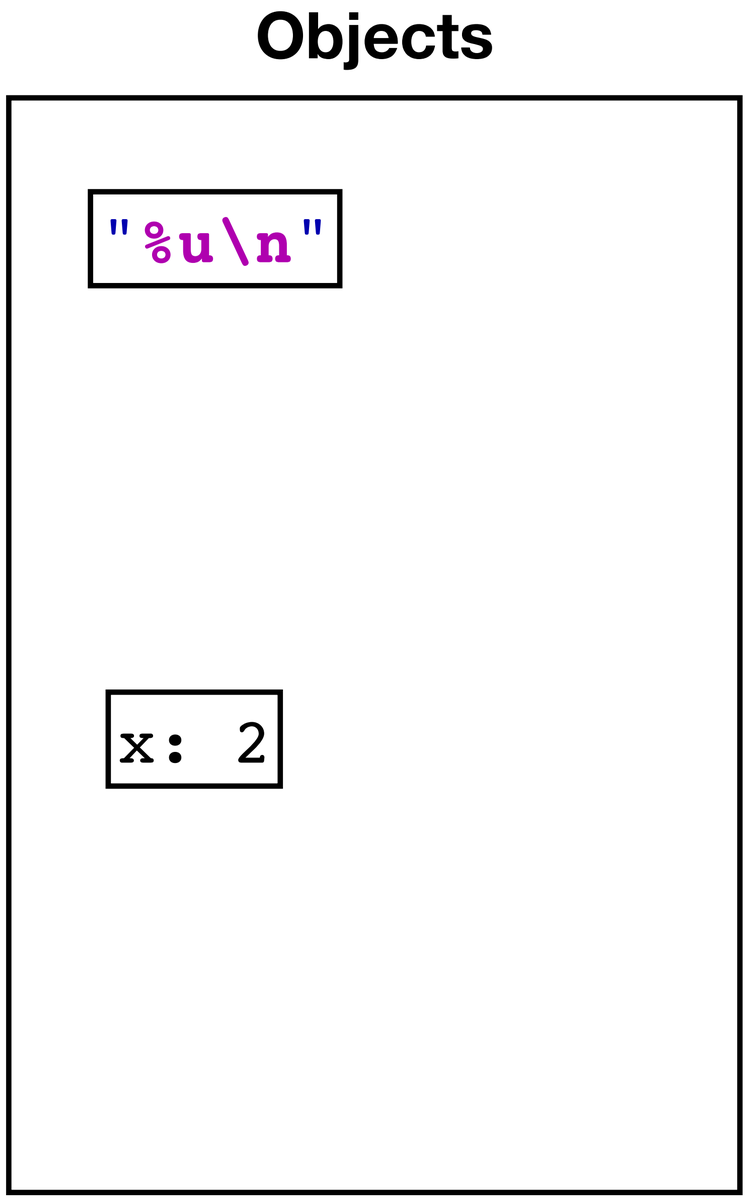

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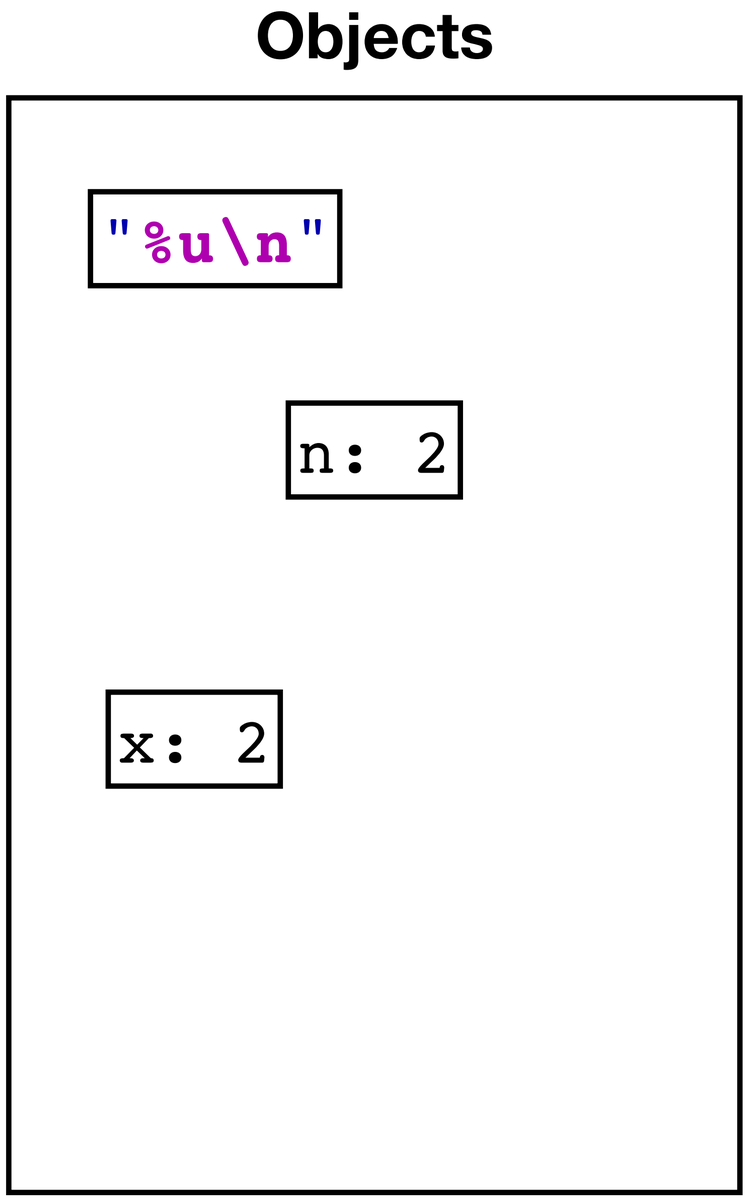

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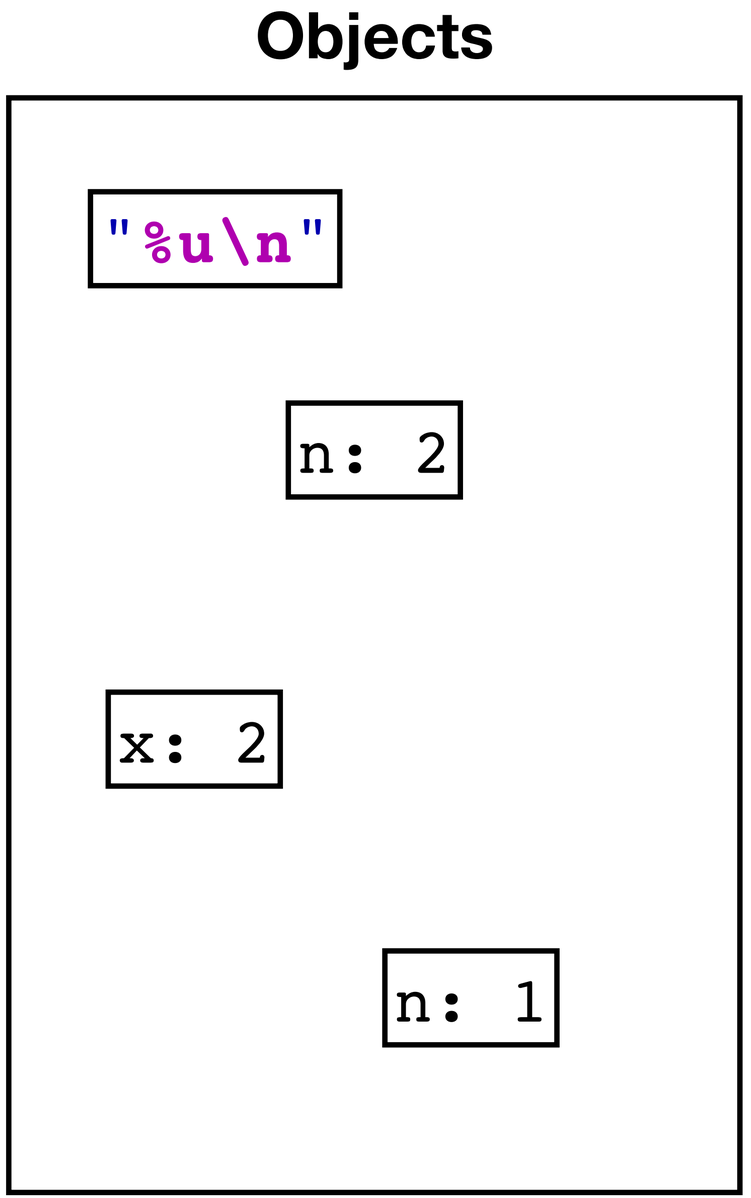

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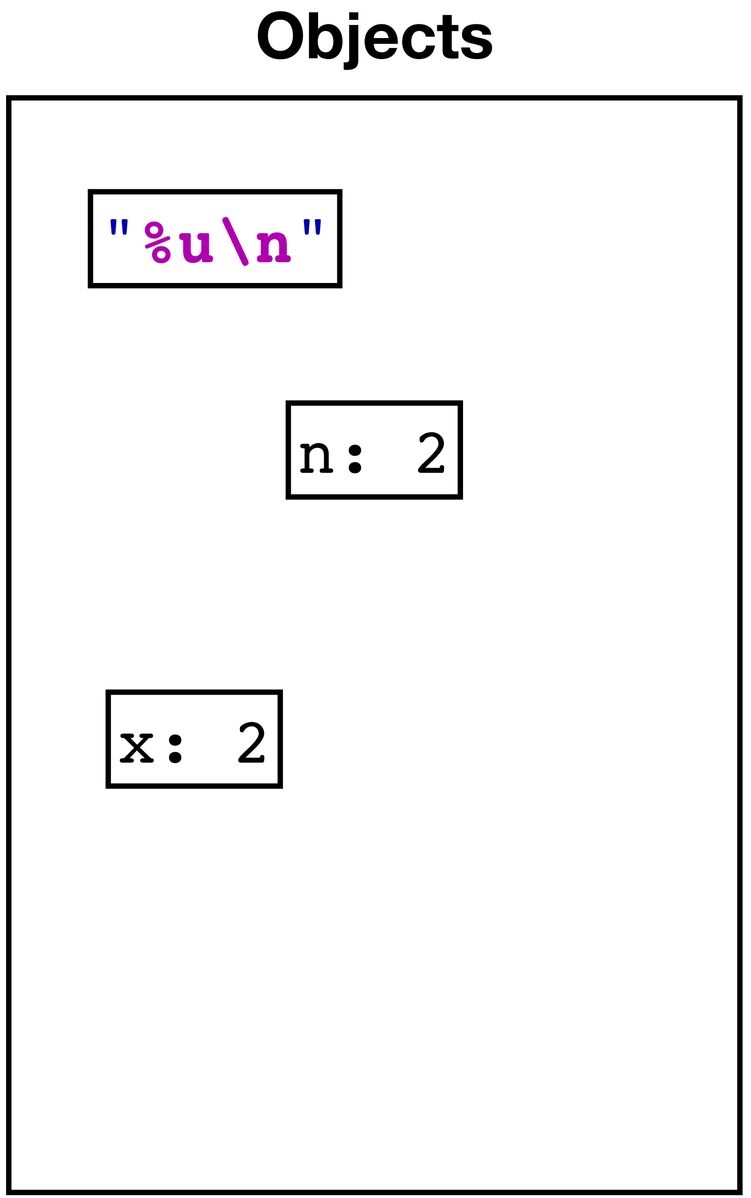

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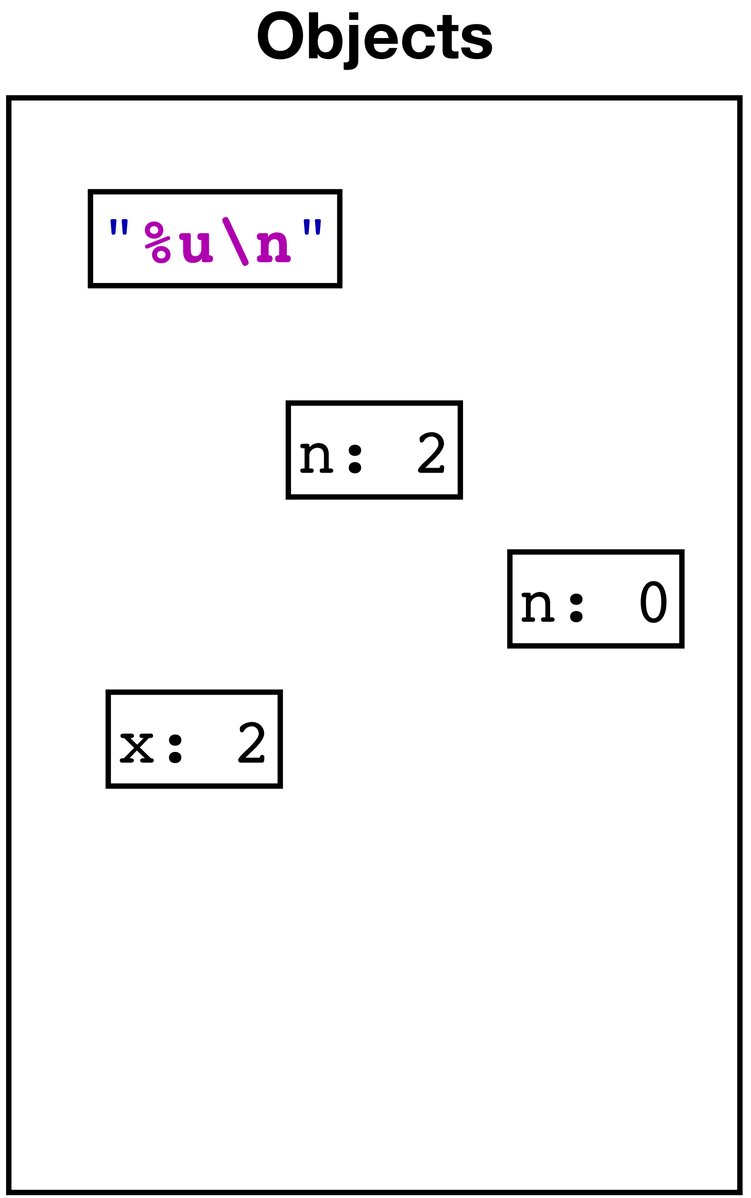

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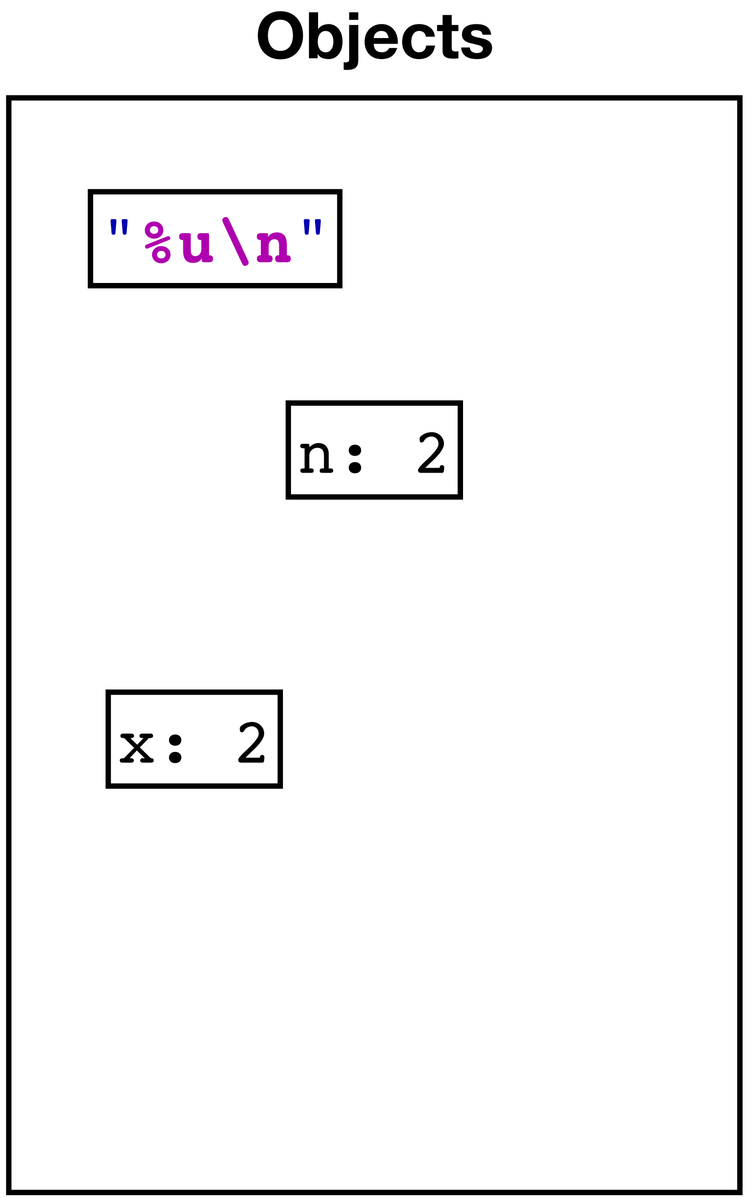

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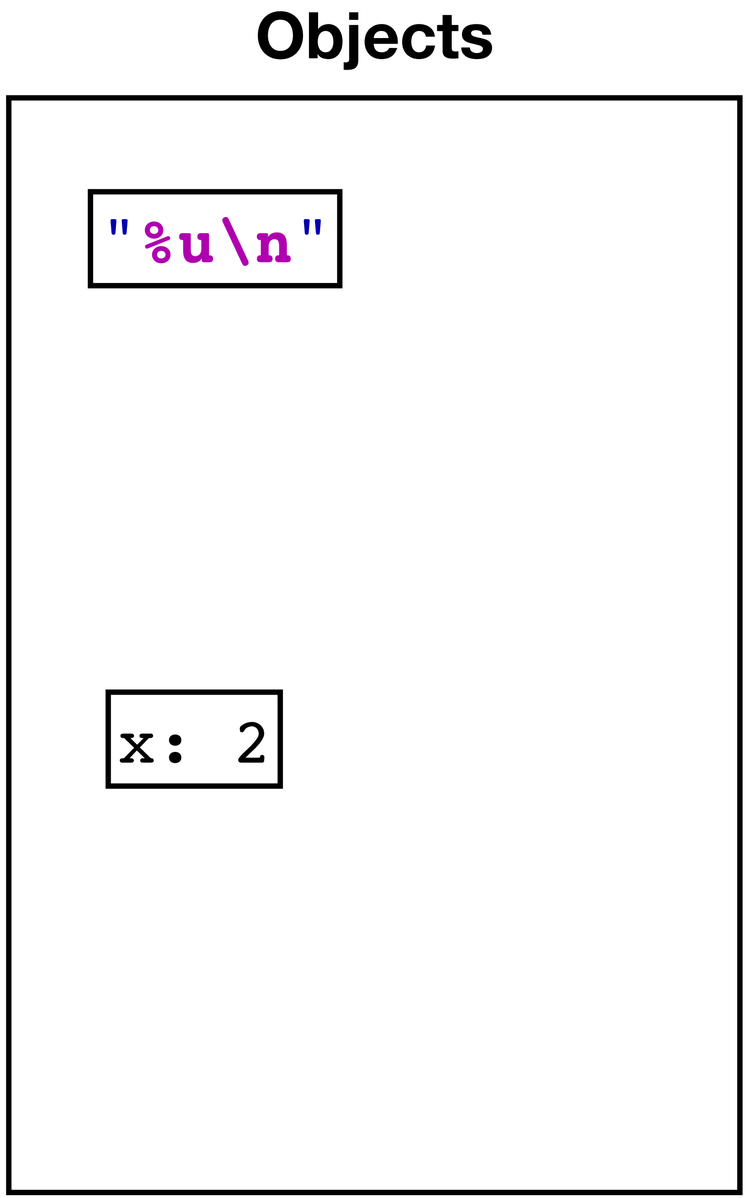

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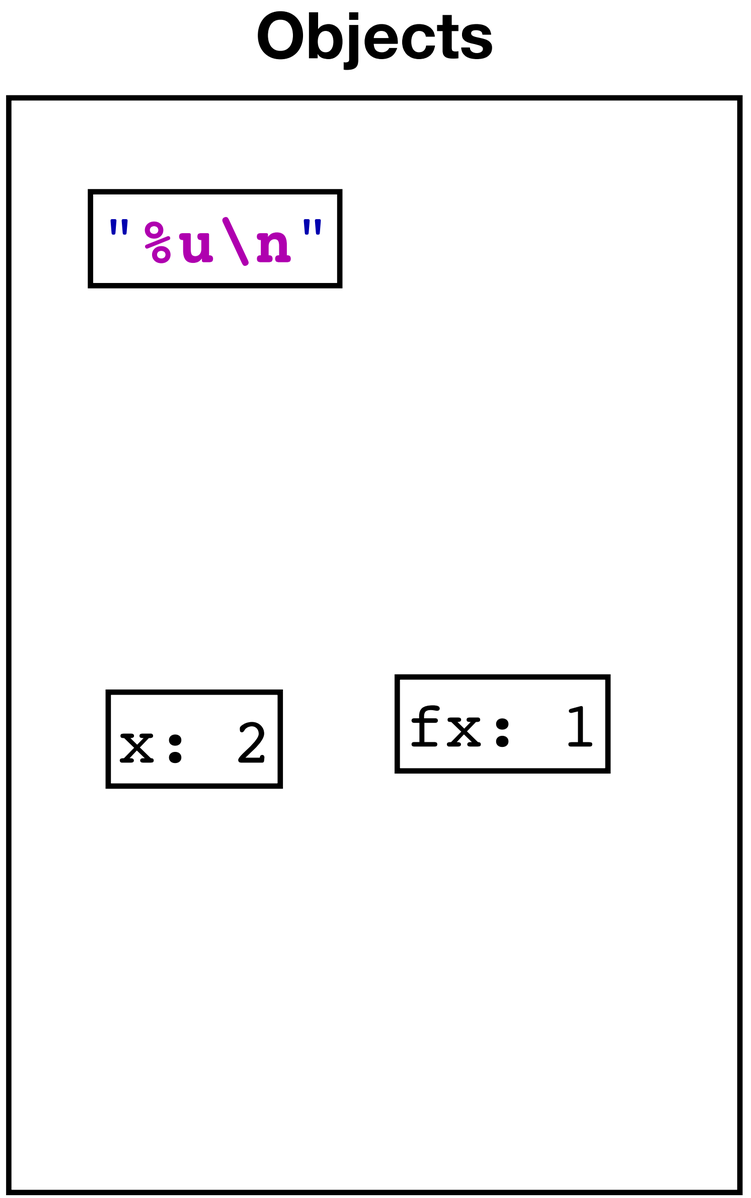
  return 0;
}
```



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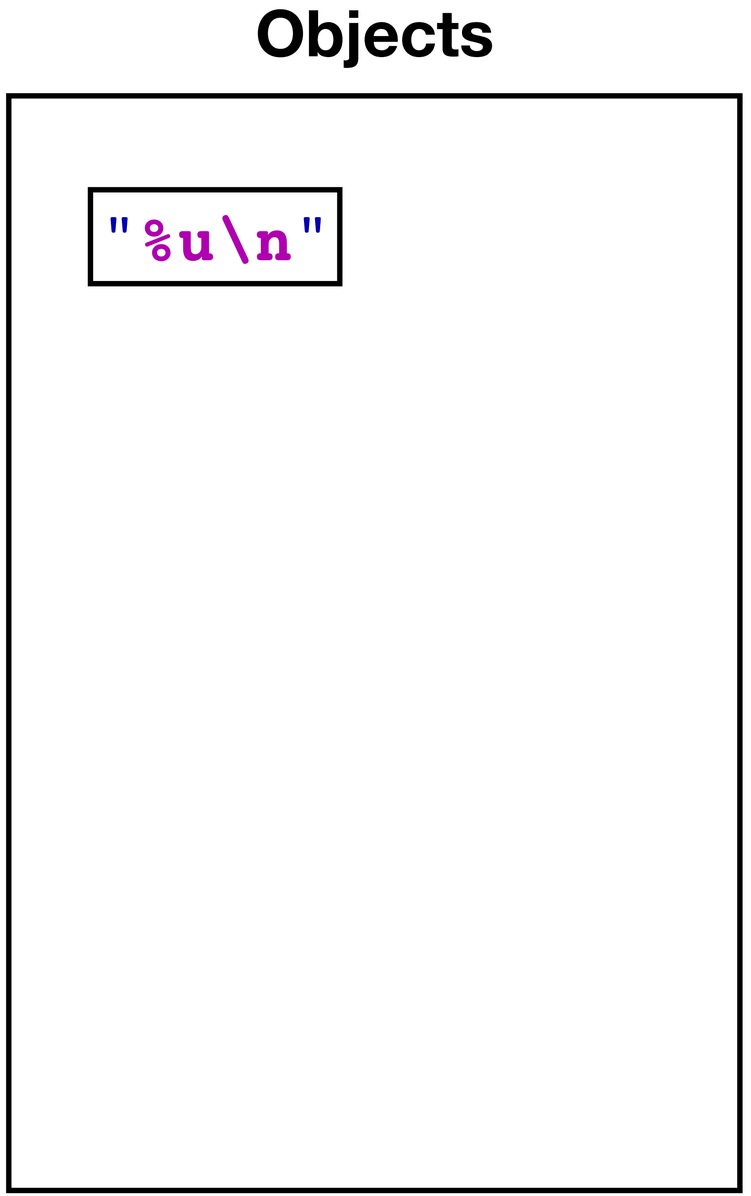
  return 0;
}
```



What most machines do

Memory is a giant array of bytes (this is a lie the OS presents to applications)

- Each object lives in some contiguous sequence of bytes in this array

Some of this memory is filled with program and library code

A region of the memory, the **stack**, stores the local variables for functions

- Each function call allocates more space on the stack for its local variables

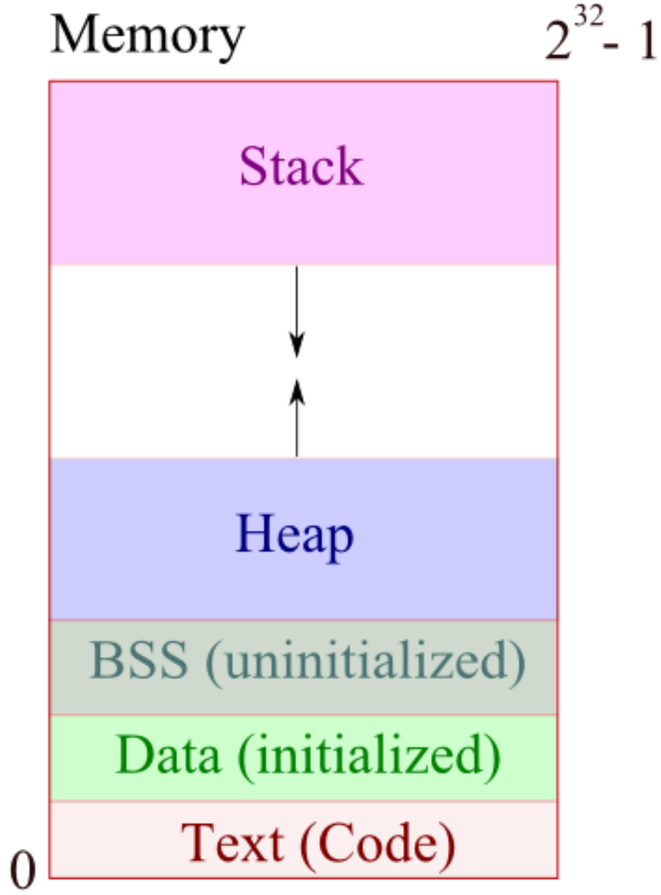
A region of the memory, the **heap**, stores dynamically created data (we'll talk more about this later)

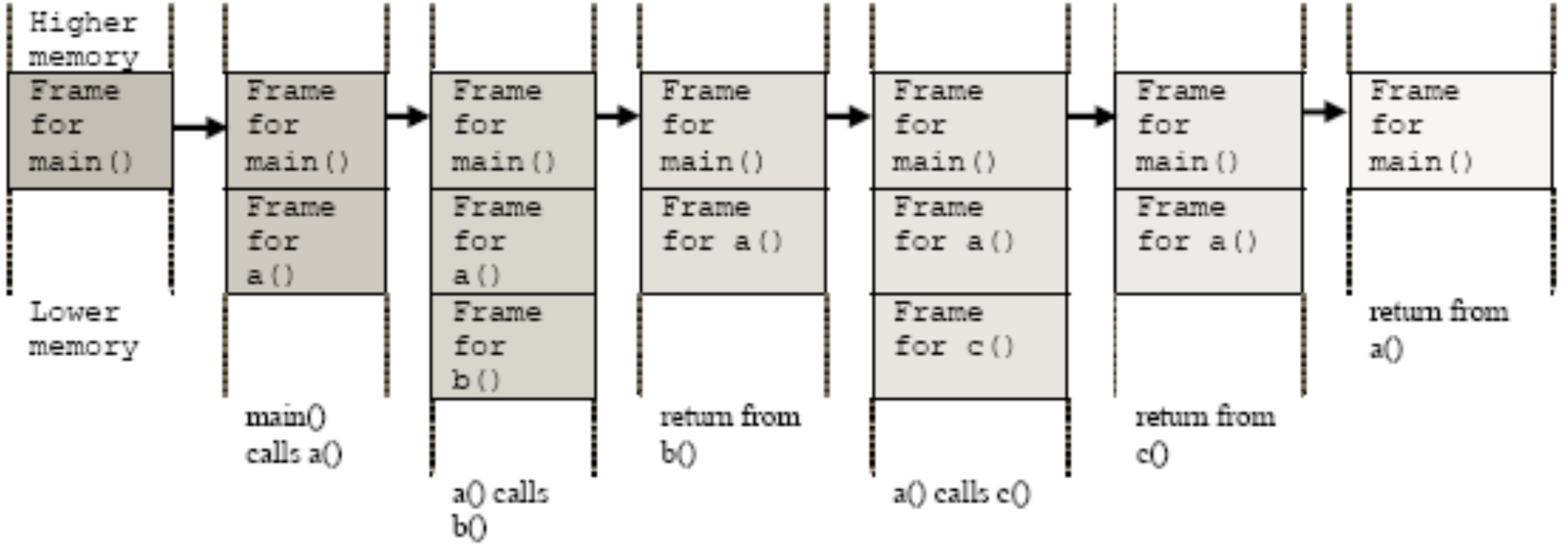
Memory Layout x86 (simplified)

Stack and Heap grow towards each other

- Efficient use of space

Stacks grow "down" in x86 (not all do)




Higher memory
Frame for main()
Frame for a()
Frame for b()
Frame for c()
Lower memory
main() calls a()
a() calls b()
return from b()
a() calls c()
return from c()
return from a()

Object addresses

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- In C, an address is just a way to refer to an object
- In reality, an address is just the index into the array of bytes that is all of memory of the first byte of the object
- The address-of unary operator, `&`, gives the address of the object

```
int x = 37;
int y = 42;
printf("x has value %d and address %p\n", x, &x);
printf("y has value %d and address %p\n", y, &y);

$ ./addr
x has value 37 and address 0x7ffee11d21b8
y has value 42 and address 0x7ffee11d21b4
```

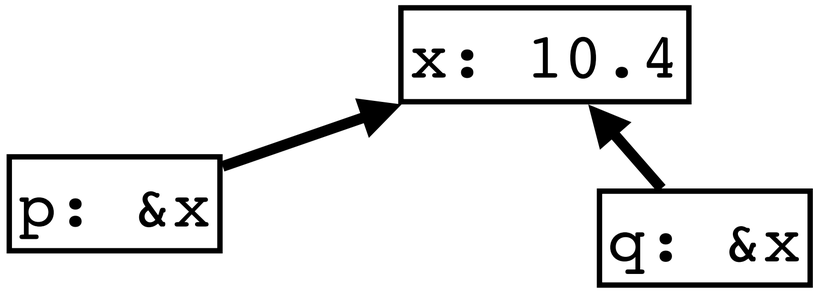
Pointers

A pointer is an object whose value is the address of some object

- If `x` is an object (say a `double`), and `p` is a pointer whose value is `&x`, then we say "`p` points to `x`"

Every pointer has a type that tells you what the type of the pointed-to object is

- ```
  double x = 10.4;
  double *p = &x;
  double *q = p;
  ```



`0` (or `NULL`) is a special pointer value used to indicate that the pointer points at no object
  ```

Dereferencing a pointer

To read or write the value of the object pointed to by the pointer, we need to **dereference** the pointer

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double *p = &x;
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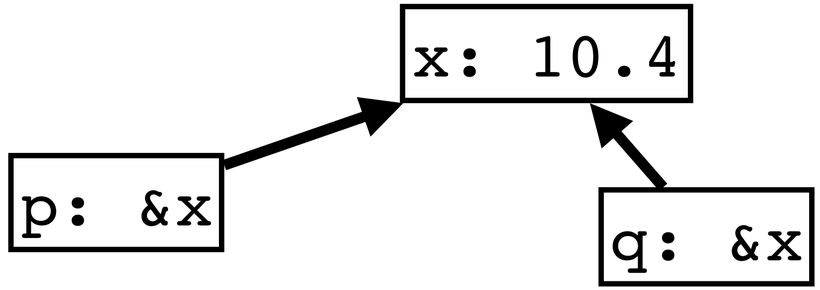
```




```
*p = 23.5; // stores 23.5 in x
printf("%.2f\n", x);   // prints 23.50
printf("%.2f\n", *p);  // prints 23.50
printf("%.2f\n", *q);  // prints 23.50
```

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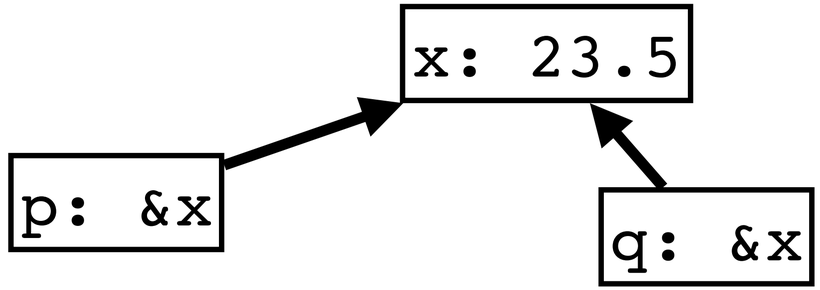


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printf("%.2f\n", *p);  // prints 23.50
printf("%.2f\n", *q);  // prints 23.50
```

What is printed by this?

```
int x = 5;
void foo(int *p) {
  p = &x;
}
int main(void) {
  int z = 3;
  int *p = &z;
  foo(p);
  *p = 0;
  printf("%d\n", z);
}
```

A. 0

B. 3

C. 5

D. Undefined behavior

E. Implementation-defined behavior