Administrivia 1

ex0 was due 30 minutes ago! Solution posted after class
- let us know if you had any logistical issues with it
ex1 is out now, due before class Friday
hw0 out later today/tonight, due by Monday night, 11 pm
- Logistics and infrastructure - should be quick
hw1 out beginning of next week, due 2 weeks later
- First (large) part of (larger) project
Reference system (grading, etc.) is CSE lab/VM Linux
Administrivia 2

Communications

- Use discussion board when possible
  ‣ Contribute & read - help each other out
  ‣ Everyone should must post a followup to the “welcome” message - get gopost to track new messages for you

- Mail to cse333-staff@cs when needed (not individual staff)

Office hours

- Where? 00x lab? Somewhere else?
- Schedule: keep doodling! Do we need something for the next couple of days?
Today’s agenda

More C details

- functions
- arrays
- refresher on C’s memory model
  ‣ address spaces
  ‣ the stack
  ‣ brief reminder of pointers
Defining a function

```
returnType name(type name, ..., type name) {
  statements;
}
```

// sum integers from 1 to max
int sumTo(int max) {
  int i, sum = 0;
  for (i=1; i<=max; i++) {
    sum += i;
  }
  return sum;
}
Problem: ordering

You shouldn’t call a function that hasn’t been declared yet

```c
#include <stdio.h>

int main(int argc, char **argv) {
    printf("sumTo(5) is: %d\n", sumTo(5));
    return 0;
}

// sum integers from 1 to max
int sumTo(int max) {
    int i, sum = 0;

    for (i=1; i<=max; i++) {
        sum += i;
    }
    return sum;
}
```

sum_badorder.c
Problem: ordering

Solution 1: reverse order of definition

```c
#include <stdio.h>

// sum integers from 1 to max
int sumTo(int max) {
    int i, sum = 0;
    for (i=1; i<=max; i++) {
        sum += i;
    }
    return sum;
}

int main(int argc, char **argv) {
    printf("sumTo(5) is: %d\n", sumTo(5));
    return 0;
}
```

Problem: ordering

Solution 2: provide a declaration of the function

- teaches the compiler the argument and return types of the function
- then definitions can be in a logical order, not who-calls-what

```c
#include <stdio.h>

// this function prototype is
// a declaration of sumTo
int sumTo(int);

int main(int argc, char **argv) {
    printf("sumTo(5) is: %d\n", sumTo(5));
    return 0;
}

// sum integers from 1 to max
int sumTo(int max) {
    int i, sum = 0;
    for (i=1; i<=max; i++) {
        sum += i;
    }
    return sum;
}
```

sum_declared.c
Declaration vs Definition

C/C++ make a careful distinction between these

Definition: The thing itself
  ‣ Code for function; a global variable definition that creates storage
  ‣ Must be exactly one actual definition of each thing (no dupes)

Declaration: Description of a thing in files that wish to use it
  ‣ Function prototype or external variable declaration
  ‣ Should be repeated in every source file that uses it
    • Often in header files and incorporated via #include
    • Should #include declaration in file with the definition to check consistency
  ‣ Should occur before first use
Arrays

\textit{type name[size];}

\begin{center}
\begin{tabular}{c}
\textbf{int scores[100];}
\end{tabular}
\end{center}

example allocates 100 ints’ worth of memory

- initially, each array element contains garbage data

an array does not know its own size

- sizeof(scores) is not reliable; only works in some situations

- recent versions of C allow the array size to be an expression
  \begin{itemize}
    \item But not good practice to put large data in local stack frames (performance)
  \end{itemize}

\begin{center}
\begin{tabular}{c}
\textbf{int n=100;}
\textbf{int scores[n];  // OK in C99}
\end{tabular}
\end{center}
Initializing and using arrays

type name[size] = {value, value, ..., value};

- allocates an array and fills it with supplied values
- if fewer values are given than the array size, fills rest with 0
- only works for initialization - can’t assign whole array values later

name[index] = expression;

- sets the value of an array element

```c
int primes[6] = {2, 3, 5, 6, 11, 13};
primes[3] = 7;
primes[100] = 0;  // smash!
```

```c
// 1000 zeroes
int allZeroes[1000] = {0};
```
Multi-dimensional arrays

dtype name[rows][columns] = {{values}, ..., {values}};

- allocates a 2D array and fills it with predefined values

```c
// a 2 row, 3 column array of doubles
double grid[2][3];

// a 3 row, 5 column array of ints
int matrix[3][5] = {
    {0, 1, 2, 3, 4},
    {0, 2, 4, 6, 8},
    {1, 3, 5, 7, 9}
};
```

matrix.c
Parameters: reference vs value

Two fundamental parameter-passing schemes

Call-by-value

- Parameter is a local variable initialized when the function is called, but has no connection with the calling argument after that [C: almost everything, Java: everything (primitive types, references values)]

Call-by-reference

- Parameter is an alias for the actual argument supplied in the call (which must be a variable); it is not a separate local variable in the function [C arrays, C++ references]
Arrays as parameters

It’s tricky to use arrays as parameters

- arrays are effectively passed by reference (not copied)
  - “array promotion” - array name treated as pointer to first element
- arrays do not know their own size

```c
int sumAll(int a[]); // prototype declaration

int main(int argc, char **argv) {
    int numbers[5] = {3, 4, 1, 7, 4};
    int sum = sumAll(numbers);
    return 0;
}

int sumAll(int a[]) {
    int i, sum = 0;
    for (i = 0; i < ...???
```
Arrays as parameters

Solution 1: declare the array size in the function

- problem: code isn’t very flexible

```c
int sumAll(int a[5]);

int main(int argc, char **argv) {
    int numbers[5] = {3, 4, 1, 7, 4};
    int sum = sumAll(numbers);
    printf("sum is: %d\n", sum);
    return 0;
}

int sumAll(int a[5]) {
    int i, sum = 0;

    for (i = 0; i < 5; i++) {
        sum += a[i];
    }
    return sum;
}
```
Arrays as parameters

Solution 2: pass the size as a parameter

```c
int sumAll(int a[], int size);

int main(int argc, char **argv) {
    int numbers[5] = {3, 4, 1, 7, 4};
    int sum = sumAll(numbers, 5);
    printf("sum is: %d\n", sum);
    return 0;
}

int sumAll(int a[], int size) {
    int i, sum = 0;
    for (i = 0; i <= size; i++) {  // CAN YOU SPOT THE BUG?
        sum += a[i];
    }
    return sum;
}
```

arraysum.c
Returning an array

Local variables, including arrays, are stack allocated

- they disappear when a function returns
- therefore, local arrays can’t be safely returned from functions (can’t assign/return whole arrays as values)

```c
int *copyarray(int src[], int size) {
    int i, dst[size];   // OK in C99
    for (i = 0; i < size; i++) {
        dst[i] = src[i];
    }
    return dst;       // no -- buggy
}
```
buggy_copyarray.c
Solution: an output parameter

Create the “returned” array in the caller

- pass it as an **output parameter** to `copyarray`
- works because arrays are effectively passed by reference

```c
void copyarray(int src[], int dst[], int size) {
    int i;
    for (i = 0; i < size; i++) {
        dst[i] = src[i];
    }
}
```

copyarray.c
OS and processes

The OS lets you run multiple applications at once

- an application runs within an OS “process”
- the OS timeslices each CPU between runnable processes
  ‣ happens very fast; ~100 times per second!

______________________________
process 1       process 2       ⋯       process N
______________________________
operating system
Processes and virtual memory

OS gives each process the illusion of its own, private memory

- this is called the process’ **address space**
- contains the process’ virtual memory, visible only to it
- $2^{32}$ bytes on 32 bit host
- $2^{64}$ bytes on 64 bit host

Contains code, data, libraries, stack, etc.

0x00000000

0xffffffff
## Loading

When the OS loads a program, it:

- creates an address space
- inspects the executable file to see what’s in it
- (lazily) copies regions of the file into the right place in the address space
- does any final linking, relocation, or other needed preparation

<table>
<thead>
<tr>
<th>Address Space</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00000000</td>
<td>OS kernel [protected]</td>
</tr>
<tr>
<td></td>
<td>stack</td>
</tr>
<tr>
<td></td>
<td>shared libraries</td>
</tr>
<tr>
<td></td>
<td>heap (malloc/free)</td>
</tr>
<tr>
<td></td>
<td>read/write segment</td>
</tr>
<tr>
<td></td>
<td>.data, .bss</td>
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<tr>
<td></td>
<td>read-only segment</td>
</tr>
<tr>
<td></td>
<td>.text, .rodata</td>
</tr>
<tr>
<td>0xFFFFFFFF</td>
<td></td>
</tr>
</tbody>
</table>

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The stack

Used to store data associated with function calls

- when you call a function, compiler-inserted code will allocate a stack frame to store:
  ‣ the function call arguments
  ‣ the address to return to
  ‣ local variables used by the function
  ‣ a few other pieces of bookkeeping

```c
int f(int p1, int p2) {
    int x;
    int a[3];
    ...
    return x;
}
```

<table>
<thead>
<tr>
<th>offset</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>p2</td>
</tr>
<tr>
<td>20</td>
<td>p1</td>
</tr>
<tr>
<td>16</td>
<td>return address</td>
</tr>
<tr>
<td>12</td>
<td>a[2]</td>
</tr>
<tr>
<td>8</td>
<td>a[1]</td>
</tr>
<tr>
<td>4</td>
<td>a[0]</td>
</tr>
<tr>
<td>0</td>
<td>x</td>
</tr>
</tbody>
</table>

a stack frame
The stack in action

```c
int main(int argc, char **argv) {
    int n1 = f(3, -5);
    n1 = g(n1);
}

int f(int p1, int p2) {
    int x;
    int a[3];
    ...
    x = g(a[2]);
    return x;
}

int g(int param) {
    return param * 2;
}
```

OS kernel [protected]
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heap (malloc/free)
| read/write segment |
| globals |

read-only segment
| (main, f, g) |
The stack in action

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OS kernel [protected]

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OS kernel [protected]  

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The stack in action

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| f |
| p1, p2, x, a |

| g |
| param |

| heap (malloc/free) |
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The stack in action

int main(int argc, 
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The stack in action

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**OS kernel [protected]**

- stack
- `main`
  - argc, argv, n1
- f
  - p1, p2, x, a
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- read/write segment
  - `globals`
- read-only segment
  - (main, f, g)
The stack in action

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- OS kernel [protected]
- stack
- **main**
  - argc, argv, n1
- **f**
  - p1, p2, x, a
- heap (malloc/free)
- read/write segment
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The stack in action

```c
int main(int argc, char **argv) {
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int g(int param) {
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OS kernel [protected]

- stack
- **main**
  - argc, argv, n1

heap (**malloc/free**)

read/write segment
  - **globals**

read-only segment
  - (main, f, g)
The stack in action

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int main(int argc, char **argv) {
    int n1 = f(3, -5);
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}

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    ...
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heap (malloc/free)

read/write segment

globals

read-only segment

(main, f, g)
The stack in action

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The stack in action

```c
int main(int argc, char **argv) {
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OS kernel [protected]

stack

main
argc, argv, n1

heap (malloc/free)

read/write segment
globals

read-only segment
(main, f, g)
```
# The stack in action

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int main(int argc, char **argv) {
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    ...
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### OS kernel [protected]

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### Heap (malloc/free)

### Read/write segment

### Globals

### Read-only segment

(master, f, g)
Addresses and &

&foo produces the virtual address of foo

```
#include <stdio.h>

int foo(int x) {
    return x + 1;
}

int main(int argc, char **argv) {
    int x, y;
    int a[2];

    printf("x is at \%p\n", &x);
    printf("y is at \%p\n", &y);
    printf("a[0] is at \%p\n", &a[0]);
    printf("a[1] is at \%p\n", &a[1]);
    printf("foo is at \%p\n", &foo);
    printf("main is at \%p\n", &main);

    return 0;
}
```
Pointers

type *name; // declare a pointer
type *name = address; // declare + initialize a pointer

A pointer is a variable that contains a memory address
- It points to somewhere in the process’ virtual address space

```c
int main(int argc, char **argv) {
    int x = 42;
    int *p; // p is a pointer to an integer
    p = &x; // p now contains the address of x
    printf("x is %d\n", x);
    printf("&x is %p\n", &x);
    printf("p is %p\n", p);
    return 0;
}
```

A stylistic choice

C gives you flexibility in how you declare pointers

- one way can lead to visual trouble when declaring multiple pointers on a single line
  
  ```
  int* p1;  
  int* p2;  // i prefer
  ```

- the other way is what I prefer
  
  ```
  int* p1, p2;  // bug?; equivalent to int *p1; int p2;  
  int* p1, *p2;  // correct
  ```

or

```
int* p1;  // correct - better  
int* p2;  // (int* p1, *p2; is also ok, but less robust)
```
Dereferencing pointers

*pointer // dereference a pointer
*pointer = value; // dereference / assign

dereference: access the memory referred to by a pointer

```c
#include <stdio.h>

int main(int argc, char **argv) {
    int x = 42;
    int *p; // p is a pointer to an integer
    p = &x; // p now contains the address of x

    printf("x is %d\n", x);
    *p = 99;
    printf("x is %d\n", x);

    return 0;
}
```
Self exercise #1

Write a function that:

- accepts an array of 32-bit unsigned integers, and a length
- reverses the elements of the array in place
- returns void (nothing)
Self exercise #2

Write a function that:

- accepts a function pointer and an integer as an argument
- invokes the pointed-to function
  - with the integer as its argument
Self exercise #3

Write a function that:

- accepts a string as a parameter
- returns
  ‣ the first whitespace-separated word in the string (as a newly allocated string)
  ‣ and, the size of that word
See you on Friday!