Poll Everywhere

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About how long did Exercise 2 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn’t submit / I prefer not to say

C Preprocessor, Linking

CSE 333 Spring 2023

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Relevant Course Information

- Exercise 3 out today, due Monday morning
  - First modularized (multi-file) exercise – separate interface, implementation, and tests
  - *Automated* testing relies on status codes
- Homework 1 due next Thursday (4/13)
  - Watch that `HashTable` doesn't violate the modularity of `LinkedList` (*i.e.*, respect the interfaces!)
  - Watch for pointer to local (stack) variables
  - ***Draw memory diagrams!***
  - Use `gdb` and valgrind and fill out your bug journal as you go!
  - Please leave "`STEP #`" markers for graders!
  - Late days: don't tag `hw1-final` until you are really ready

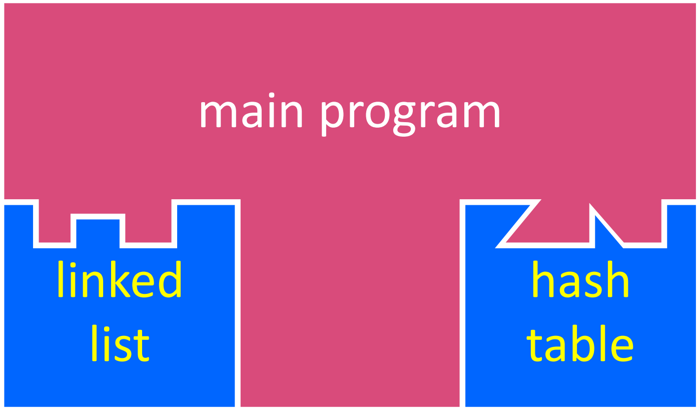
Quick Catchup from last Lecture

- `struct`s and `typedef`
- Generic Data Structures in C
- **Modules & Interfaces**

Multi-File C Programs

- Let's create a linked list *module*
  - A module is a self-contained piece of an overall program
    - Has externally visible functions that customers can invoke
    - Has externally visible `typedef`s, and perhaps global variables, that customers can use
    - May have internal functions, `typedef`s, or global variables that customers should *not* look at
  - Can be developed independently and re-used in different projects

- The module's *interface* is its set of public functions, `typedef`s, and global variables



C Header Files

- Header: a file whose only purpose is to be `#include`'d
  - Generally has a filename `.h` extension
  - Holds the variables, types, and function prototype declarations that make up the interface to a module
  - There are <system-defined> and "programmer-defined" headers

- Main Idea:
  - Every `name.c` is intended to be a module that has a `name.h`
  - `name.h` declares the interface to that module
  - Other modules can use `name` by `#include`-ing `name.h`
    - They should assume as little as possible about the implementation in `name.c`

C Module Conventions (1 of 2)

STYLE TIP

- File contents:
  - `.h` files only contain *declarations*, never *definitions*
  - `.c` files never contain prototype declarations for functions that are intended to be exported through the module interface
  - Public-facing functions are **`ModuleName_FunctionName`**`()` and take a pointer to "`this`" as their first argument
- Including:
  - ***NEVER*** `#include` a `.c` file – only `#include .h` files
  - `#include` all of headers you reference, even if another header (transitively) includes some of them
- Compiling:
  - Any `.c` file with an associated `.h` file should be able to be compiled (together via `#include`) into a `.o` file

C Module Conventions (2 of 2)

STYLE TIP

- Commenting:
  - If a function is declared in a header file (`.h`) and defined in a C file (`.c`), *the header needs full documentation because it is the public specification*
    - Don't copy-paste the comment into the C file (don't want two copies that can get out of sync)
  - If prototype and implementation are in the same C file:
    - School of thought #1: Full comment on the prototype at the top of the file, no comment (or "declared above") on code
    - School of thought #2: Prototype is for the compiler and doesn't need comment; comment the code to keep them together

e.g., 333 project code (→ School of thought #1)

Lecture Outline

- **C Preprocessor**
- Visibility of Symbols
  - `extern`, `static`

`#include` and the C Preprocessor

- The C preprocessor (`cpp`) is a *sequential* and *stateful* search-and-replace text-processor that transforms your source code before the compiler runs
  - The input is a C file (text) and the output is still a C file (text)
  - It processes the directives it finds in your code (`#`*directive*)
    - *e.g.*, `#include "ll.h"` is replaced by the post-processed content of `ll.h`
    - *e.g.*, `#define PI 3.1415` *defines* a symbol and replaces later occurrences
    - Several others that we'll see soon…
  - Run automatically on your behalf by `gcc` during compilation

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Exploration: Which of the following text will remain in the preprocessor output?

```c
#define BAR 2 + FOO

typedef long long int verylong;
```

cpp_example.h

```c
#define FOO 1

#include "cpp_example.h"

int main(int argc, char** argv) {
  int x = FOO;    // a comment
  int y = BAR;
  verylong z = FOO + BAR;
  return 0;
}
```

cpp_example.c

Keep in mind:
1. Pre-processor goes line by line
2. builds up "state" as it processes directives

A. #define
B. BAR
C. FOO
D. verylong
E. // a comment

C Preprocessor Example

Arrow points to *next* line to process

- We can manually run the preprocessor:
  - cpp is the preprocessor (can also use gcc -E)
  - "-P" option suppresses some extra debugging annotations

```
#define BAR 2 + FOO

typedef long long int verylong;
```

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```
#define FOO 1

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int main(int argc, char** argv) {
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  int y = BAR;
  verylong z = FOO + BAR;
  return 0;
}
```

cpp_example.c

```
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$ cat out.c
```

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FOO	1

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  int y = BAR;
  verylong z = FOO + BAR;
  return 0;
}
```

cpp_example.c

```
$ cpp -P cpp_example.c out.c
$ cat out.c

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int main(int argc, char** argv) {
  int x = 1;
```

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```c
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#include "cpp_example.h"

int main(int argc, char** argv) {
  int x = FOO;    // a comment
  int y = BAR;
  verylong z = FOO + BAR;
  return 0;
}
```

cpp_example.c

```
$ cpp -P cpp_example.c out.c
$ cat out.c

typedef long long int verylong;
int main(int argc, char** argv) {
  int x = 1;
  int y = 2 + 1;
  verylong z = 1 + 2 + 1;
```

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#include "cpp_example.h"

int main(int argc, char** argv) {
  int x = FOO;    // a comment
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}
```

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```
$ cpp -P cpp_example.c out.c
$ cat out.c

typedef long long int verylong;
int main(int argc, char** argv) {
  int x = 1;
  int y = 2 + 1;
  verylong z = 1 + 2 + 1;
  return 0;
}
```

Program Using a Linked List

```c
#include <stdlib.h>
...
#include "ll.h"

Node* Push(Node* head,
           void* element) {
  ... // implementation here
}
```

ll.c

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

Node* Push(Node* head,
           void* element);
```

ll.h

```c
#include "ll.h"

int main(int argc, char** argv) {
  Node* list = NULL;
  char* hi = "hello";
  char* bye = "goodbye";

  list = Push(list, (void*)hi);
  list = Push(list, (void*)bye);

  ...

  return 0;
}
```

example_ll_customer.c

Compiling the Program

- Four parts:
  - 1/2) Compile `example_ll_customer.c` into an object file
  - 2/1) Compile `ll.c` into an object file
  - 3) Link both object files into an executable
  - 4) Test, Debug, Rinse, Repeat

```
$ gcc -Wall -g -c -o example_ll_customer.o example_ll_customer.c
$ gcc -Wall -g -c -o ll.o ll.c
$ gcc -g -o example_ll_customer ll.o example_ll_customer.o
$ ./example_ll_customer
Payload: 'yo!'
Payload: 'goodbye'
Payload: 'hello'
$ valgrind -leak-check=full ./example_ll_customer
... etc ...
```

But There's a Problem with `#include`

- What happens when we compile `foo.c`?

```
struct Pair {
  int a, b;
};
```

pair.h

```
#include "pair.h"

// a useful function
struct Pair* MakePair(int a, int b);
```

util.h

```
#include "pair.h"
#include "util.h"

int main(int argc, char** argv) {
  // do stuff here
  ...
  return 0;
}
```

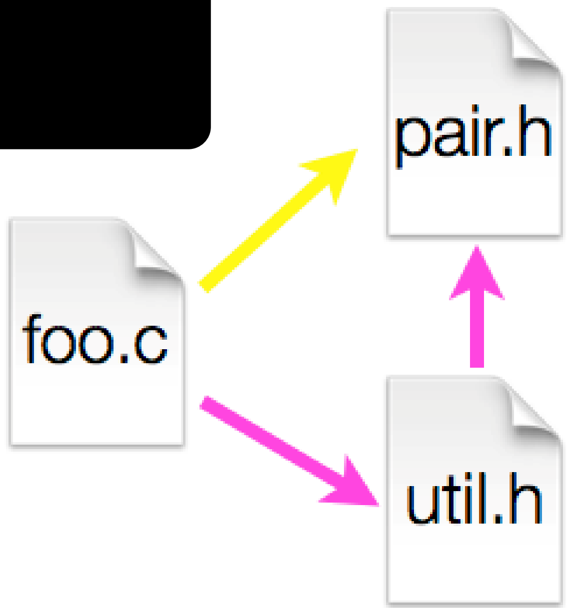
foo.c

A Problem with #include

- What happens when we compile `foo.c`?

```
$ gcc -Wall -g -o foo foo.c
In file included from util.h:1,
                 from foo.c:2:
pair.h:1:8: error: redefinition of 'struct Pair'
    1 | struct Pair { int a, b; };
      |        ^~~~
In file included from foo.c:1:
pair.h:1:8: note: originally defined here
    1 | struct Pair { int a, b; };
      |        ^~~~
```

- `foo.c` includes `pair.h` twice!
  - Second time is indirectly via `util.h`
  - Struct definition shows up twice
    - Can see using `cpp`



Preprocessor Tricks: Header Guards

- A standard C Preprocessor trick to deal with this
  - Uses macro definition (`#define`) in combination with conditional compilation (`#ifndef` and `#endif`)

pair.h

```c
#ifndef PAIR_H_
#define PAIR_H_

struct Pair {
  int a, b;
};

#endif   // PAIR_H_
```

util.h

```c
#ifndef UTIL_H_
#define UTIL_H_

#include "pair.h"

// a useful function
struct Pair* MakePair(int a, int b);

#endif   // UTIL_H_
```

foo.c

```c
#include "pair.h"
#include "util.h"

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

Preprocessor Tricks: Constants

STYLE TIP

- A way to deal with "magic constants"

```c
int global_buffer[1000];

void circalc(float rad,
             float* circumf,
             float* area) {
  *circumf = rad * 2.0 * 3.1415;
  *area = rad * 3.1415 * 3.1415;
}
```

Bad code
(littered with magic constants)

```c
#define BUFSIZE 1000
#define PI 3.14159265359

int global_buffer[BUFSIZE];

void circalc(float rad,
             float* circumf,
             float* area) {
  *circumf = rad * 2.0 * PI;
  *area = rad * PI * PI;
}
```

Better code

Preprocessor Tricks: Macros

STYLE TIP

- You can pass arguments to macros

```c
#define ODD(x) ((x) % 2 != 0)

void foo() {
  if ( ODD(5) )
    printf("5 is odd!\n");
}
```

cpp →

```c
void foo() {
  if ( ((5) % 2 != 0) )
    printf("5 is odd!\n");
}
```

- Beware of operator precedence issues!
  - Use parentheses

```c
#define ODD(x) ((x) % 2 != 0)
#define WEIRD(x) x % 2 != 0

ODD(5 + 1);

WEIRD(5 + 1);
```

cpp →

```c
((5 + 1) % 2 != 0);

5 + 1 % 2 != 0;
```

- Discouraged in favor of inline functions (Google)

Macro Alternatives

- `const`: a type qualifier that indicates that the data is read only
  - Compile-time construct that will generate a compiler error or warning if violated
  - Much more heavily used in C++ and we'll return to the nuances here later on in the course (pointers are weird!)
  - Can replace constant macro with a `const` variable
- `inline`: keyword used in front of a function definition to suggest to the compiler to optimize the function call away
  - Mostly beyond the scope of this course
  - Can replace macro with arguments with (`static`) inline functions

Preprocessor Tricks: Defining Tokens

- Besides `#define`s in the code, preprocessor values can be given as part of the `gcc` command:

```
bash$ gcc -Wall -g -DTRACE -o ifdef ifdef.c
```

- assert can be controlled the same way – defining `NDEBUG` causes assert to expand to "empty"
  - It's a macro – see `assert.h`

```
bash$ gcc -Wall -g -DNDEBUG -o faster useassert.c
```

Preprocessor Tricks: Conditional Compilation

- You can change what gets compiled
  - In this example, `#define TRACE` before `#ifdef` to include debug `printf`s in compiled code

```
#ifdef TRACE
#define ENTER(f) printf("Entering %s\n", f)
#define EXIT(f)  printf("Exiting  %s\n", f)
#else
#define ENTER(f)
#define EXIT(f)
#endif

// print n
void Pr(int n) {
  ENTER("Pr");
  printf("\n = %d\n", n);
  EXIT("Pr");
}
```

ifdef.c

Lecture Outline

- C Preprocessor
- **Visibility of Symbols**
  - `extern`, `static`

Namespace Problem

- If we define a global variable named "counter" in one C file, is it visible in a different C file in the same program?
  - Yes, if you use *external linkage*
    - The name "counter" refers to the same variable in both files
    - The variable is *defined* in one file and *declared* in the other(s)
    - When the program is linked, the symbol resolves to one location
  - No, if you use *internal linkage*
    - The name "counter" refers to a different variable in each file
    - The variable must be *defined* in each file
    - When the program is linked, the symbols resolve to two locations

External Linkage

- `extern` makes a *declaration* of something externally-visible
  - Works slightly differently for variables and functions…

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

// A global variable, defined and
// initialized here in foo.c.
// It has external linkage by
// default.
int counter = 1;

int main(int argc, char** argv) {
  printf("%d\n", counter);
  Bar();
  printf("%d\n", counter);
  return EXIT_SUCCESS;
}
```

foo.c

```c
#include <stdio.h>

// "counter" is defined and
// initialized in foo.c.
// Here, we declare it, and
// specify external linkage
// by using the extern specifier.
extern int counter;

void Bar() {
  counter++;
  printf("(Bar): counter = %d\n",
         counter);
}
```

bar.c

Internal Linkage

- `static` (in the global context) restricts a definition to visibility within that file

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

// A global variable, defined and
// initialized here in foo.c.
// We force internal linkage by
// using the static specifier.
static int counter = 1;

int main(int argc, char** argv) {
  printf("%d\n", counter);
  Bar();
  printf("%d\n", counter);
  return EXIT_SUCCESS;
}
```

foo.c

```
#include <stdio.h>

// A global variable, defined and
// initialized here in bar.c.
// We force internal linkage by
// using the static specifier.
static int counter = 100;

void Bar() {
  counter++;
  printf("(Bar): counter = %d\n",
         counter);
}
```

bar.c

Function Visibility

bar.c

```
// By using the static specifier, we are indicating
// that Foo() should have internal linkage.  Other
// .c files cannot see or invoke Foo().
static int Foo(int x) {
  return x*3 + 1;
}

// Bar is "extern" by default.  Thus, other .c files
// could declare our Bar() and invoke it.
int Bar(int x) {
  return 2*Foo(x);
}
```

main.c

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

extern int Bar(int x); // "extern" is default, usually omit

int main(int argc, char** argv) {
  printf("%d\n", Bar(5));
  return EXIT_SUCCESS;
}
```

Linkage Issues

STYLE TIP

- Every global (variables and functions) is `extern` by default
  - Unless you add the `static` specifier, if some other module uses the same name, you'll end up with a collision!
    - Best case: compiler (or linker) error
    - Worst case: stomp all over each other

- It's good practice to:
  - Use `static` to "defend" your globals
    - Hide your private stuff!
  - Place external declarations in a module's header file
    - Header is the public specification

Static Confusion…

- C has a *different* use for the word "`static`": to create a persistent *local* variable
  - The storage for that variable is allocated when the program loads, in either the `.data` or `.bss` segment
  - Retains its value across multiple function invocations

```
void Foo() {
  static int count = 1;
  printf("Foo has been called %d times\n", count++);
}

void Bar() {
  int count = 1;
  printf("Bar has been called %d times\n", count++);
}

int main(int argc, char** argv) {
  Foo(); Foo(); Bar(); Bar(); return EXIT_SUCCESS;
}
```

static_extent.c

Additional C Topics

- Teach yourself!
  - man pages are your friend!
  - String library functions in the C standard library
    - `#include <string.h>`
      - strlen(), strcpy(), strdup(), strcat(), strcmp(), strchr(), strstr(), …
    - `#include <stdlib.h>` or `#include <stdio.h>`
      - atoi(), atof(), sprint(), sscanf()
  - How to declare, define, and use a function that accepts a variable-number of arguments (`varargs`)
  - `union`s and what they are good for
  - `enum`s and what they are good for
  - Pre- and post-increment/decrement
  - Harder: the meaning of the "`volatile`" storage class

Extra Exercise #1

- Extend the linked list program we covered in class:
  - Add a function that returns the number of elements in a list
  - Implement a program that builds a list of lists
    - *i.e.* it builds a linked list where each element is a (different) linked list
  - Bonus: design and implement a "Pop" function
    - Removes an element from the head of the list
    - Make sure your linked list code, and customers' code that uses it, contains no memory leaks

Extra Exercise #2

- Modify the linked list code from Extra Exercise #1
  - Add static declarations to any internal functions you implemented in `linkedlist.c`
  - Add a header guard to the header file