Data Structures and Modules
CSE 333 Summer 2018

Instructor: Hal Perkins

Teaching Assistants:
Renshu Gu        William Kim        Soumya Vasisht
Administrivia

- Exercise 3 was due this morning
- Exercise 4 out today and due Friday morning
- Exercise 5 will rely on material from section tomorrow, but not due until Monday
  - Will post tomorrow afternoon if people want to get started early

- Homework 1 due in a week
  - Advice: be *sure* to read headers carefully while implementing
  - Advice: use git add/commit/push often to save your work
Lecture Outline

- Implementing Data Structures in C
- Multi-file C Programs
  - C Preprocessor Intro
Simple Linked List in C

- Each node in a linear, singly-linked list contains:
  - Some element as its payload
  - A pointer to the next node in the linked list
    - This pointer is NULL (or some other indicator) in the last node in the list
Linked List Node

- Let’s represent a linked list node with a struct
  - For now, assume each element is an `int`
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
```c
typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}
```

**push_list.c**
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
**Push Onto List**

```
typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL);  // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}
```

`push_list.c`

Arrow points to `next` instruction.
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
### Push Onto List

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

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}
```

`push_list.c`
Push Onto List

typedef struct node_st {
  int element;
  struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

int main(int argc, char** argv) {
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c

Arrow points to next instruction.
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL);  // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL);  // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}

push_list.c
Push Onto List

typedef struct node_st {
    int element;
    struct node_st* next;
} Node;

Node* Push(Node* head, int e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL);  // crashes if false
    n->element = e;
    n->next = head;
    return n;
}

int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}
	push_list.c
A Generic Linked List

- Let’s generalize the linked list element type
  - Let customer decide type (instead of always int)
  - Idea: let them use a generic pointer (i.e. a void*)

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

Node* Push(Node* head, void* e) {
    Node* n = (Node*) malloc(sizeof(Node));
    assert(n != NULL);  // crashes if false
    n->element = e;
    n->next = head;
    return n;
}
```
Using a Generic Linked List

- Type casting needed to deal with `void*` (raw address)
  - Before pushing, need to convert to `void*`
  - Convert back to data type when accessing

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

Node* Push(Node* head, void* e);     // assume last slide’s code

int main(int argc, char** argv) {
    char* hello = "Hi there!";
    char* goodbye = "Bye bye";
    Node* list = NULL;

    list = Push(list, (void*) hello);
    list = Push(list, (void*) goodbye);
    printf("payload: '%s'\n", (char*) ((list->next)->element) );
    return 0;
}
```

`manual_list_void.c`
Resulting Memory Diagram

(main) list

(element)

(next)

Bye

Bye.

(main) goodbye

(element)

(next)

Hi

there

hello

(main) hello

(element)

(next)

∅
Lecture Outline

- Implementing Data Structures in C
- Multi-file C Programs
  - C Preprocessor Intro
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 typedefs, and perhaps global variables, that customers can use
    - May have internal functions, typedefs, or global variables that customers should *not* look at

  - The module’s interface is its set of public functions, typedefs, and global variables
Modularity

The degree to which components of a system can be separated and recombined

- “Loose coupling” and “separation of concerns”
- Modules can be developed independently
- Modules can be re-used in different projects
C Header Files

- **Header**: a C 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

- **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

- Most C projects adhere to the following rules:
  - .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
    - Those function prototype declarations belong in the .h file
  - NEVER #include a .c file – only #include .h files
  - #include all of headers you reference, even if another header (accidentally or not) includes some of them
  - Any .c file with an associated .h file should be able to be compiled into a .o file
    - The .c file should include the .h file; the compiler will check definitions and declarations
#include and the C Preprocessor

- The C preprocessor (cpp) transforms your source code before the compiler runs
  - Input is a C file (text) and output is still a C file (text)
  - 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 (a string!) and replaces later occurrences
    - Several others that we’ll see soon...
  - Run on your behalf by gcc during compilation
  - Note: `#include <foo.h>` looks in system (library) directories; `#include "foo.h"` looks first in current directory
C Preprocessor Example

- What do you think the preprocessor output will be?

```c
#define BAR 2 + FOO
typedef long long int verylong;

#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.h

```c
#define FOO 1

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

cpp_example.c
C Preprocessor Example

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

```c
#define BAR 2 + FOO
typedef long long int verylong;

#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;
}
```

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

```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 <assert.h>
#include "ll.h"

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

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

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

```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;
}
```

```c
ll.h

#error "ll.h"

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

```
bash$ gcc -Wall -g -c -o example_ll_customer.o example_ll_customer.c
bash$ gcc -Wall -g -c -o ll.o ll.c
bash$ gcc -g -o example_ll_customer ll.o example_ll_customer.o
bash$ ./example_ll_customer
Payload: 'yo!'
Payload: 'goodbye'
Payload: 'hello'
bash$ valgrind -leak-check=full ./example_ll_customer
... etc ...
```
Where Do the Comments Go?

- 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*
  - No need to copy/paste the comment into the C file
    - Don’t want two copies that can get out of sync
    - Recommended to leave “specified in <filename>.h” comment in C file code to help the reader
Where Do the Comments Go?

- If a function has a prototype and implementation in same C file:
  - One school of thought: Full comment on the prototype at the top of the file, no comment (or “declared above”) on code
    - 333 project code is like this
  - Another school: Prototype is for the compiler and doesn’t need comment; put the comments with the code to keep them together
    - Not used in 333
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

- Implement and test a binary search tree
    - Don’t worry about making it balanced
  - Implement key insert() and lookup() functions
    - Bonus: implement a key delete() function
  - Implement it as a C module
    - bst.c, bst.h
  - Implement test_bst.c
    - Contains main() and tests out your BST
Extra Exercise #3

- Implement a Complex number module
  - complex.c, complex.h
  - Includes a typedef to define a complex number
    - a + bi, where a and b are doubles
  - Includes functions to:
    - add, subtract, multiply, and divide complex numbers
  - Implement a test driver in test_complex.c
    - Contains main()