CSE 333
Lecture 6 - data structures

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Exercises:

- ex5 is out: clean up the code from section yesterday, split into separate files, fix bugs
  - More towards the end of the hour
- no more exercises due until end of week after HW1

HW:

- HW1 due very soon; get going NOW if you haven’t yet
Today’s topics:

- implementing data structures in C
- multi-file C programs
- brief intro to the C preprocessor
Let’s build a simple linked list

You’ve seen a linked list in CSE143

- each node in a linked list contains:
  - some element as its payload
  - a pointer to the next node in the linked list
- the last node in the list contains a NULL pointer (or some other indication that it is the last node)
Linked list node

Let’s represent a linked list node with a struct

- and, for now, assume each element is an int

```c
#include <stdio.h>

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

int main(int argc, char **argv) {
  Node n1, n2;

  n2.element = 2;
  n2.next = NULL;
  n1.element = 1;
  n2.next = &n2;
  return 0;
}
```

manual_list.c
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

typedef struct Node {
    int element;
    struct Node *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;
}
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#include <stdlib.h>
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    return 0;
}
A generic linked list

Previously, our linked list elements were of type `int`

- what if we want to let our customer decide the element type?
- idea: let them push a generic pointer -- i.e., a `(void *)`

define struct Node {
    void *element;
    struct Node *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

To use it, customers will need to use type casting

- convert their data type to a (void *) before pushing
- convert from a (void *) back to their data type when accessing

```c
typedef struct Node {
    void *element;
    struct Node *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;
}
```
Using a generic linked list

Results in:

(main) list

(element) goodbye

(element) hello

(main) goodbye

Bye bye

(main) hello

Hello there!

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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, 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 a filename with the .h extension
- holds the variables, types, and function prototype declarations that make up the interface to a module

the main idea

- every `name.c` intended to be a module has a `name.h`
- `name.h` declares the interface to that module
- other modules that want to use `name` will `#include name.h`
  - and 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 never contain definitions, only declarations
- .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
- any .c file with an associated .h file should be able to be compiled into a .o file
#include and the C preprocessor

The C preprocessor (cpp) transforms your source code before the compiler runs:

- transforms your original C source code into transformed C source code
- processes the directives it finds in your code (#something)
  ‣ #include "ll.h" -- replaces with post-processed content of ll.h
  ‣ #define PI 3.1415 -- defines a symbol, replaces later occurrences
  ‣ and there are several others we’ll see soon...
- run on your behalf by gcc during compilation
Example

```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;
}
```

cpp_example.h

```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;
}
```

cpp_example.c

Let’s manually run the pre-processor on cpp_example.c:

- `cpp` is the preprocessor
- “-P” suppresses some extra debugging annotations

```
bash$ cpp -P cpp_example.c out.c
bash$ cat out.c
```
Program that uses a linked list

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

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

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

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

```c
int main(int argc, char **argv) {
    Node *list = NULL;
    char *hi = "hello";
    char *bye = "goodbye";
    list = Push(list, hi);
    list = Push(list, bye);
    return 0;
}
```

Example of using linked list:

```c
example_ll_customer.c
```
Compiling the program

Four steps:
- compile `example_ll_customer.c` into an object file
- compile `ll.c` into an object file
- link `ll.o, example_ll_customer.o` into an executable
- test, debug, rinse, repeat

```bash
bash$ gcc -Wall -g -o example_ll_customer.o -c example_ll_customer.c
bash$ gcc -Wall -g -o ll.o -c ll.c
bash$ gcc -o example_ll_customer -g ll.o example_ll_customer.o
bash$
bash$ ./example_ll_customer

Payload: 'yo!'
Payload: 'goodbye'
Payload: 'hello'

bash$ valgrind --leak-check=full ./example_customer
...etc.
```
Building systems

This doesn’t really scale: gcc -Wall -g -o gadget *.c
- Could take hours (think gcc source, linux kernel, etc.)

If we change a single source file, what needs building?
- foo.c - at least recompile to get foo.o then relink
- foo.h - probably need to recompile foo.c then relink
  - But also need to recompile everything that #includes foo.h
    - Directly or indirectly...

Easy to forget something and get a broken build

Solution: let the computer figure it out!
Build dependencies

All build tools work from same core idea: capture build dependencies and recompile only what’s needed.

ex: Dependency graph for example_ll_customer
make

Venerable unix tool to automate build tasks

Input is a Makefile with rules describing dependencies:

```
target: sources
    command(s)
```

Meaning: if any source is newer (file system timestamp) than target then run command(s)

- Nothing actually requires command(s) to have anything to do with sources or target, although that is the typical usage. Makefiles can do interesting things.
Makefile for ll project

# default target (i.e., first one) is the executable program
example_ll_customer: example_ll_customer.o ll.o
    gcc -Wall -g -o example_ll_customer example_ll_customer.o ll.o

# targets for individual source files
example_ll_customer.o: example_ll_customer.c ll.h
    gcc -Wall -g -c example_ll_customer.c

ll.o: ll.c ll.h
    gcc -Wall -g -c ll.c

# clean: remove files built by makefile and emacs backup files
clean:
    rm -f example_ll_customer *.o *~

Run “make” to build the default (first) target
Run “make target” to build named target
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
    - but each element in the list 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
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(), tests out your BST
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()
See you on Monday!