

CSE 333

Lecture 5 - data structures & modules

Hal Perkins

Department of Computer Science & Engineering

University of Washington



Administrivia

HW1 due in just under 2 weeks - should be started now!

Advice: be *sure* to read headers carefully while implementing

Advice: use git add/commit/push often to save your work

New exercise out today, due before class Friday

Exercise after that will be based on things covered in tomorrow's sections - malloc/free/valgrind/data structures + Friday's lecture (make); due after the long weekend

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

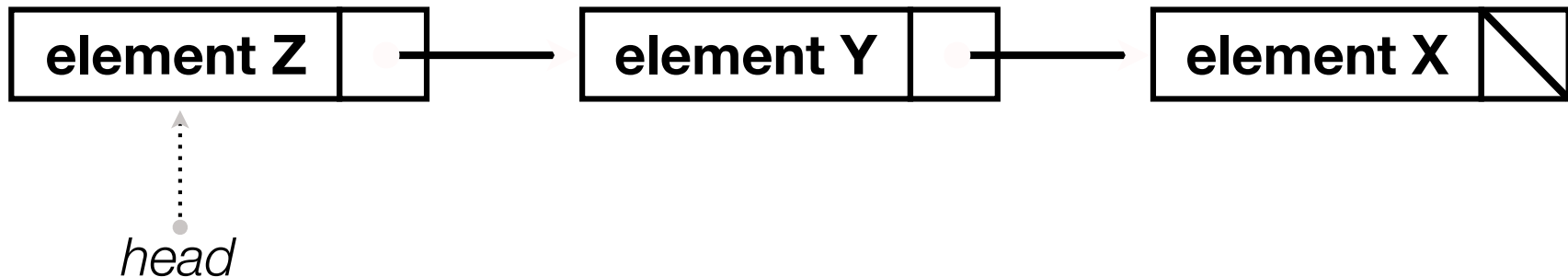
You've seen a linked list in CSE143

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

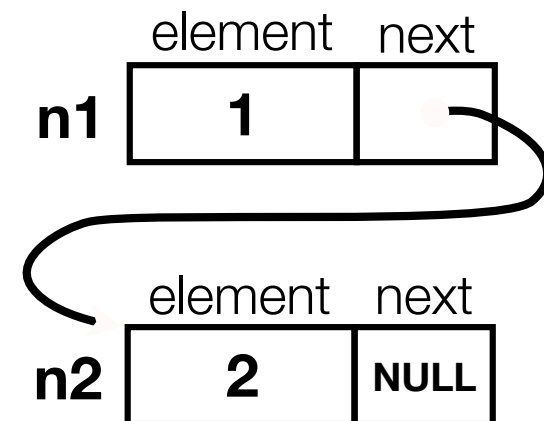
```
#include <stdio.h>

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

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

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

manual_list.c



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL

(Push) head

NULL

(Push) e

1

(Push) n

???

Push onto list

push_list.c

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

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;
}
```

(main) list

NULL

(Push) head

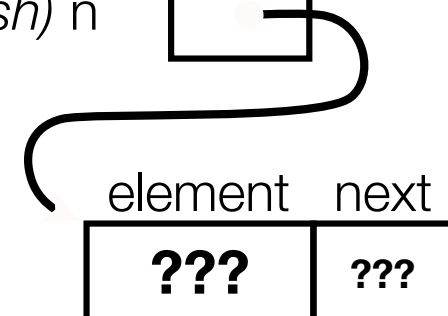
NULL

(Push) e

1

(Push) n

--



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL

(Push) head

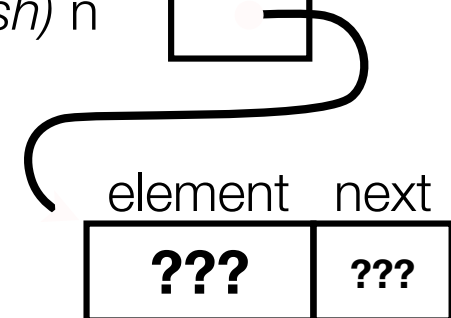
NULL

(Push) e

1

(Push) n

--



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL

(Push) head

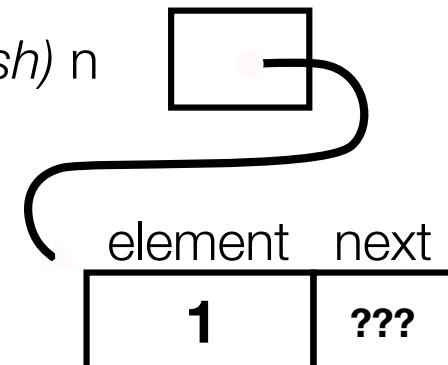
NULL

(Push) e

1

(Push) n

--



Push onto list

push_list.c

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

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;
}
```

(main) list

NULL

(Push) head

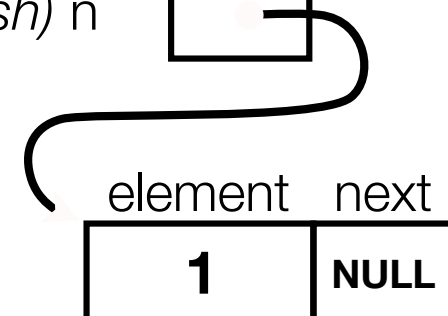
NULL

(Push) e

1

(Push) n

--



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

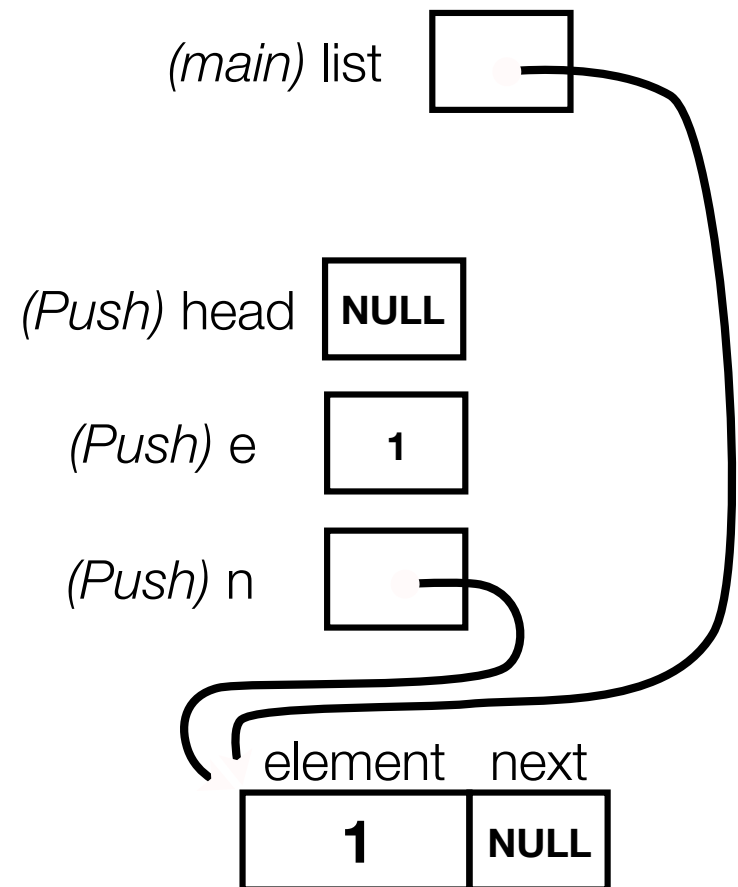
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

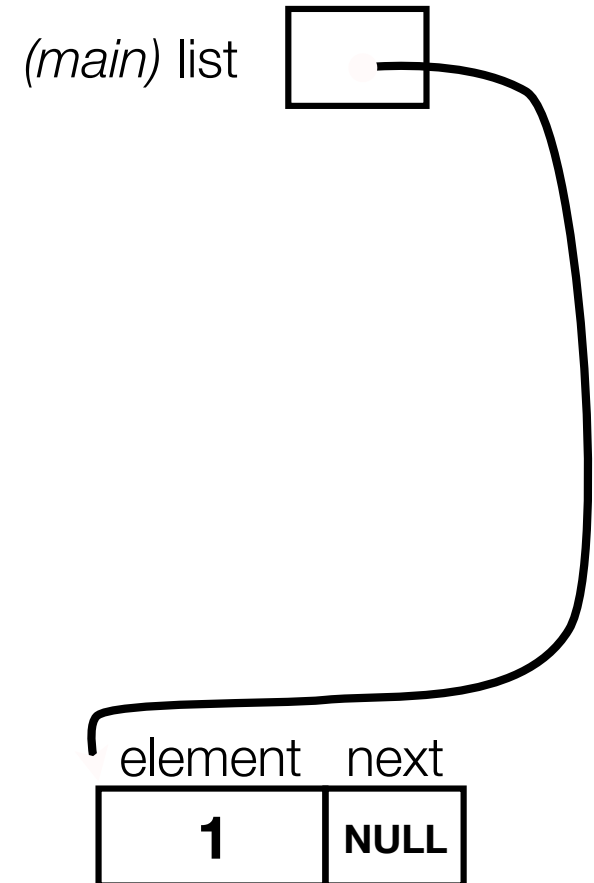
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

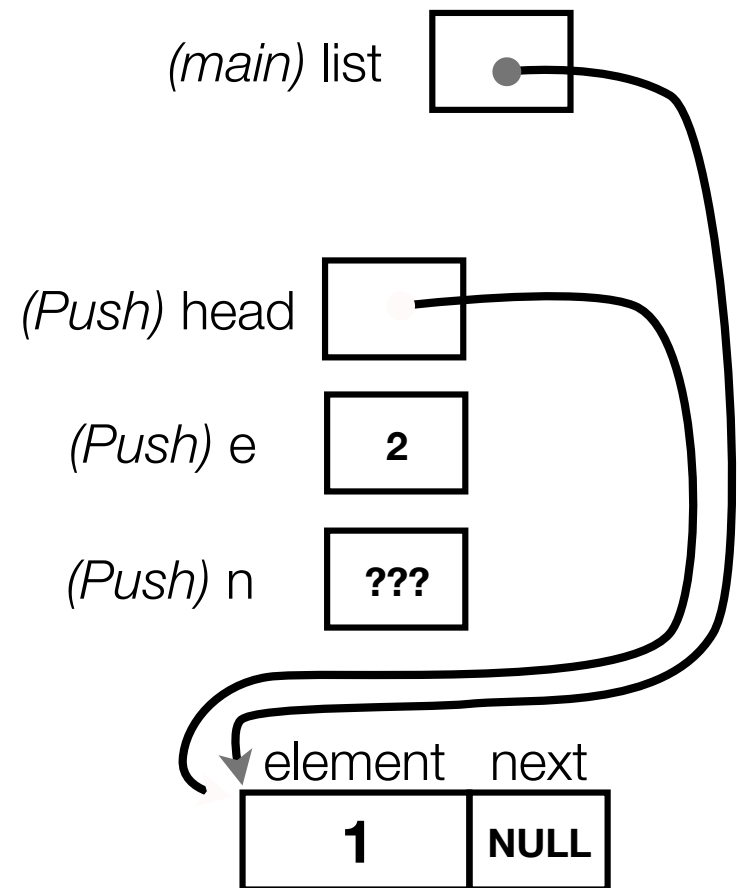
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

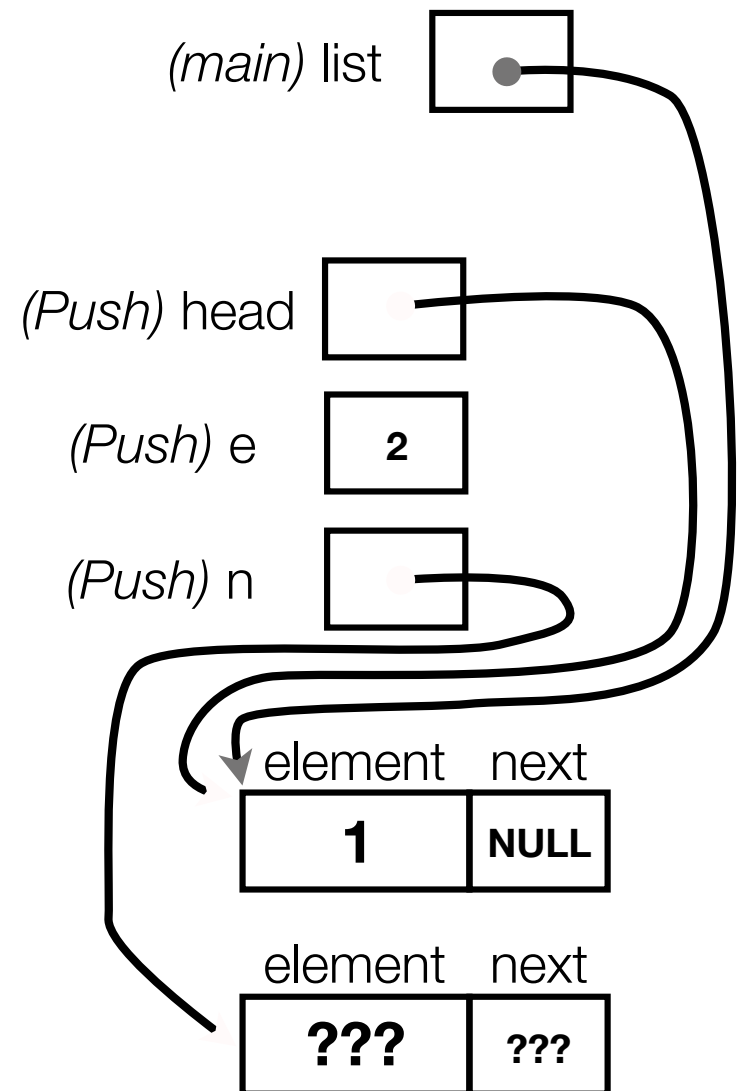
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

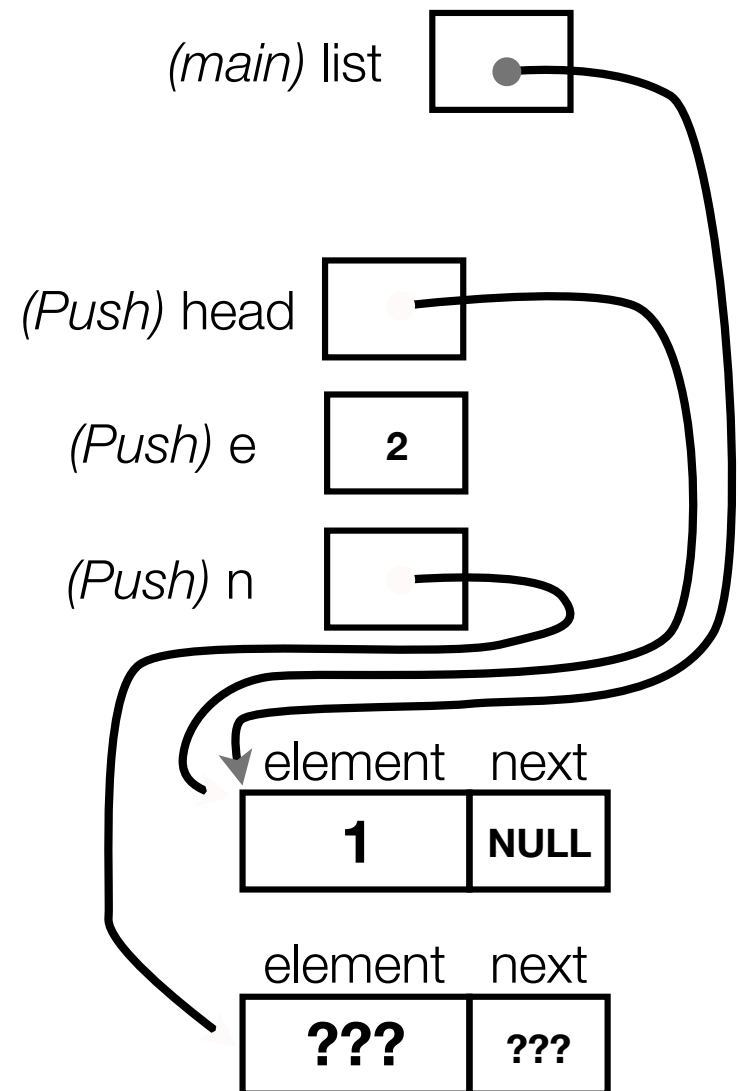
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

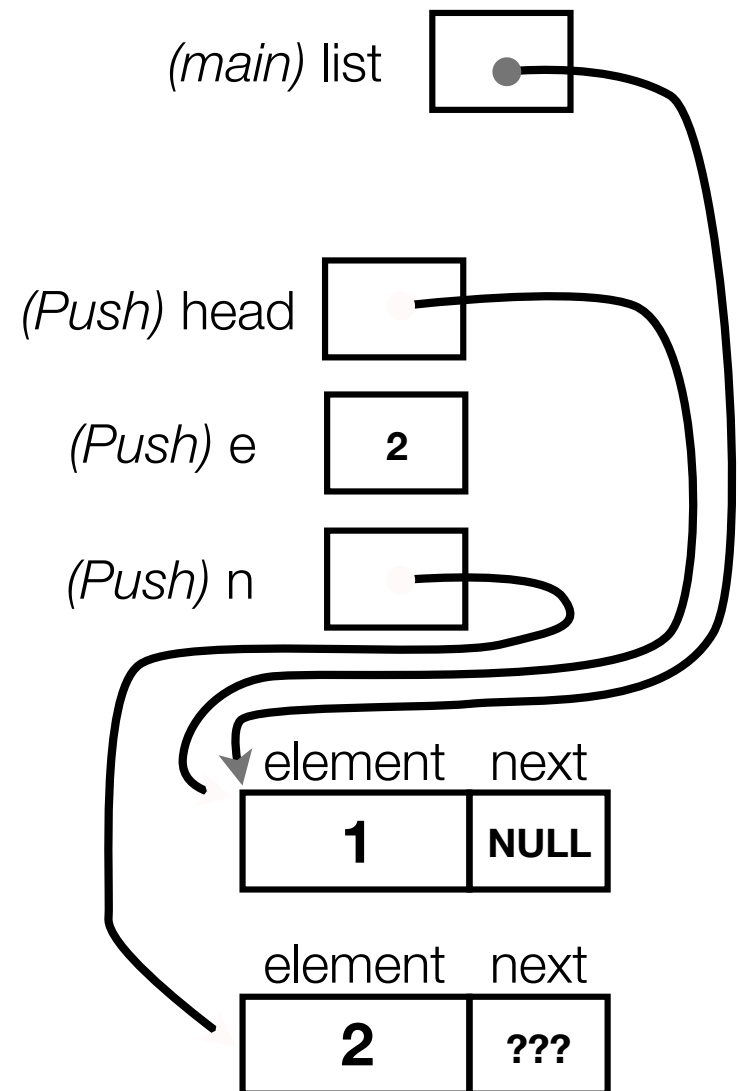
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

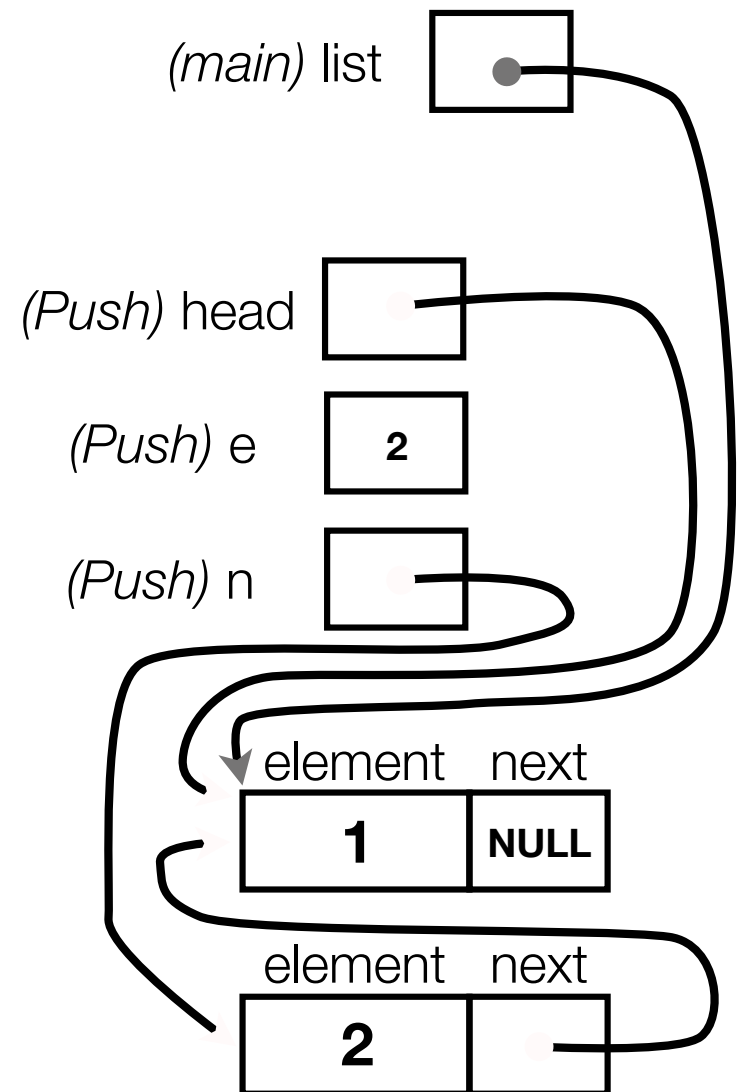
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

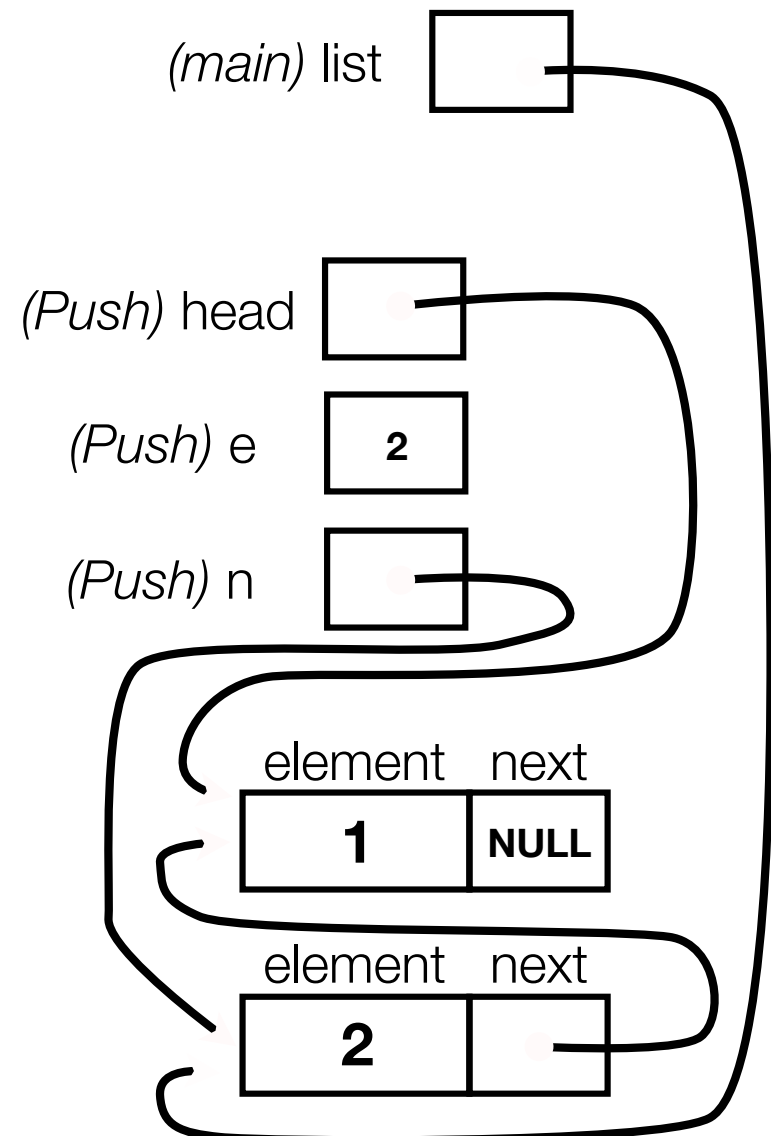
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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

Node *Push(Node *head, int e) {
    Node *n = (Node *) malloc(sizeof(Node));

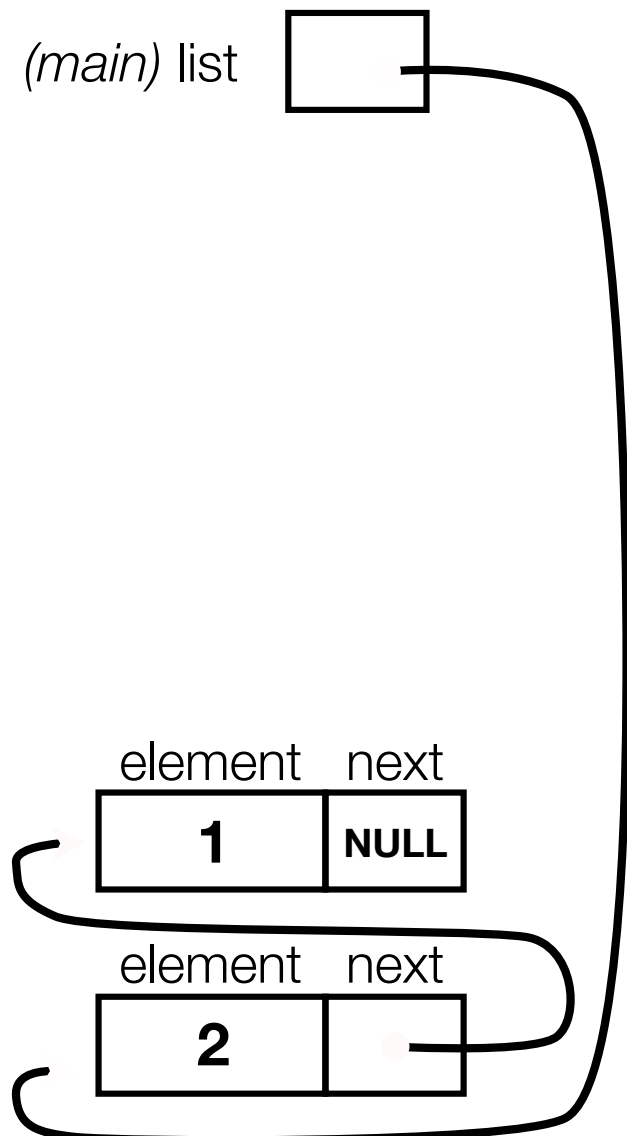
    assert(n != NULL); // crashes if false
    n->element = e;
    n->next = head;

    return n;
}

int main(int argc, char **argv) {
    Node *list = NULL;

    list = Push(list, 1);
    list = Push(list, 2);

    return 0;
}
```



Push onto list

push_list.c

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

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;
}
```

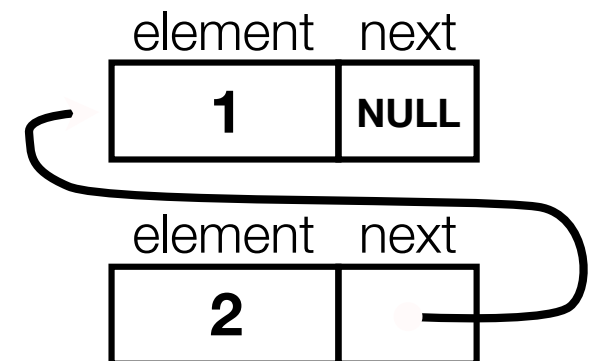
a (benign) leak!!

try running with valgrind:

```
bash$ gcc -o push_list -g -Wall
push_list.c

bash$ valgrind --leak-check=full
./push_list
```

why is this leak not a serious problem?



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?

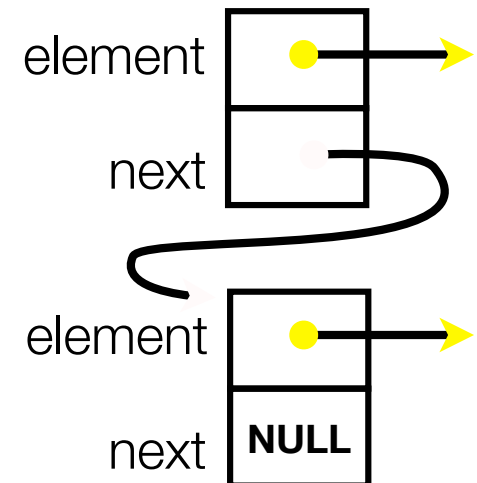
idea: let them push a generic pointer -- i.e., a **(void *)**

```
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

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

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

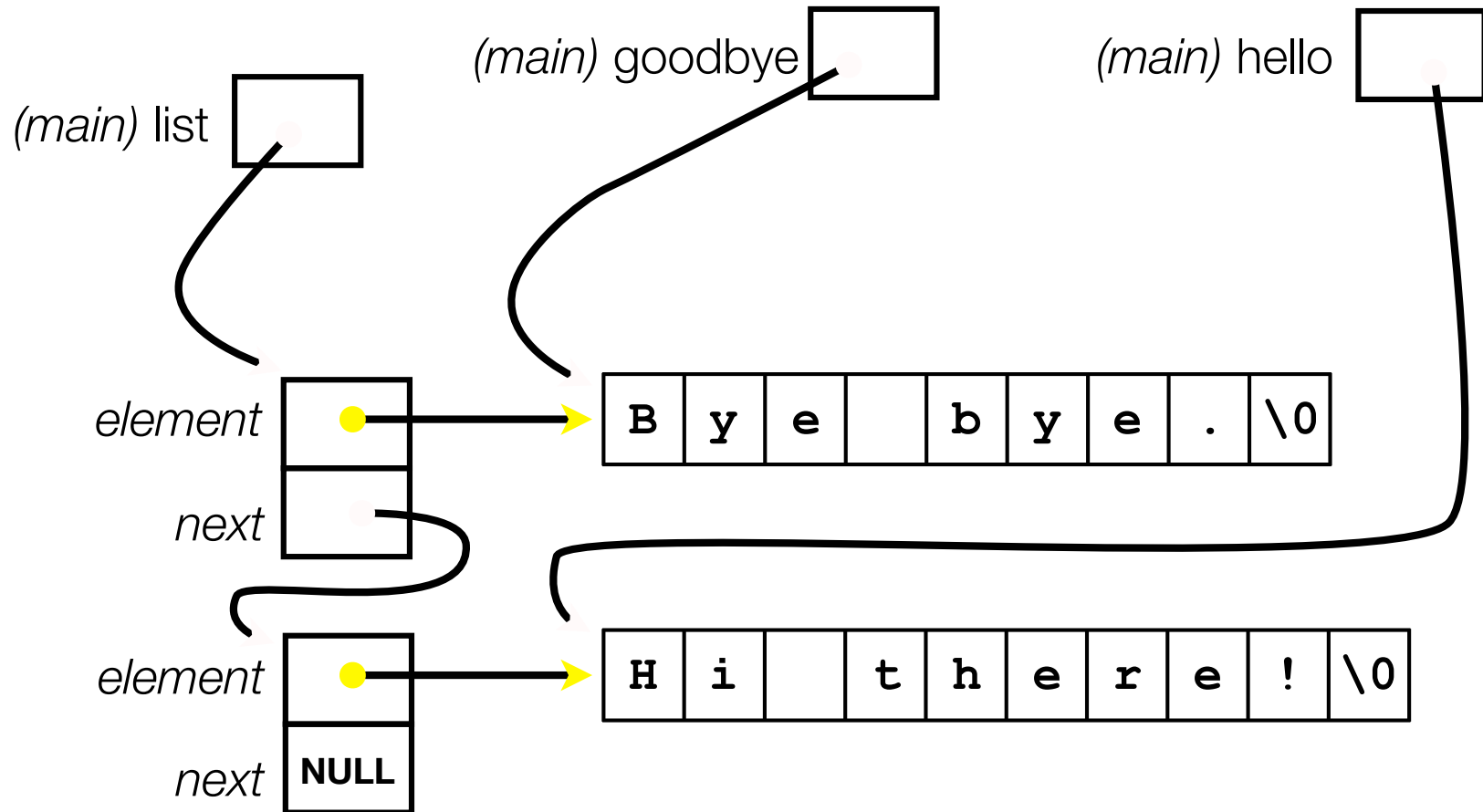
Node *Push(Node *head, void *e); // assume last slide's code

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;
}
```


Using a generic linked list

Result is:



Multi-file C programs

Let's create a linked list *module*

- a module is a self-contained piece of an overall program

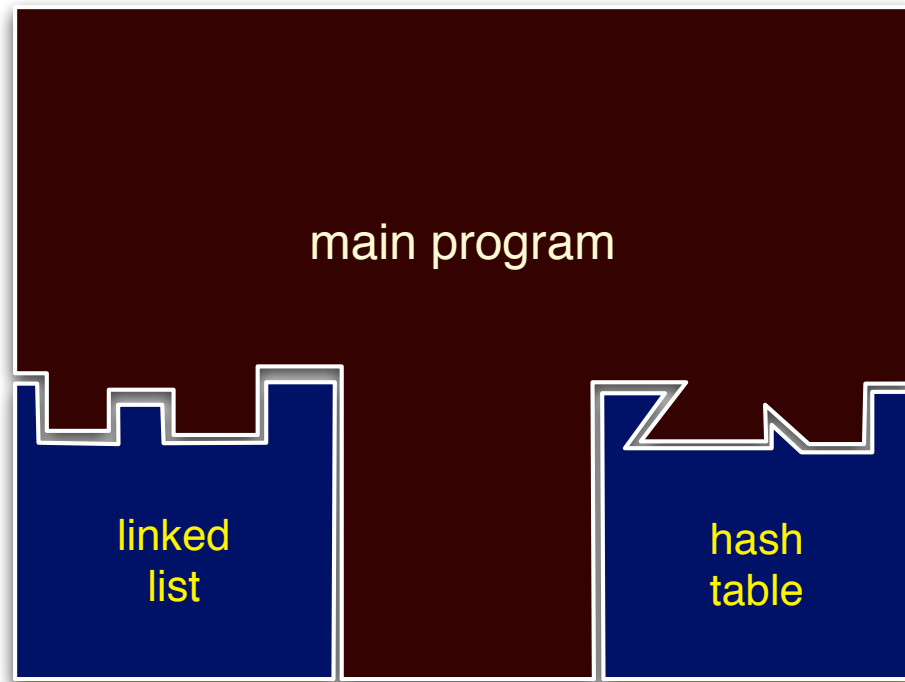
 - has externally visible functions that customers can invoke

 - 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 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 the 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

#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

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

cpp_example.h

```
#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

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

`cpp` is the preprocessor

"-P" suppresses some extra debugging annotations

(can also use `gcc -E`)

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

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

#include "ll.h"

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

ll.c

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

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

ll.h

```
#include "ll.h"

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_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$ 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$
bash$ ./example_ll_customer
```

```
Payload: 'yo!'
```

```
Payload: 'goodbye'
```

```
Payload: 'hello'
```

```
bash$ valgrind --leak-check=full ./example_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. It is the public specification.

No need to cut/paste the comment into the C file

Don't want two copies that can get out of sync

But help the reader with a "specified in foo.h" comment in the C file code

If a function has a prototype and implementation in the same C file

One school: full comment on the prototype at the top of the file, no comment (or "declared above") on code (e.g., project code is like this)

Another: prototype is for the compiler, doesn't need a comment; put the comments with the code to keep them together (my preference)

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

http://en.wikipedia.org/wiki/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 Friday!