CSE 333

Lecture 5 - data structures & modules

Hal Perkins

Paul G. Allen School of Computer Science & Engineering

University of Washington

Administrivia 1

Exercise 5 (fix and modularize buggy program) posted after sections yesterday. Due Monday morning.

Planning ahead for next week:

- New exercise out Monday, due Wednesday morning
- HW1 due Thursday night
- Exercise after that based on next week's sections, due following Monday

Later: Midterm exam will be Fri. Nov. 3, in class

Administrivia 2

HW1, due Thursday night

- Watch that hashtable.c doesn't violate the modularity of ll.h
- Watch for pointers to local (stack) variables - don't store in persistent data
- What do you do if one of the test_suite tests fails and it's not obvious why?
- Hints: segfault? use gdb (bt, …); make small tests; breakpoints in Verify333
- Suggestion from past graders: clean up the "to do" comments, but if you can, leave the "step 1", "step 2" markers so they can find things quickly
- Extra credit: if you add unit tests, put them in a new file and adjust the makefile
- Quiz: what is the late day policy?
- If you decide to use a late day, don't tag hw1-final until you are really ready

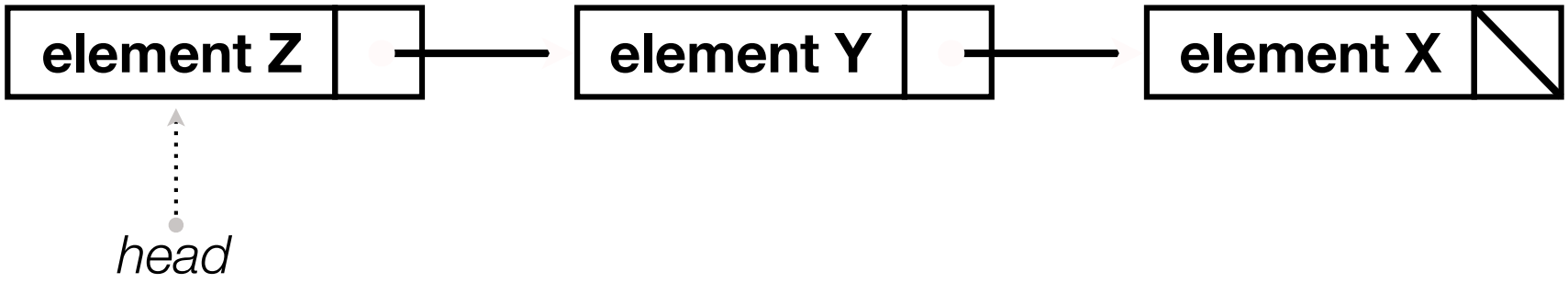
Today's topics:

- 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)



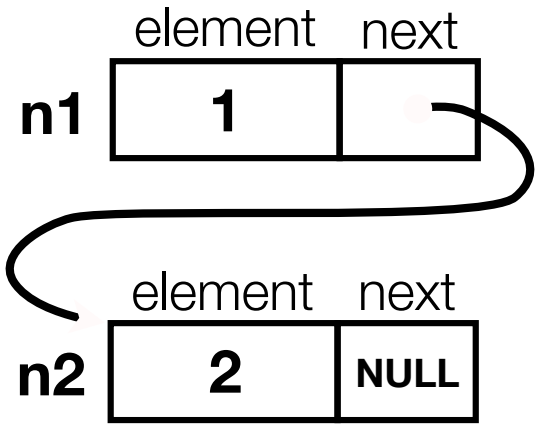
Linked list node

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

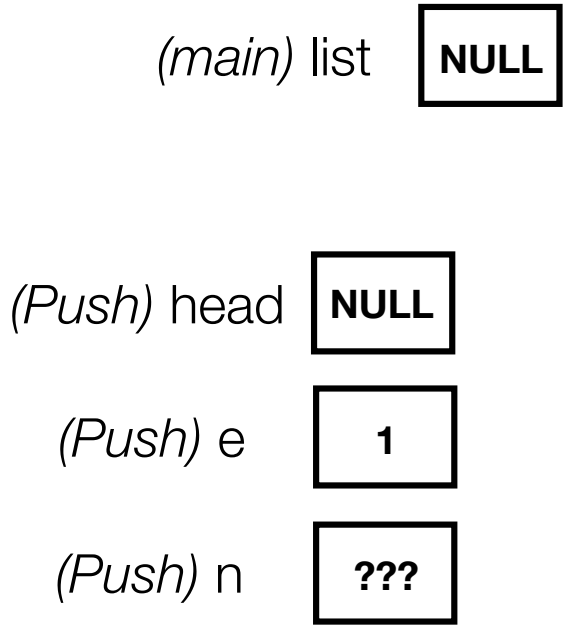
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

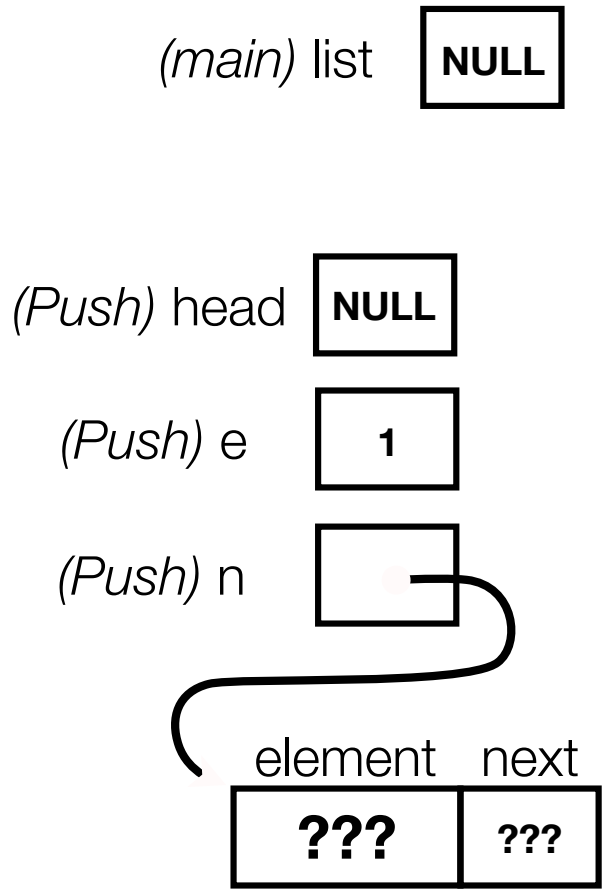
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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;
}
```



Push onto list

push_list.c

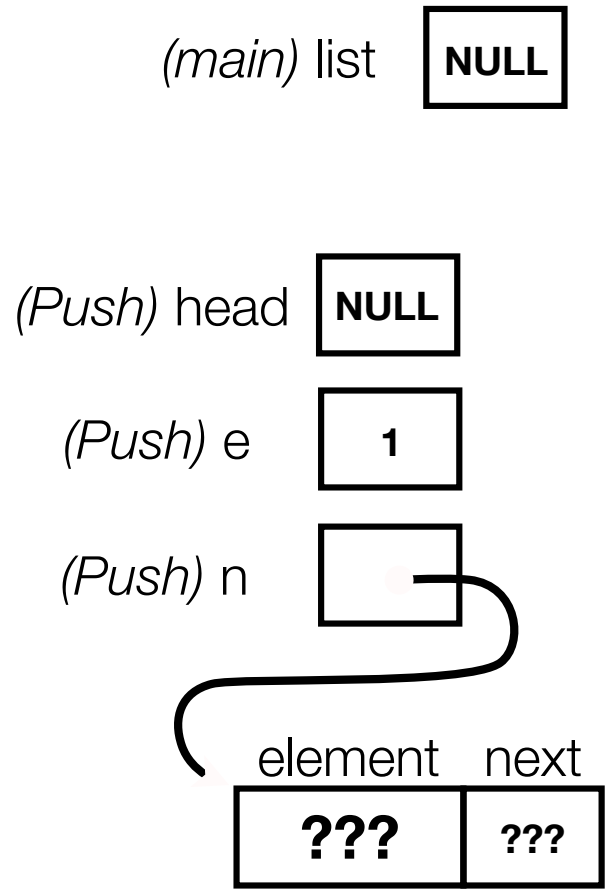
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

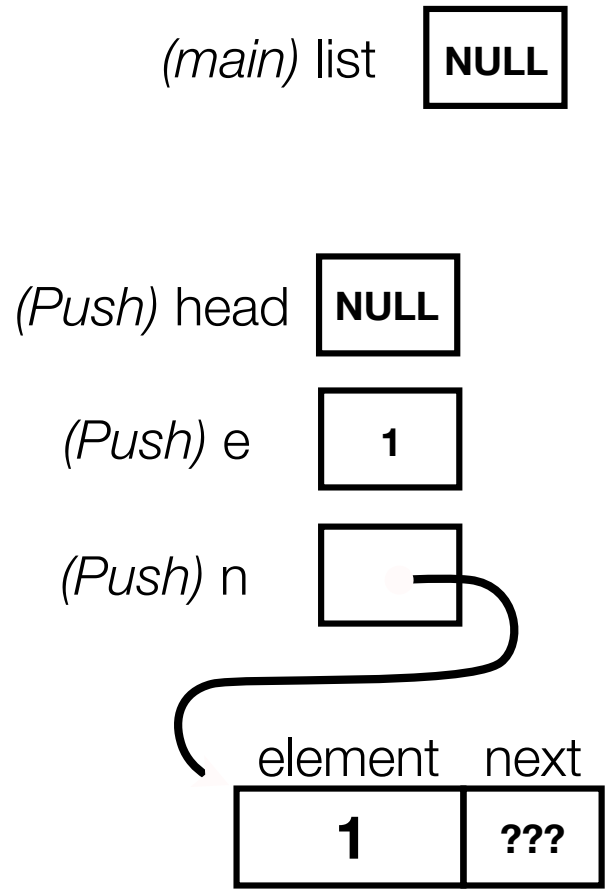
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

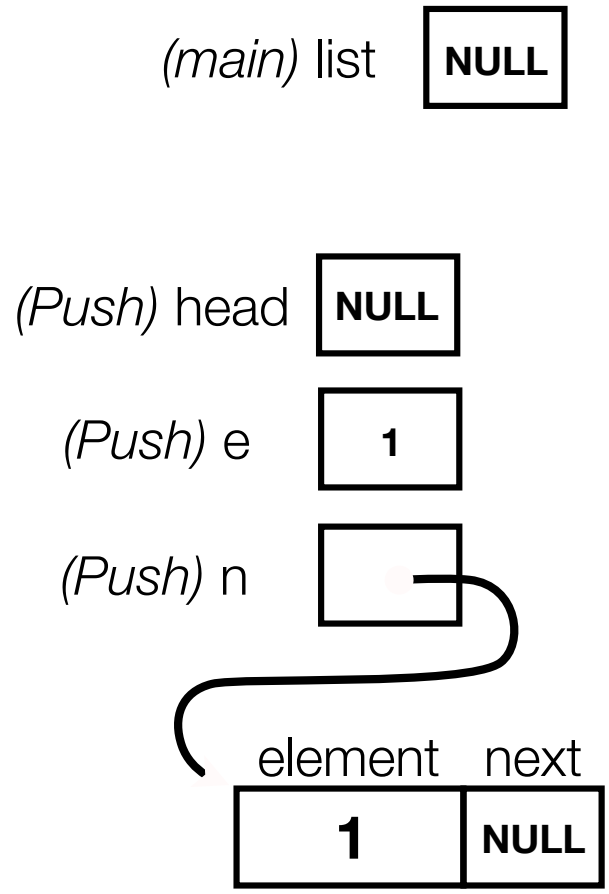
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

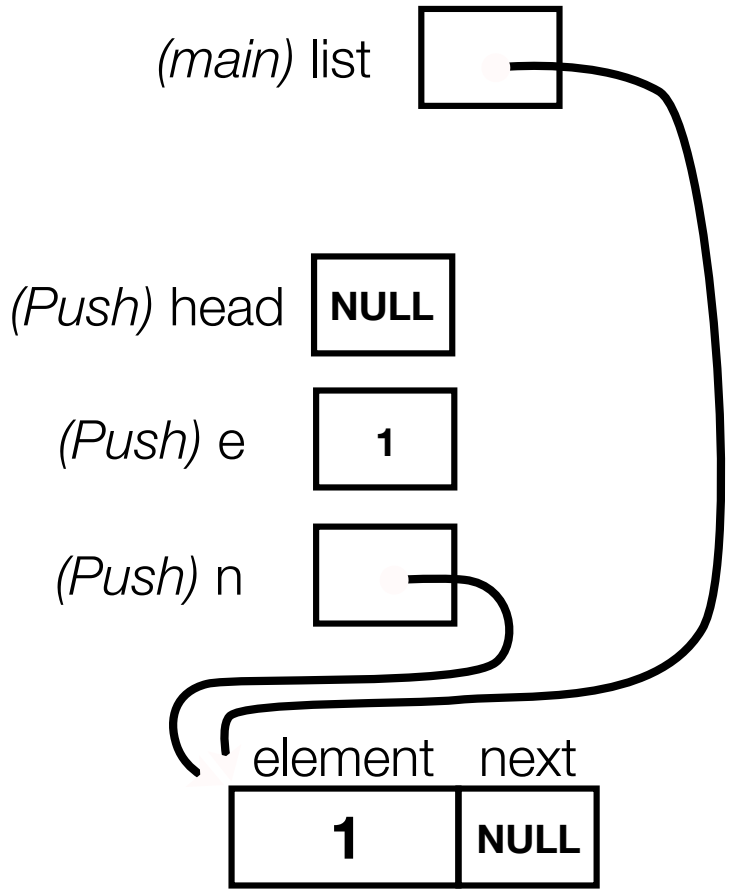
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

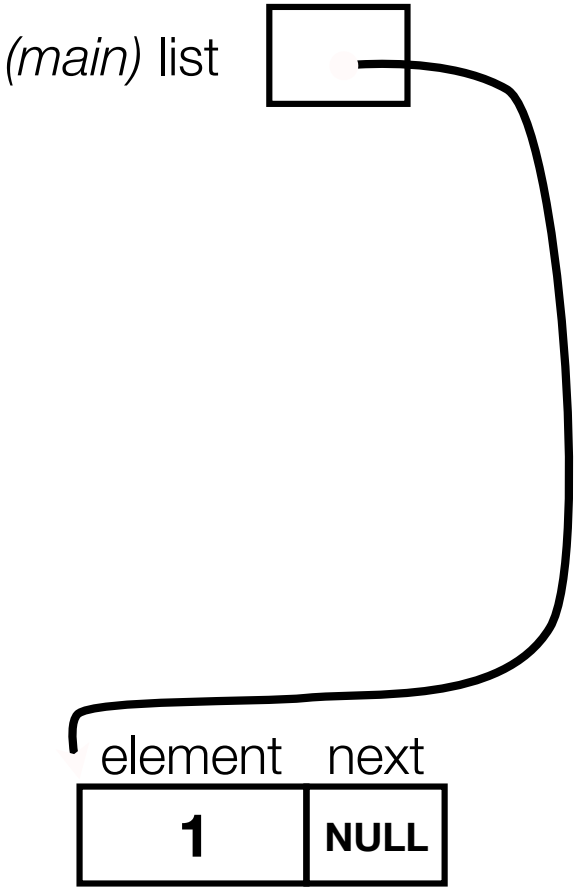
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

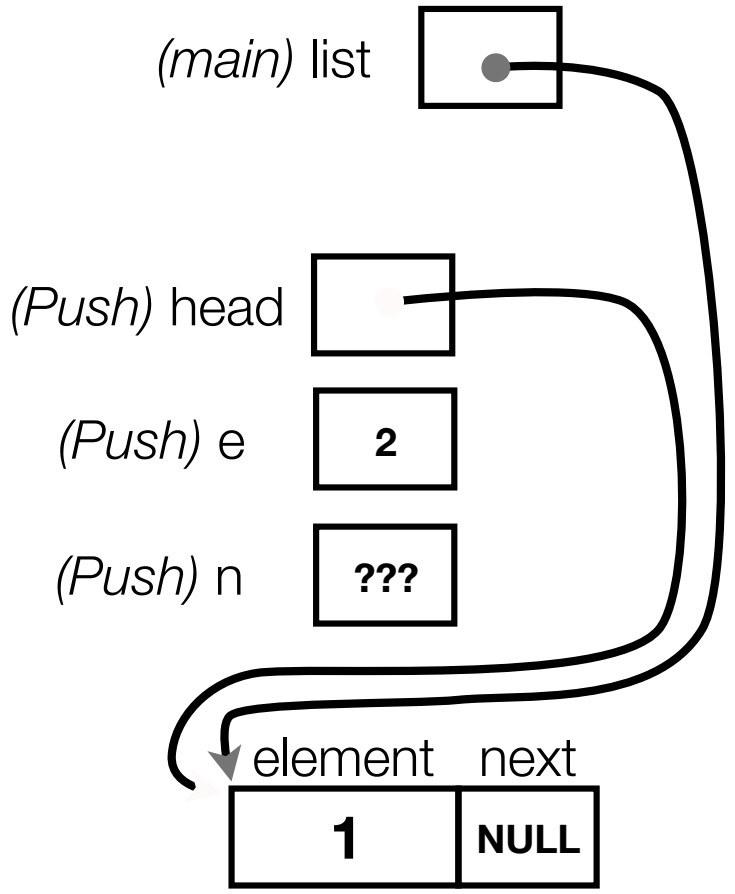
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

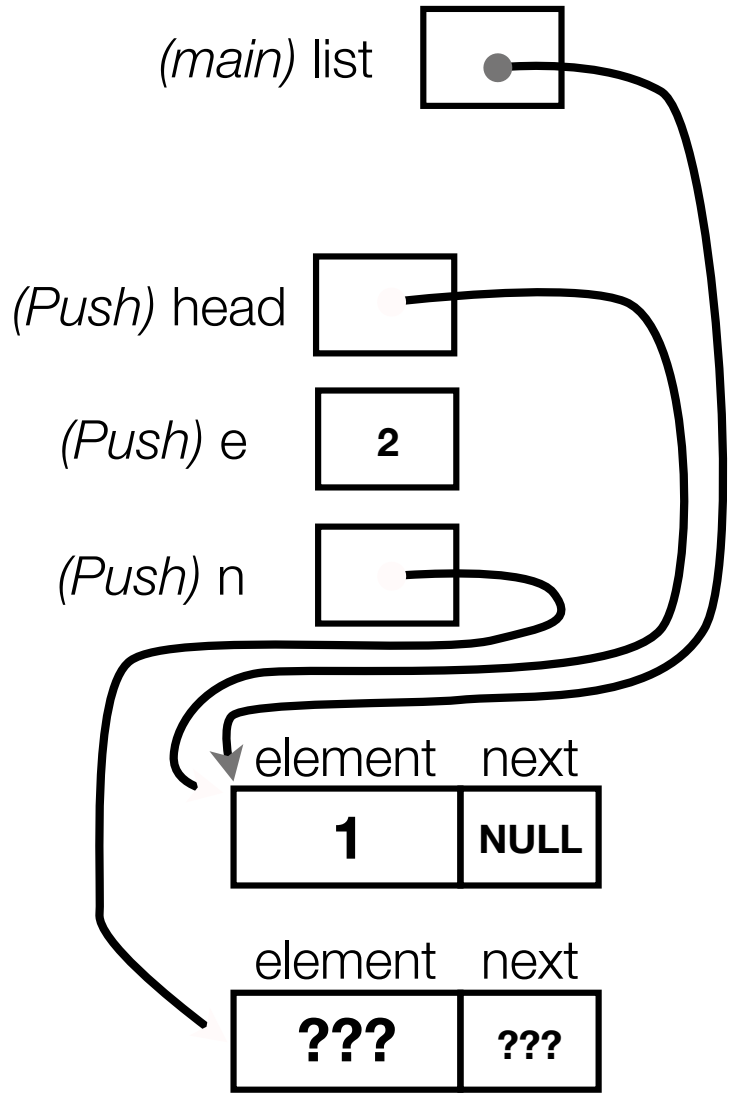
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

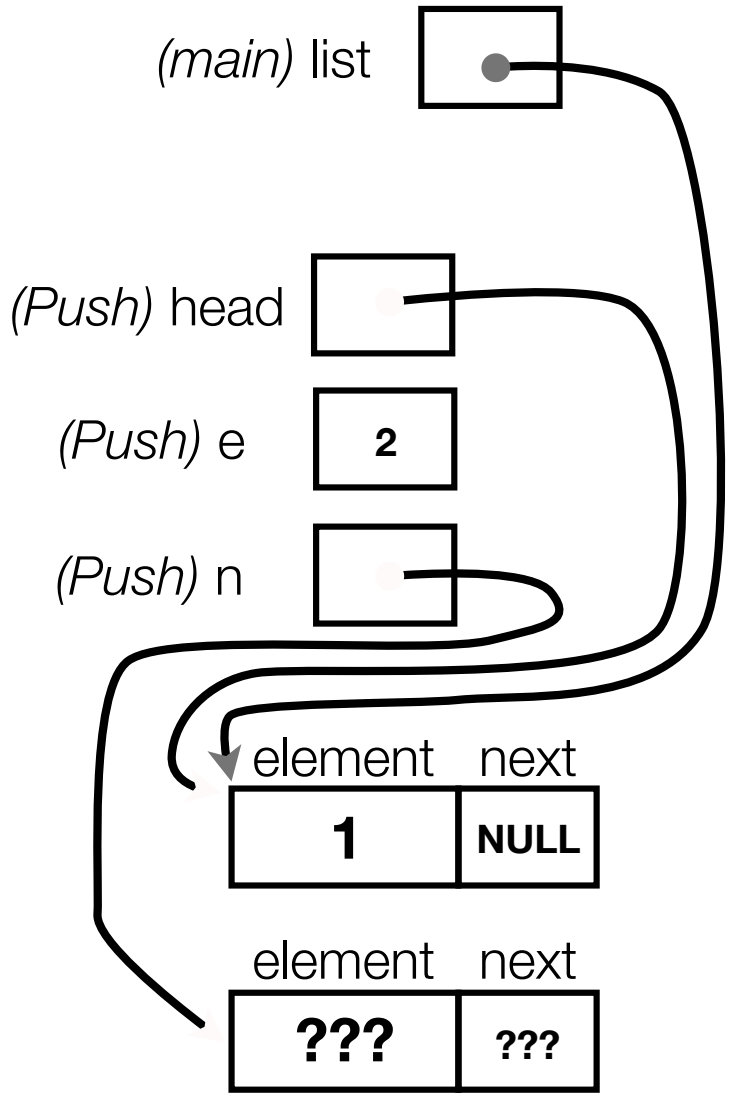
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

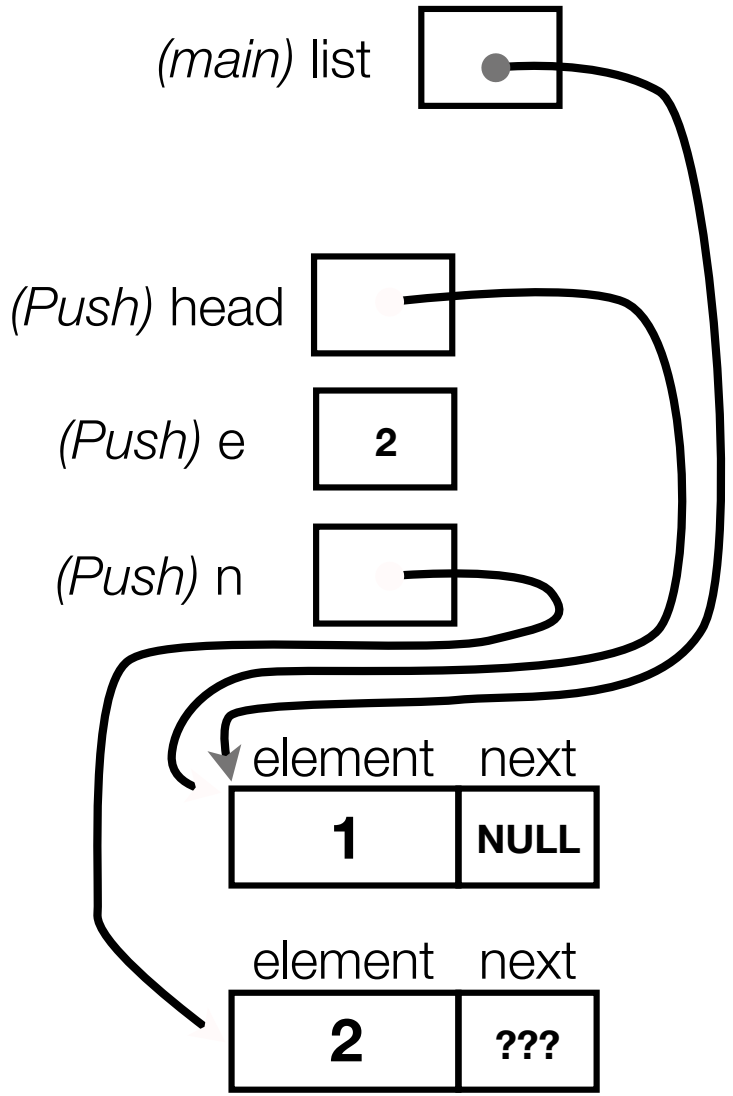
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

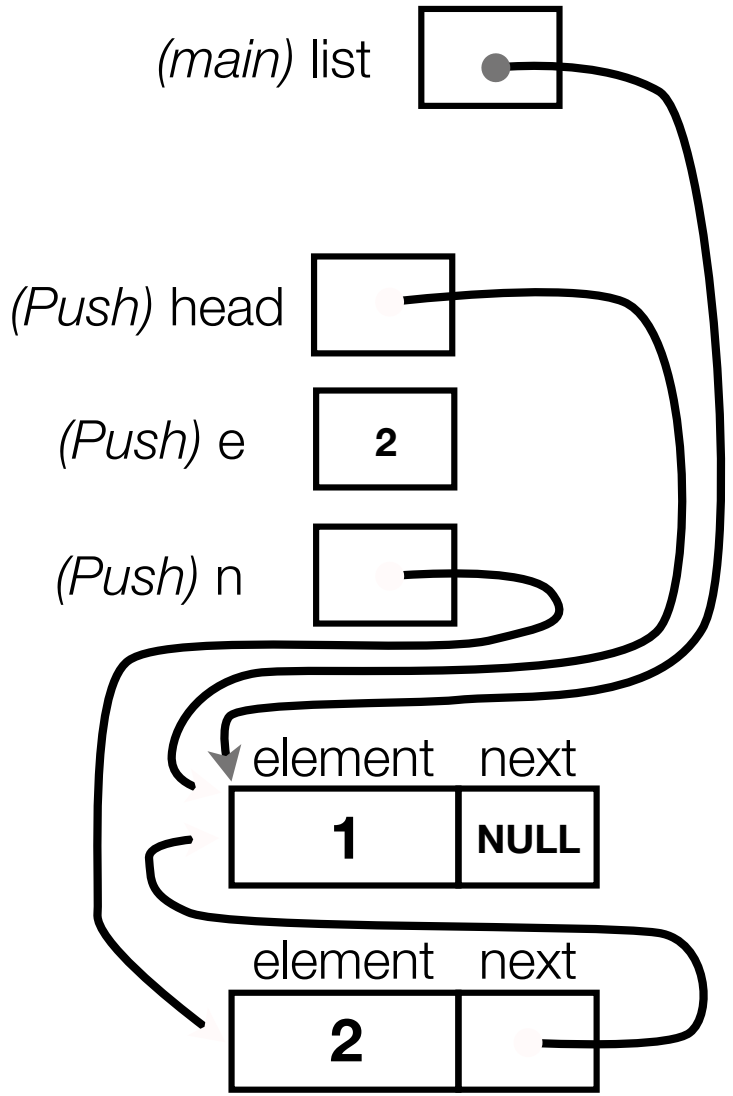
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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;
}
```



Push onto list

push_list.c

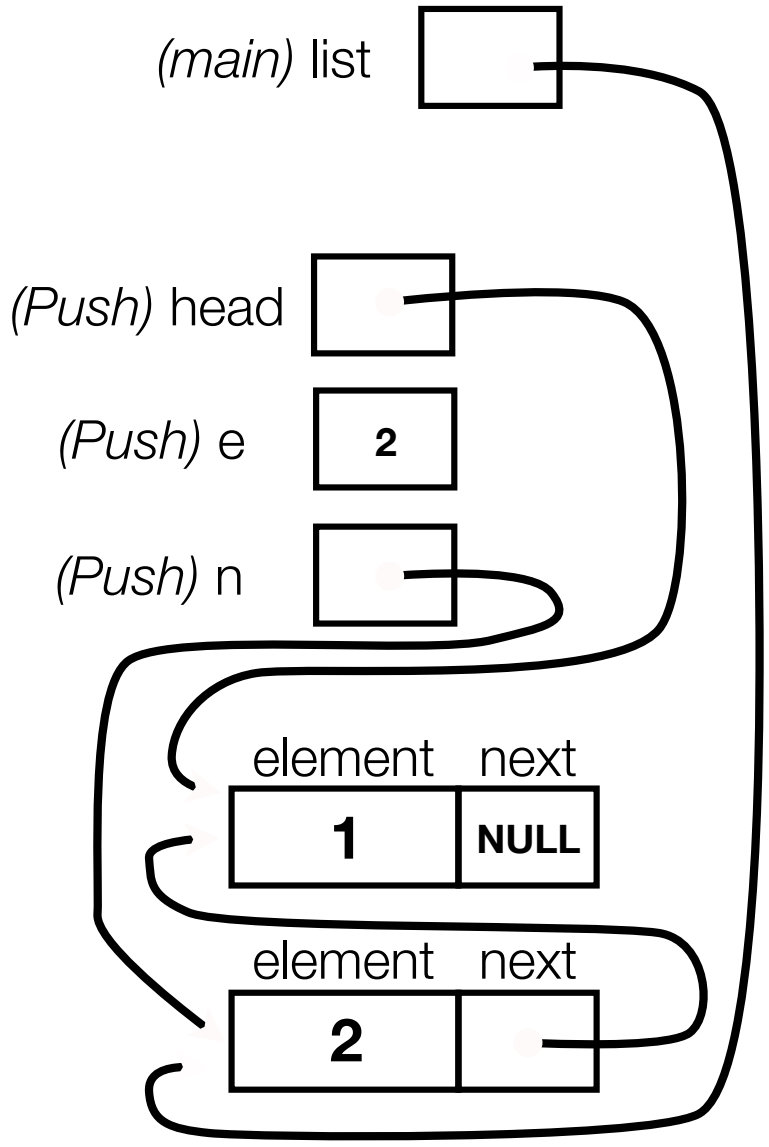
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

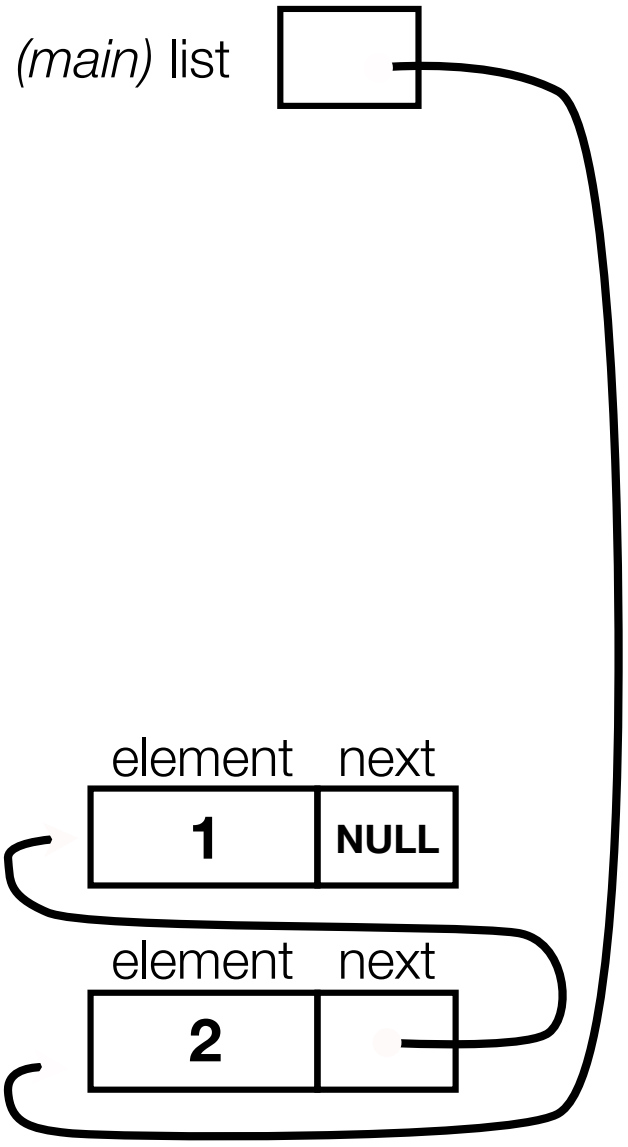
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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

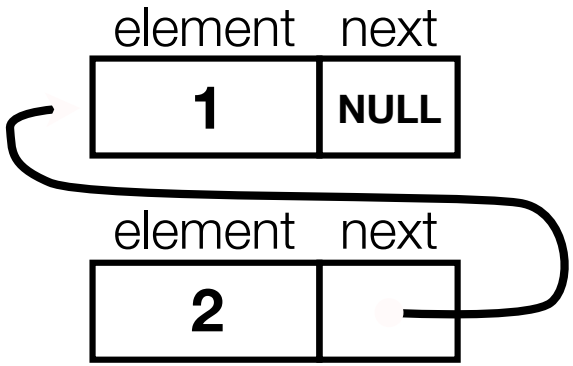
```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

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?



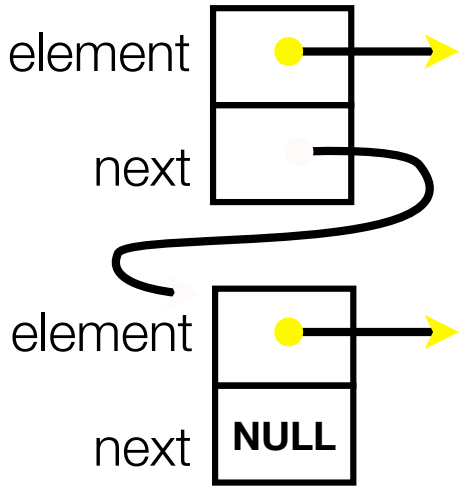
A generic linked list

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

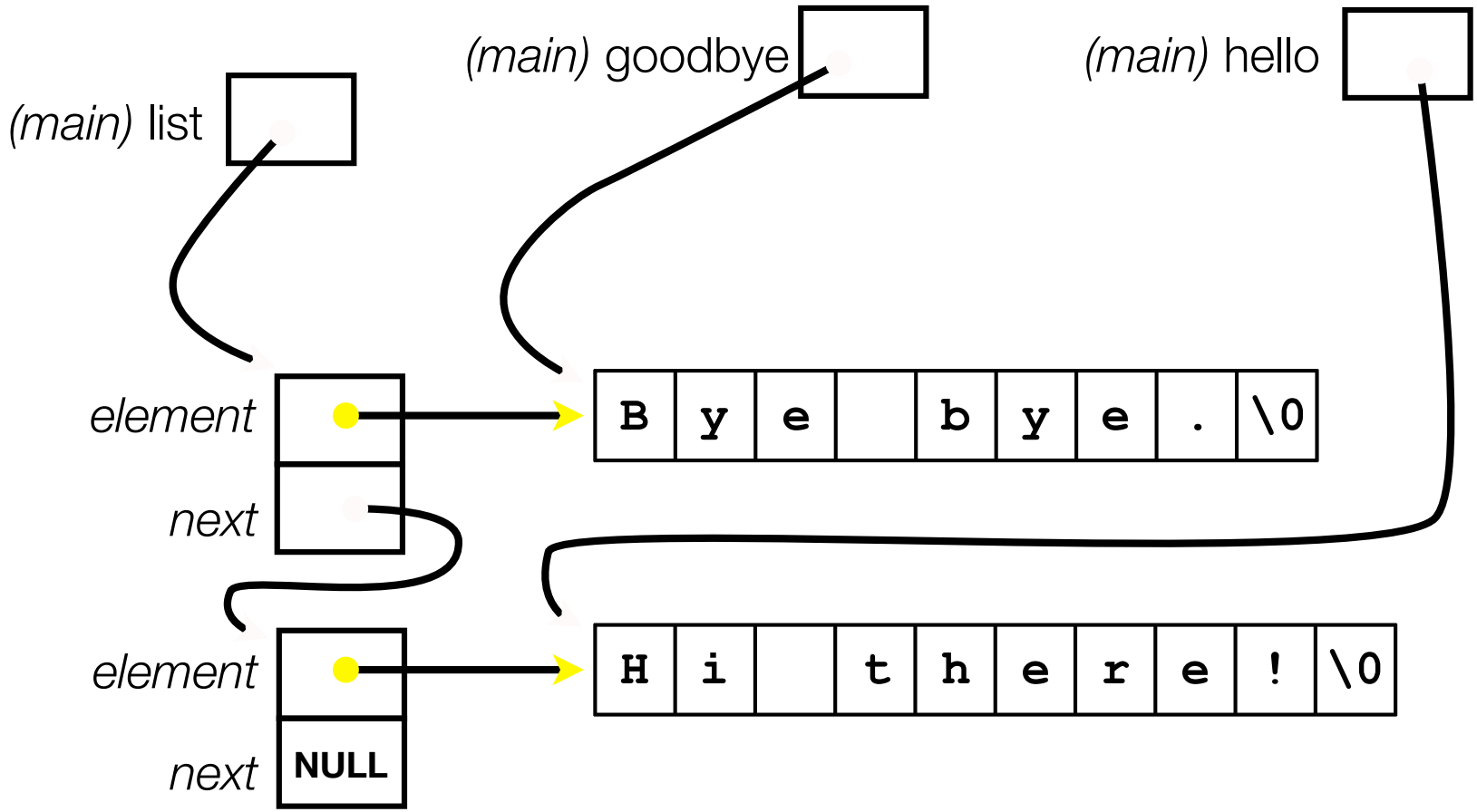
convert from a (void *) back to their data type when accessing

manual_list_void.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;
}
```

Using a generic linked list

Result is:

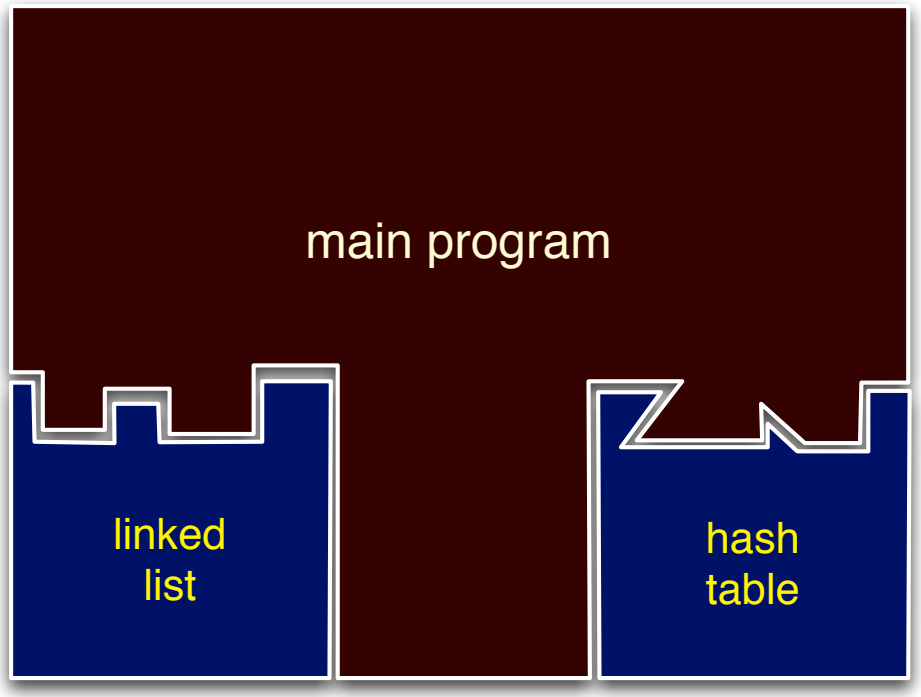


Multi-file C programs

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 a .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
  - The .c file should include the .h file; compiler will check definitions & declarations

#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, but not used in 333)

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 Monday!