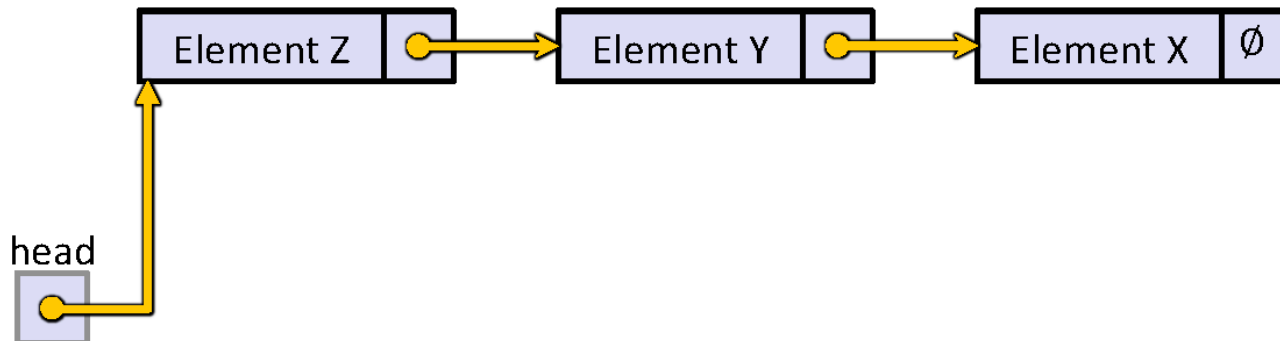


Lecture Outline

- ❖ **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`

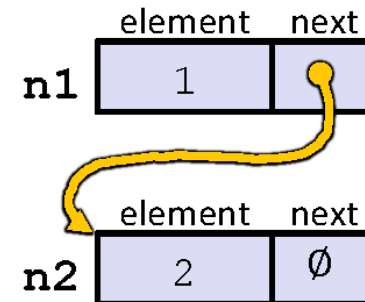
```
#include <stdio.h>

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

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

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

manual_list.c



Push Onto List

Arrow points to
next instruction.

```
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 ∅

push_list.c

Push Onto List

Arrow points to
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```
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 ∅

(Push) head ∅

(Push) e 1

(Push) n



push_list.c

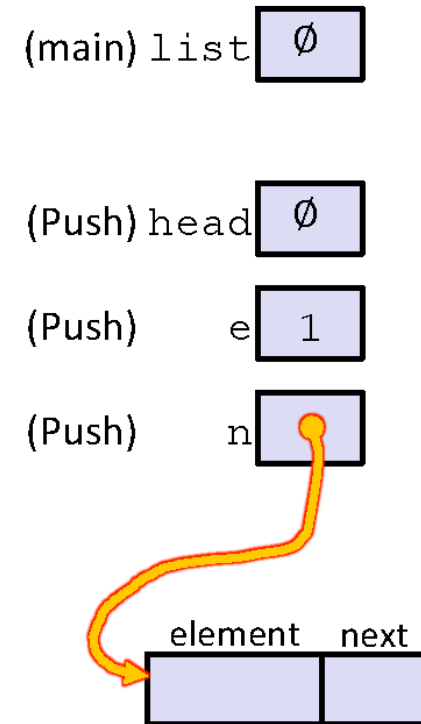
Push Onto List

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```
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    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

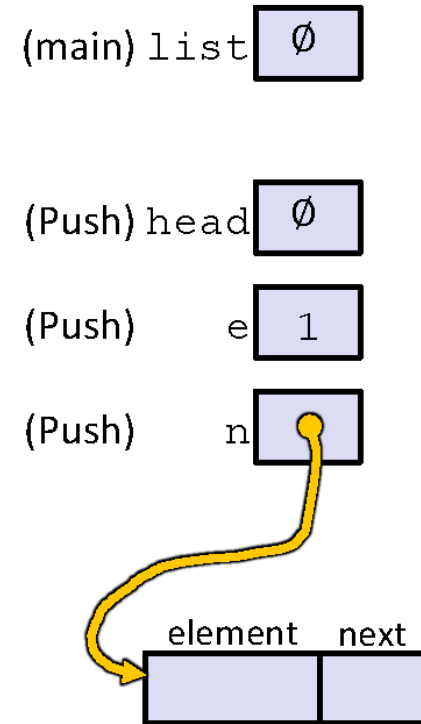
Push Onto List

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next instruction.

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    int element;
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} 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

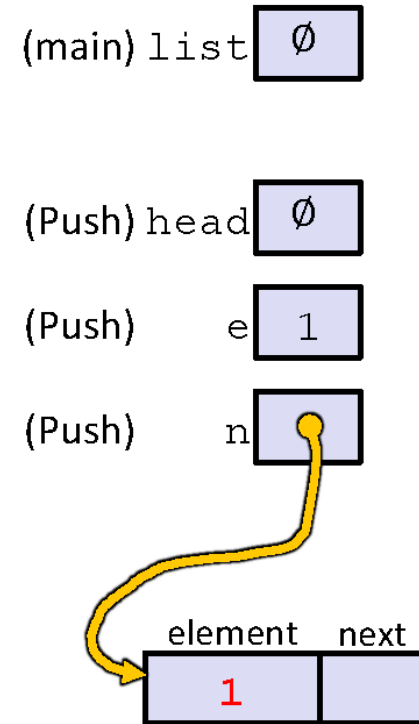
Push Onto List

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} Node;

Node* Push(Node* head, int e) {
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    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

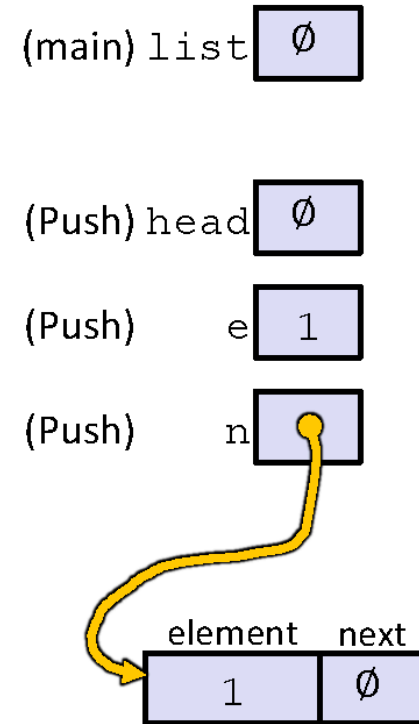
Push Onto List

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} 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

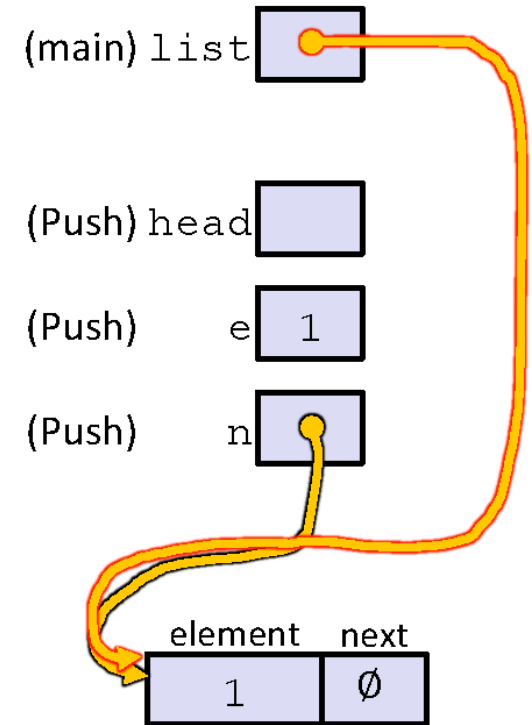
Push Onto List

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next instruction.

```
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    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

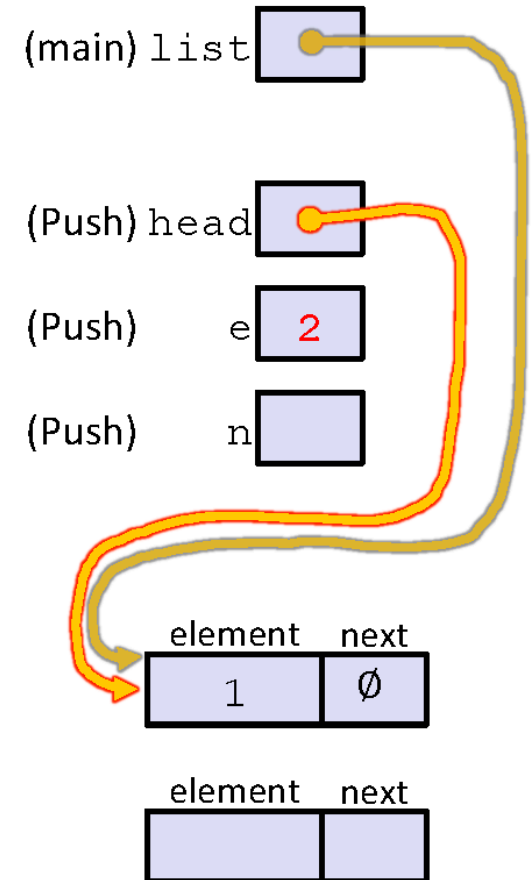
Push Onto List

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} Node;

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    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

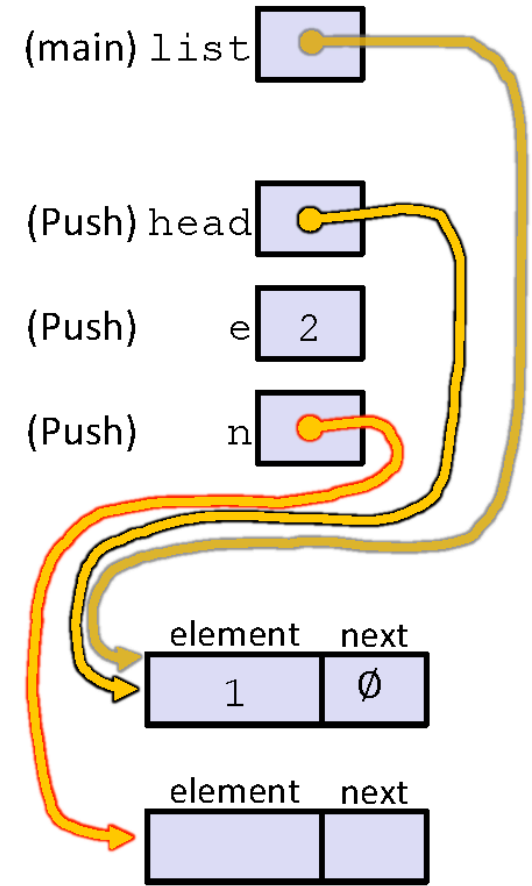
Arrow points to
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```
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} Node;

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    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

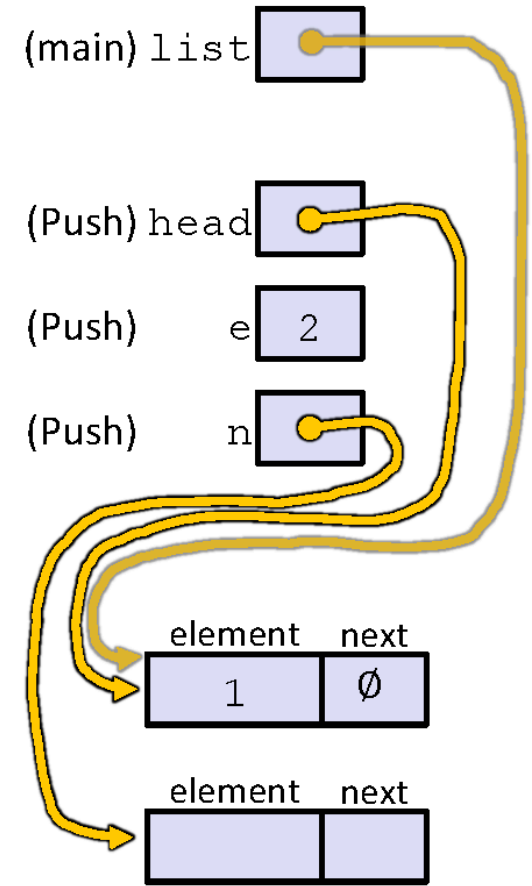
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next instruction.

```
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    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

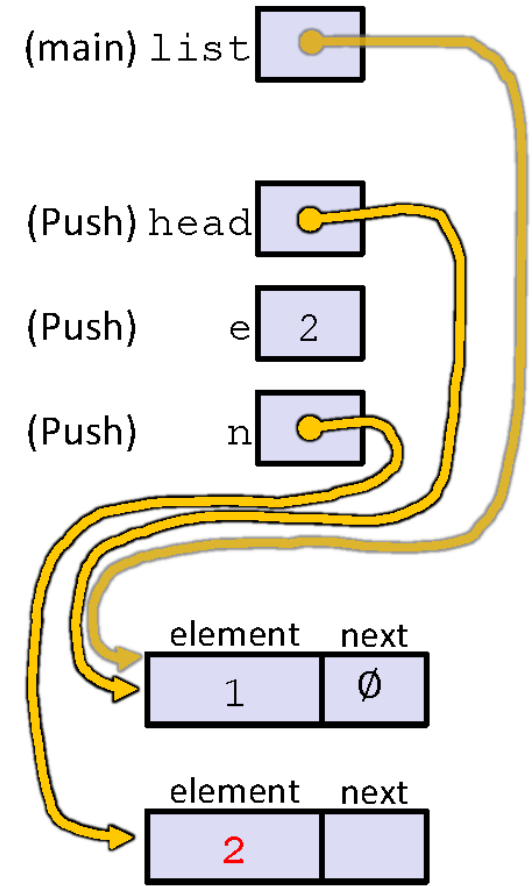
Arrow points to
next instruction.

```
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} 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

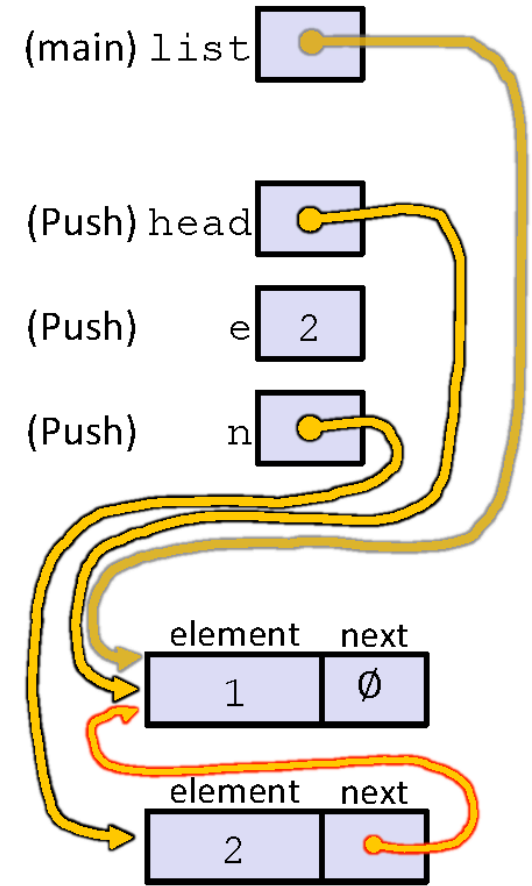
Arrow points to
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```
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    struct node_st* next;
} Node;

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



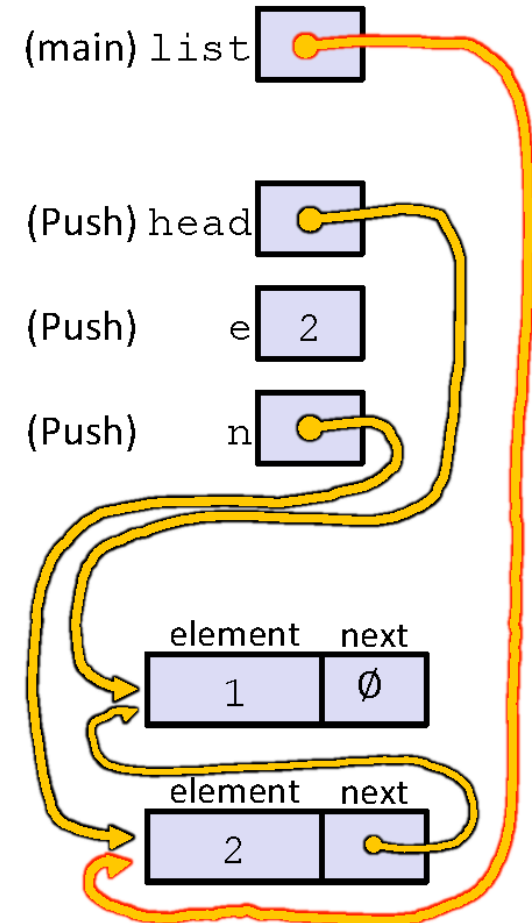
Push Onto List

Arrow points to
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} 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

Arrow points to
next instruction.

```
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;
}

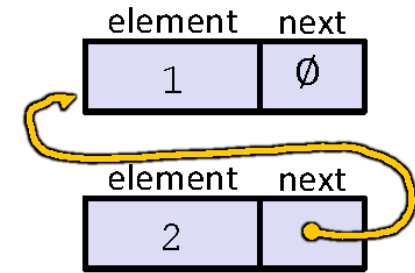
int main(int argc, char** argv) {
    Node* list = NULL;
    list = Push(list, 1);
    list = Push(list, 2);
    return 0;
}
```

push_list.c

A (benign) memory leak!
Try running with Valgrind:

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

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

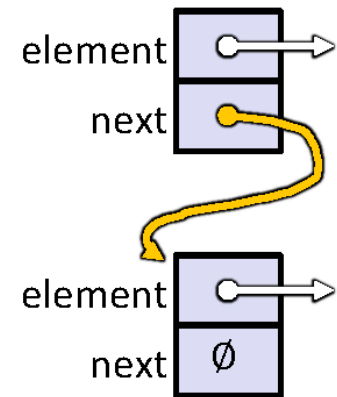


A Generic Linked List

- ❖ 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*`)

```
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

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

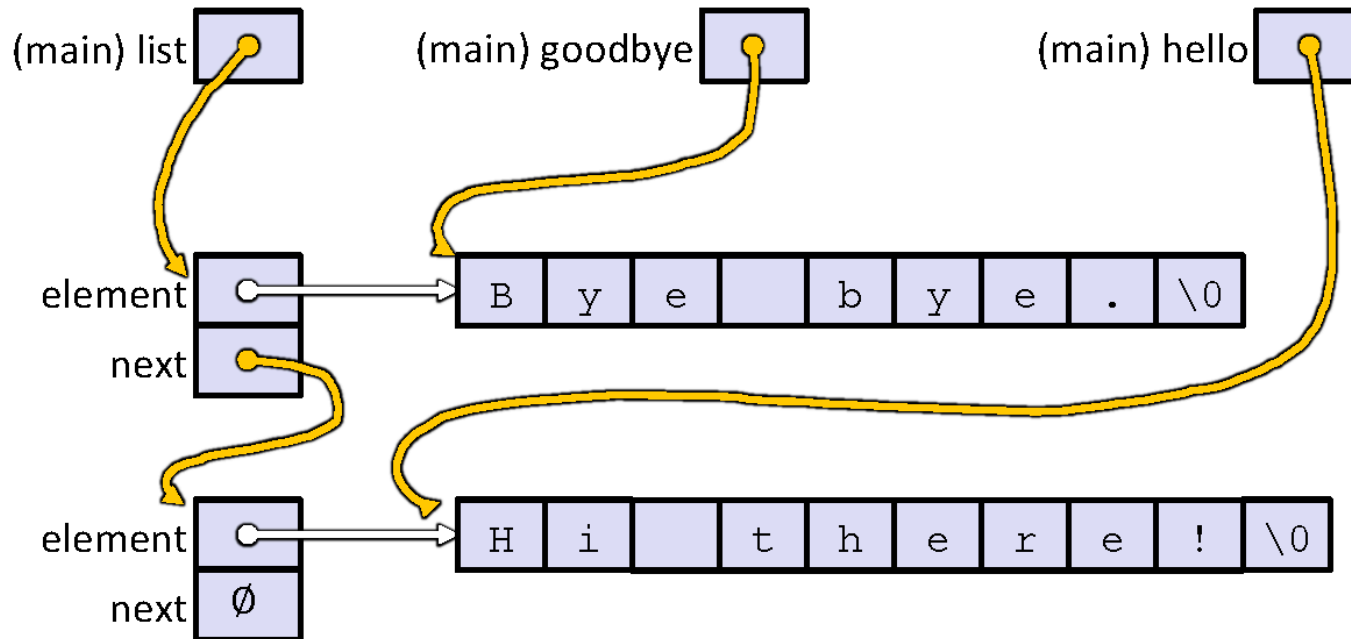
Node* Push(Node* head, void* e);    // assume last slide's code

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





Lecture Outline

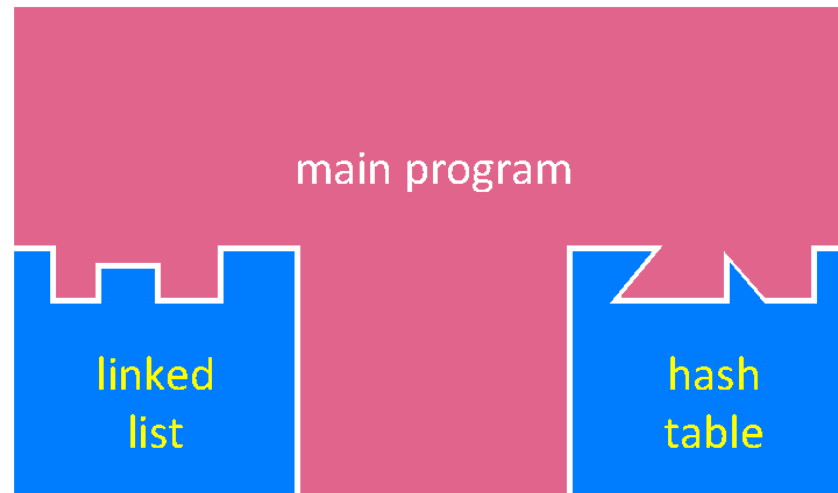
- ❖ Implementing Data Structures in C
- ❖ **Multi-file C Programs**
 - C Preprocessor Intro

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?

```
#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

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

```
#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`

```
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 Using 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, (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

```
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

 - Another school: Prototype is for the compiler and doesn't need comment; put the comments with the code to keep them together


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
 - https://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()` 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()`