Data Structures and Modules

CSE 333 Winter 2025

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Administrivia

- Exercise 3 was due this morning
  - Sample solution posted after class
- New exercise 4 out today, due Friday 10 am
  - Simple multi-file program. Hopefully pretty short/quick.
- Sections tomorrow: visualizing, diagraming, & debugging memory; including gdb and valgrind, how to use them effectively, and how to interpret their output.

HW1 advice

- Reminders about hw1:
  - You ***may not*** modify interfaces (`.h` files)
  - But ***do*** read the interfaces while you're writing code(!)
  - Suggestion: look at `example_program_{ll|ht}.c` for typical usage of lists and hash tables
  - Suggestion: have more fun, less anxiety: pace yourself and make steady progress; don't leave it until the last minute!
- Remember: the only supported systems for the class are the Current Allen School Linux machines using gcc 11. You should use these systems. The projects you build ***must*** work there.
  - We do not have the cycles to try to support other Unix-like things or chase bugs due to configuration or software differences (including file transfers to/from Windows systems for editing [i.e., messing up newlines etc.])

More hw1 hints

- Watch that `HashTable.c` doesn't violate the modularity of `LinkedList.h` (i.e., don't access private/hidden implementation details of linked lists)
- Watch for pointers to local (stack) variables (0x7fff… addresses)
  - Symptom: variables appear to spontaneously change values for no reason
- Keep track of types of things – draw memory diagrams
  - Is this variable a Thing, Thing*, Thing**, typedefed Thing*?
- Advice: use git add/commit/push often to save your work
  - Not one massive commit at the end!
  - Don't push .o and executable files or other build products
    - Clutter, makes it harder to do clean rebuilds, not portable, etc.
  - Don't use git as a file transfer program (don't edit on one machine, commit/push/pull to another, compile, and repeat every few minutes)

Yet more hw1 hints

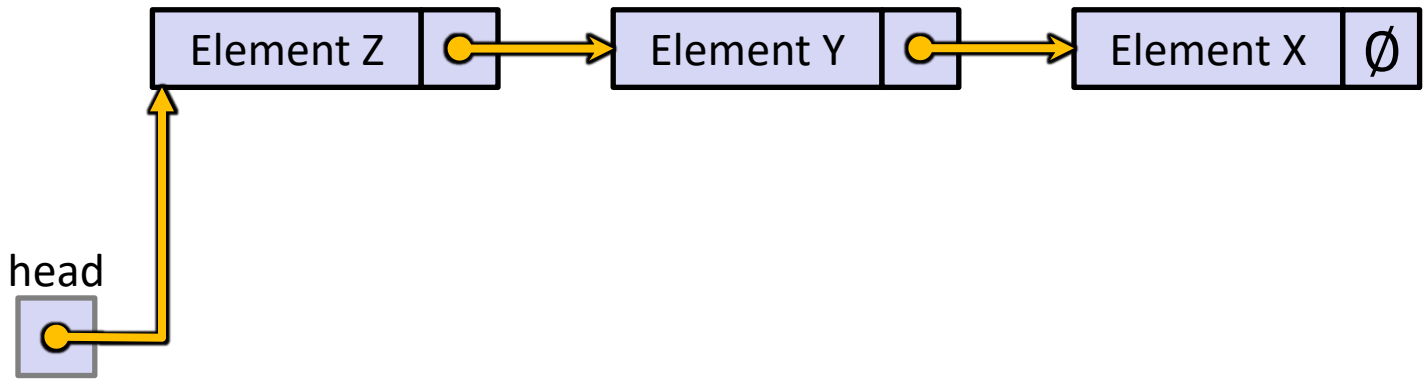
- Debugging
  - Use a debugger (*e.g.* `gdb`) if you're getting segfaults – fix reality!
  - Write and run little tests to track down problems (don't kill lots of time trying to debug large test_suite code)
  - gdb hint: What if `Verify333` fails? How can you debug it? Answer: look at the `Verify333` macro (`#define`), figure out what function it calls on failure, and put a breakpoint there
- Late days: don't tag `hw1-final` until you are really ready (then check your work – clone repo – and re-read assignment to be sure you didn't miss anything!)
- Extra Credit: if you add unit tests, put them in a new file and adjust the Makefile and be sure to tag the extra credit part with `hw1-bonus`

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`

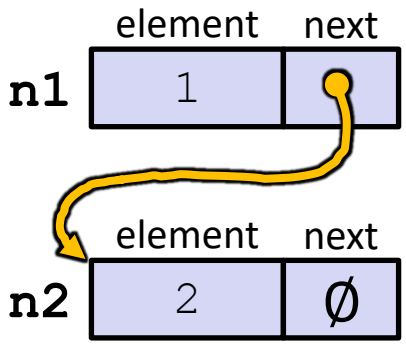
```
#include <stdio.h>

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 EXIT_SUCCESS;
}
```

Need to use `struct node_st` here. `Node` not defined until after end of `typedef`.



manual_list.c

Push Onto List

Arrow points to *next* instruction.

```
typedef struct node_st {
  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 EXIT_SUCCESS;
}
```

(main) `list` Ø

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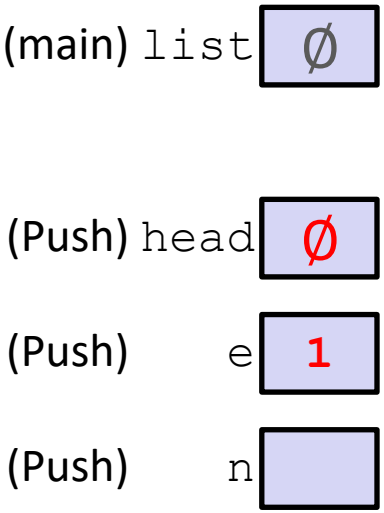

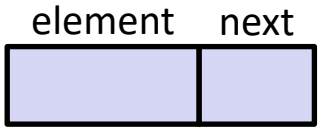

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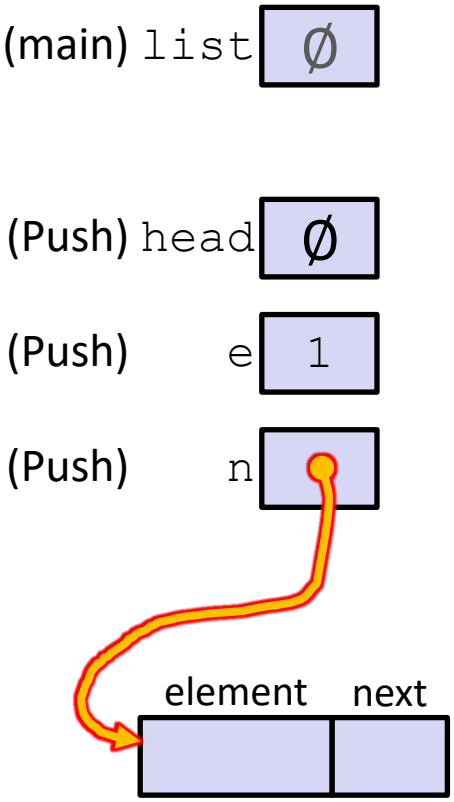

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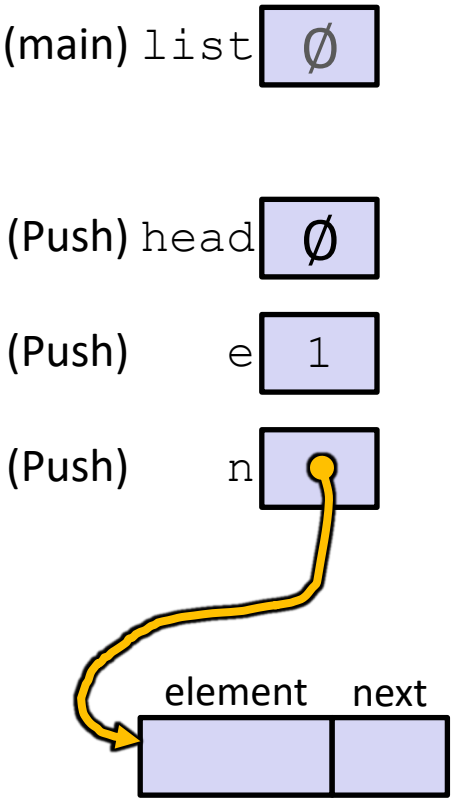

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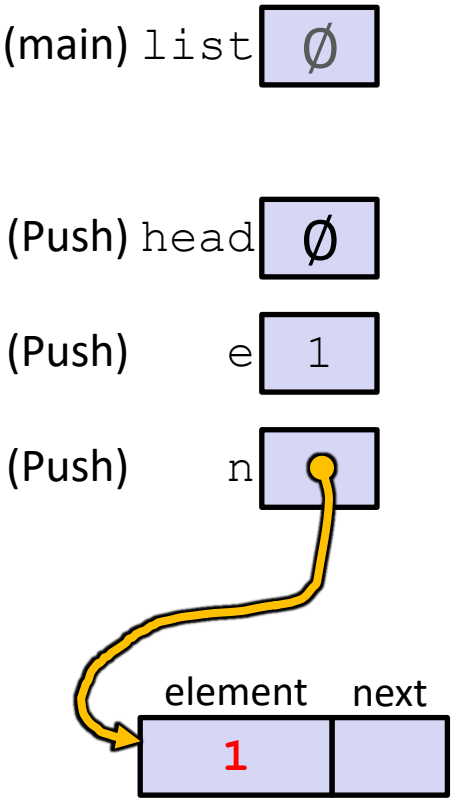

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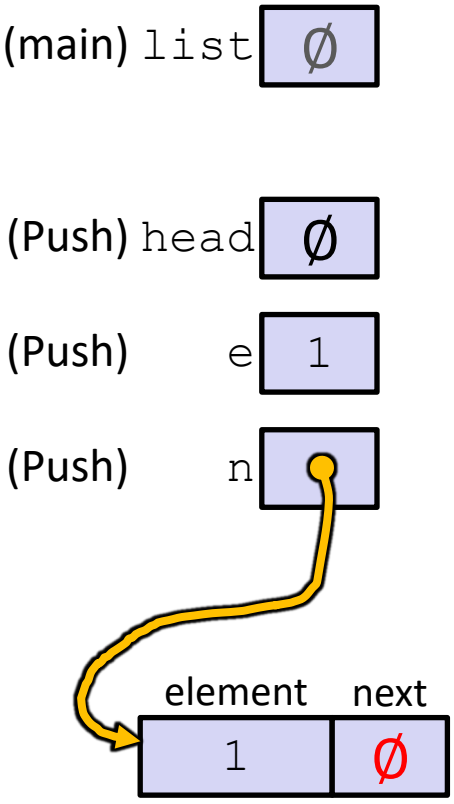

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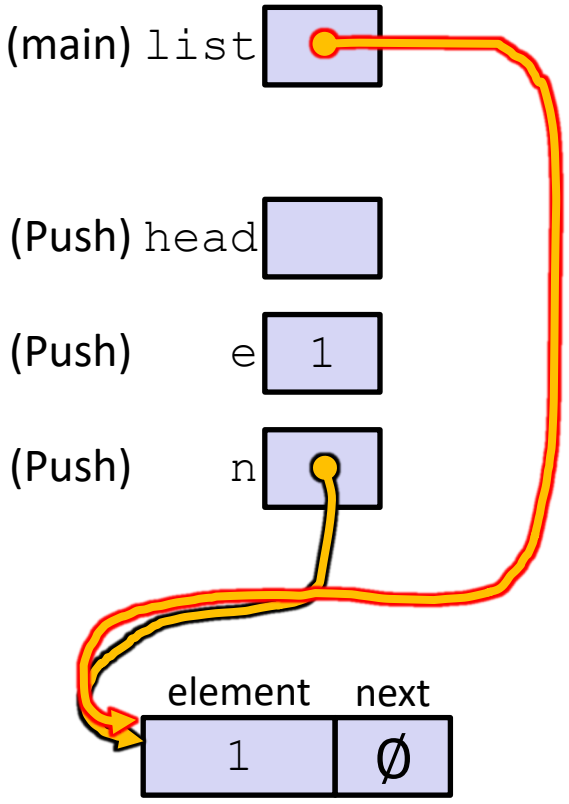

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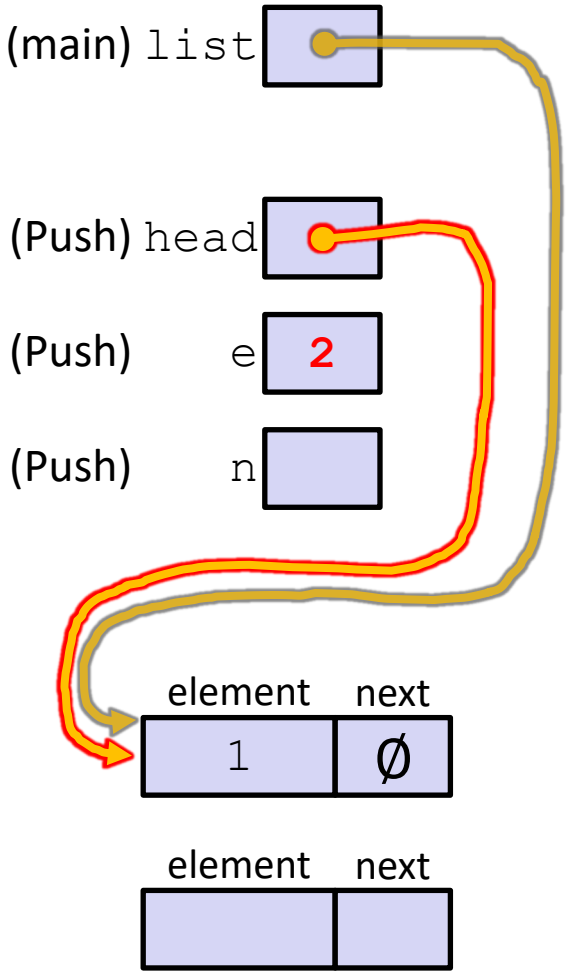

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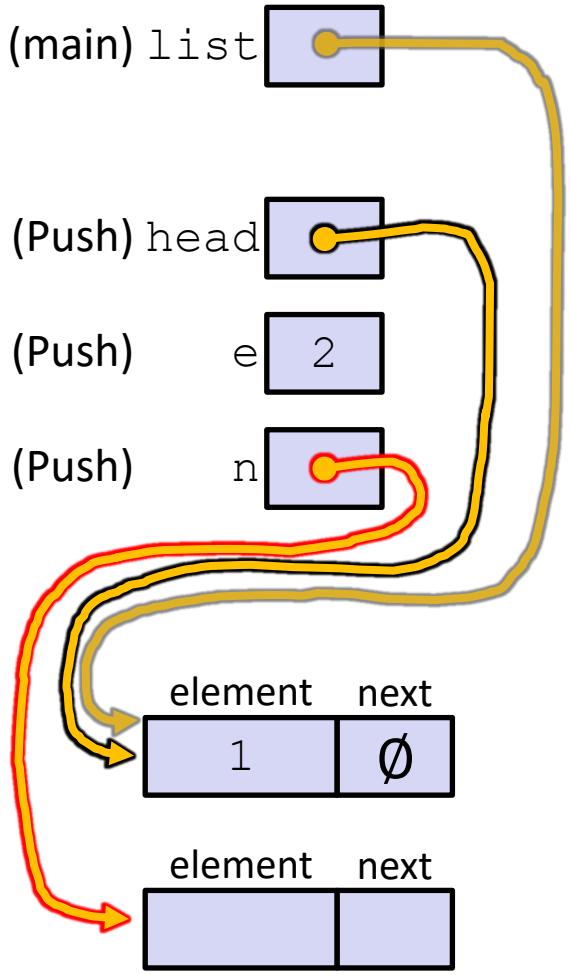

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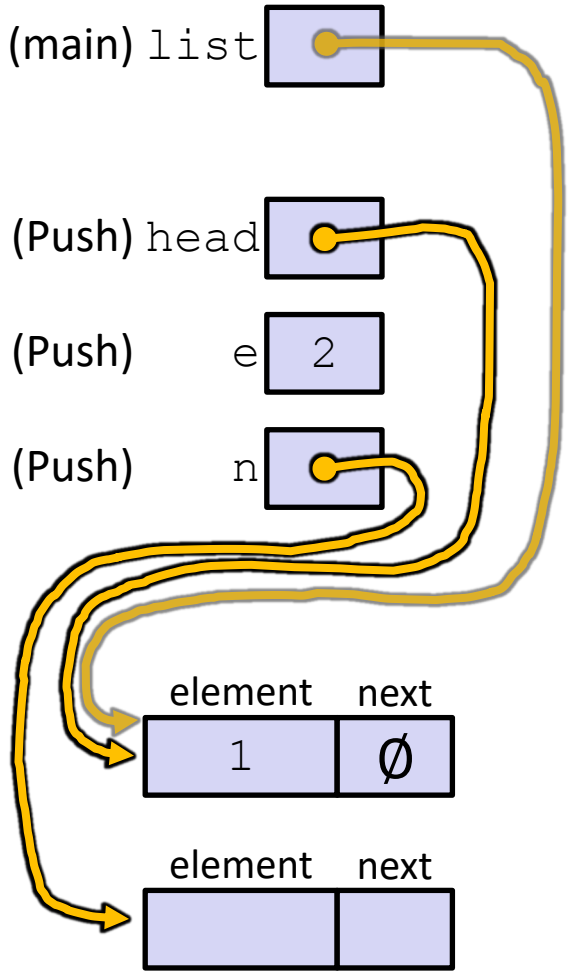

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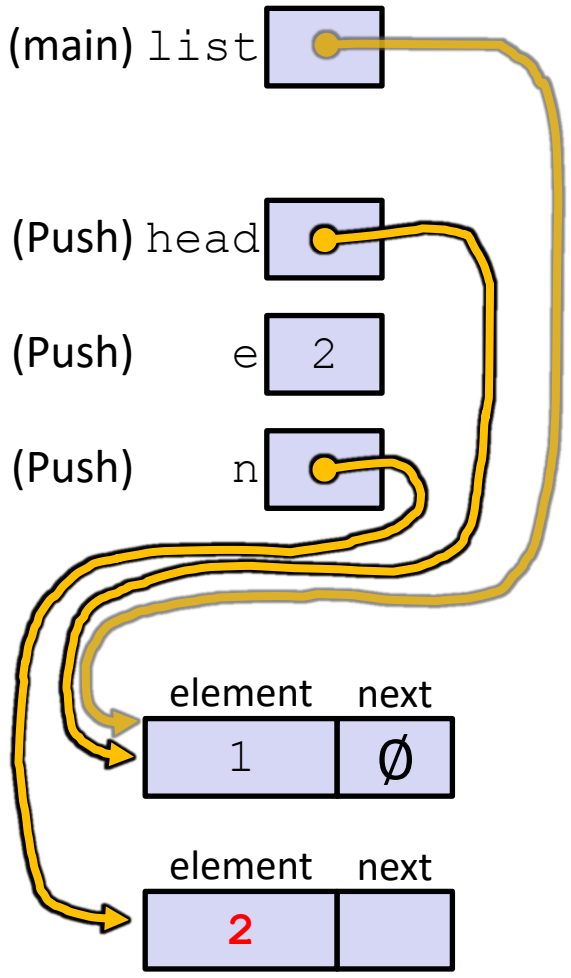

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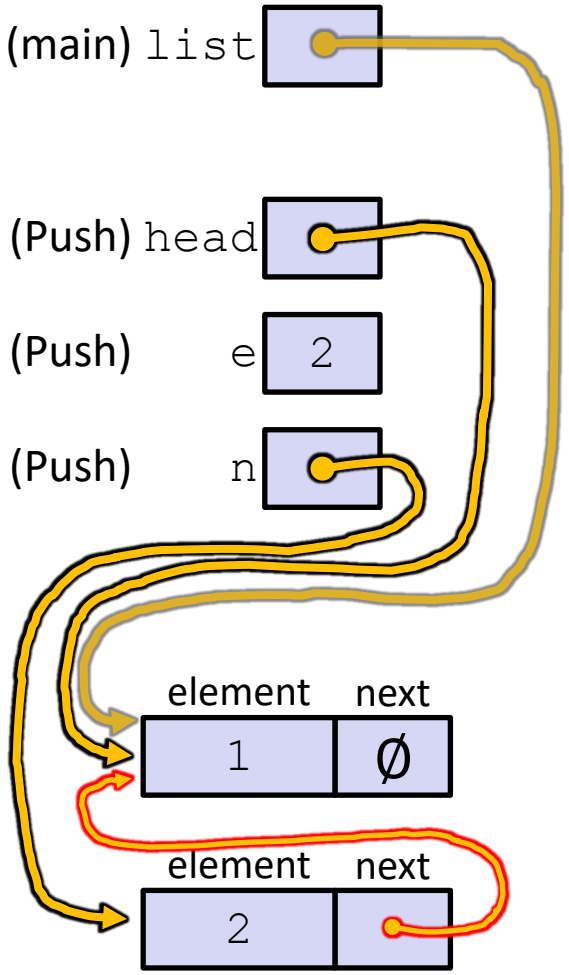

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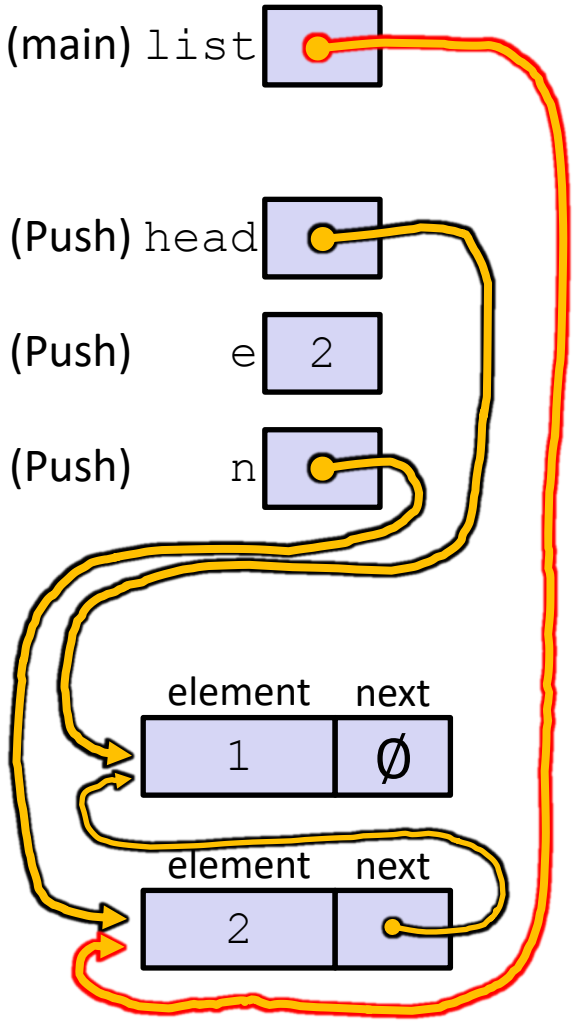

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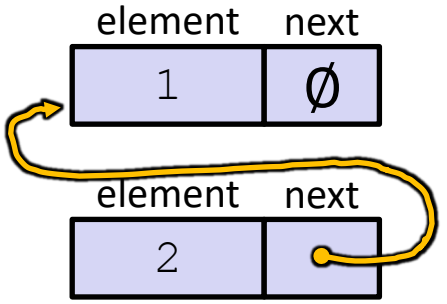
  list = Push(list, 2);
  return EXIT_SUCCESS;
}
```

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
```

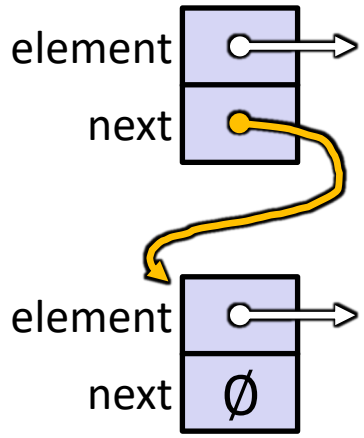


A Generic Linked List

- 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;

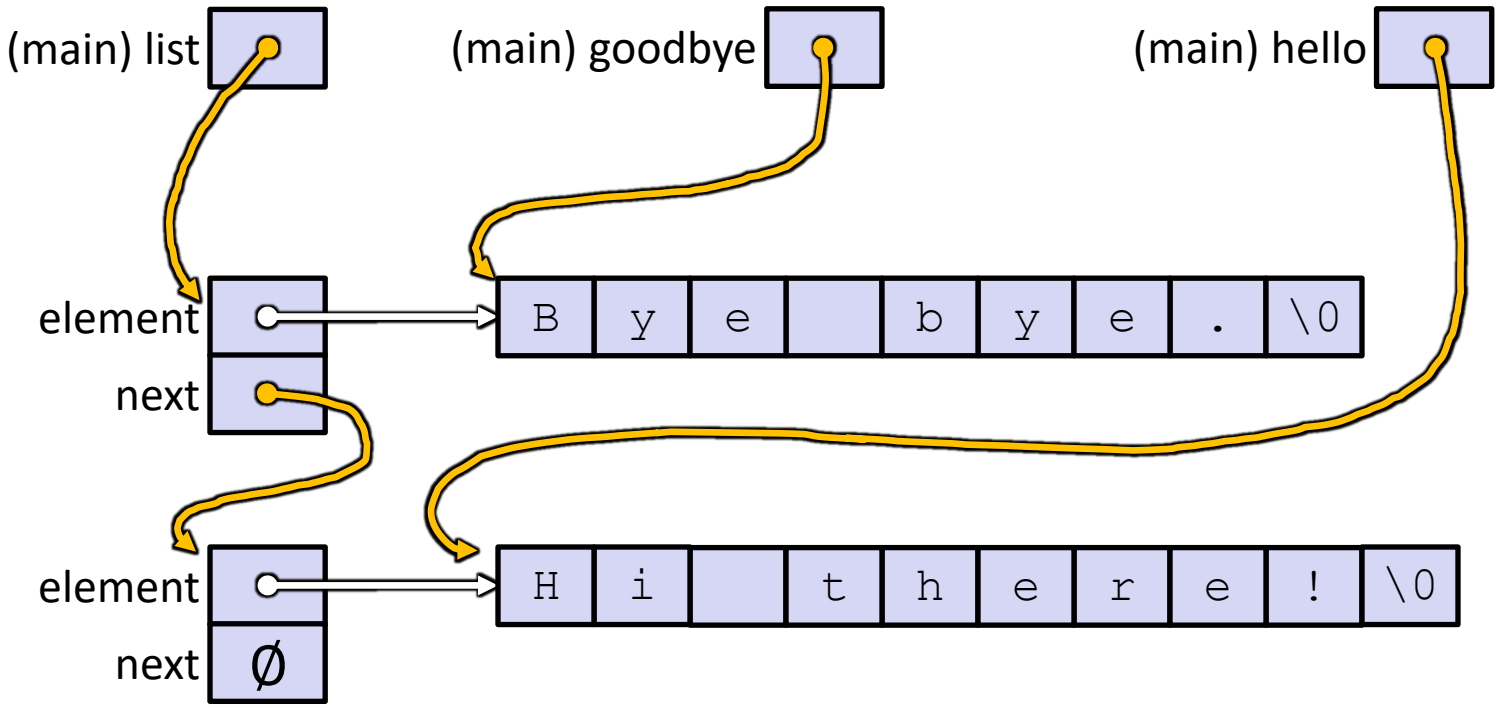
Node* Push(Node* head, void* e);   // assume last slide's code

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 EXIT_SUCCESS;
}
```

manual_list_void.c

Resulting Memory Diagram



Lecture Outline

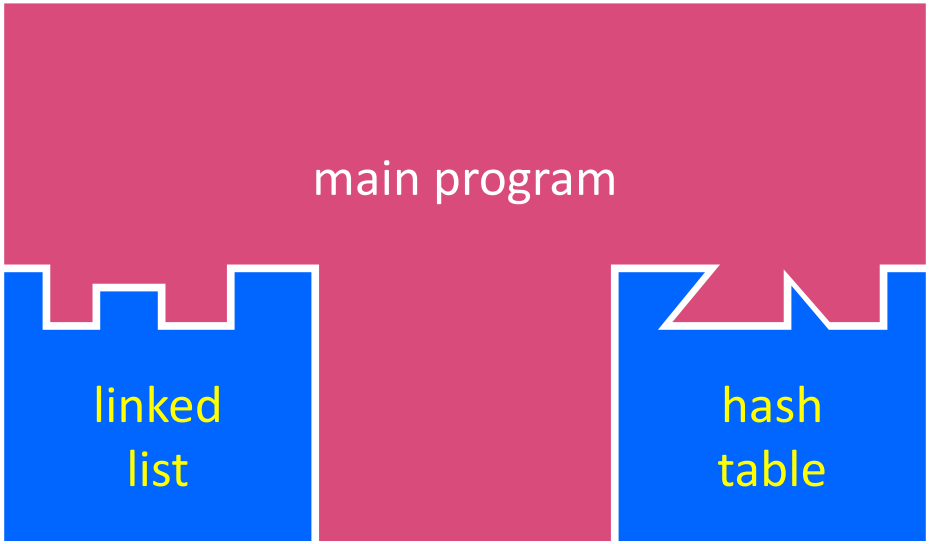
- Implementing Data Structures in C
- **Multi-file C Programs**
  - **C Preprocessor Intro**

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 `typedef`s, and perhaps global variables, that customers can use
    - May have internal functions, `typedef`s, or global variables that customers should *not* look at
  - The module's *interface* is its set of public functions, `typedef`s, 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 declarations and definitions for consistency

`#include` and the C Preprocessor

- The C preprocessor (`cpp`) transforms your source code before the compiler runs – it's a simple copy-and-replace text processor(!) with a memory
  - 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, then system

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;
}
```

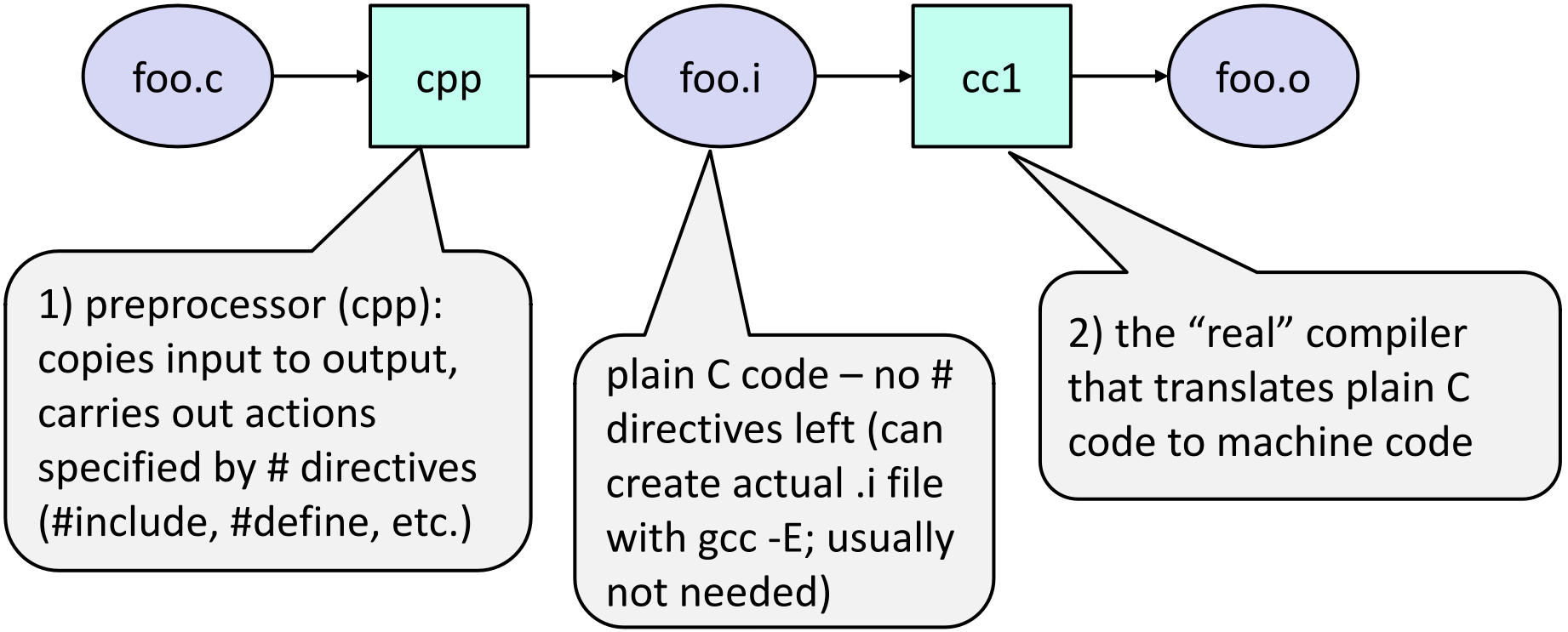
cpp_example.c

```
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;
}
```

What Is gcc Really Doing?

- gcc is actually a pretty simple program that runs the actual programs that do the real work. Here's what gcc runs to translate foo.c to foo.o (gcc -c foo.c):



Program Using a Linked List

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

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

ll.c

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

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

ll.h

```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 EXIT_SUCCESS;
}
```

example_ll_customer.c

Compiling the Program

- Four parts:
  - 1) Compile `example_ll_customer.c` into an object file
  - 2) 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 (local) function has its 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
  - 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()`