Structs, Modules

CSE 333 Summer 2023

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Relevant Course Information

- HW0 Uploaded and graded
  - If you do not see a submission for HW0 on Gradescope, make a private Ed post.
- Homework 1 due a week from Thursday
  - You should be well under way now
  - Be sure to read headers *carefully* while implementing
  - Use git add/commit/push regularly to save work – easier to share with partner and course staff
- Section this week will involve group debugging!
  - Be prepared to draw memory diagrams and use your terminal (bring a laptop!)

Lecture Outline

- `structs` and `typedef`
- Generic Data Structures in C
- Modules & Interfaces

Structured Data (351 Review)

- A `struct` is a C datatype that contains a set of fields
  - Similar to a Java class, but with no methods or constructors
  - Useful for defining new structured types of data
  - Behave similarly to primitive variables

- Generic declaration:

```
struct tagname {
  type1 name1;
  ...
  typeN nameN;
};
```

```
// the following defines a new
// structured datatype called
// a "struct Point"
struct Point {
  float x, y;
};

// declare and initialize a
// struct Point variable
struct Point origin = {0.0,0.0};
```

Using structs (351 Review)

- Use “ . ” to refer to a field in a struct
- Use “->” to refer to a field from a struct pointer
  - Dereferences pointer first, then accesses field

```
struct Point {
  float x, y;
};

int main(int argc, char** argv) {
  struct Point p1 = {0.0, 0.0};  // p1 is stack allocated
  struct Point* p1_ptr = &p1;

  p1.x = 1.0;
  p1_ptr->y = 2.0;  // equivalent to (*p1_ptr).y = 2.0;
  return EXIT_SUCCESS;
}
```

simplestruct.c

Copy by Assignment

- You can assign the value of a struct from a struct of the same type – *this copies the entire contents!*

```
struct Point {
  float x, y;
};

int main(int argc, char** argv) {
  struct Point p1 = {0.0, 2.0};
  struct Point p2 = {4.0, 6.0};

  printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
  p2 = p1;
  printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
  return EXIT_SUCCESS;
}
```

structassign.c

Typedef (351 Review)

- Generic format: `typedef type name;`
- Allows you to define new data type *names/synonyms*
  - Both `type` and `name` are usable and refer to the same type
  - Be careful with pointers – `*` before `name` is part of `type`!

```
// make "superlong" a synonym for "unsigned long long"
typedef unsigned long long superlong;

// make "str" a synonym for "char*"
typedef char *str;

// make "Point" a synonym for "struct point_st { ... }"
// make "PointPtr" a synonym for "struct point_st*"
typedef struct point_st {
  superlong x;
  superlong y;
} Point, *PointPtr;  // similar syntax to "int n, *p;"

Point origin = {0, 0};
```

Dynamically-allocated Structs

- You can `malloc` and `free` structs, just like other data type
  - `sizeof` is particularly helpful here

```
// a complex number is a + bi
typedef struct complex_st {
  double real;    // real component
  double imag;    // imaginary component
} Complex;

Complex* AllocComplex(double real, double imag) {
  Complex* retval = (Complex*) malloc(sizeof(Complex));
  if (retval != NULL) {
    retval->real = real;
    retval->imag = imag;
  }
  return retval;
}
```

complexstruct.c

Structs as Arguments

- Structs are passed by value, like everything else in C
  - Entire struct is copied – where?
  - To manipulate a struct argument, pass a pointer instead

structarg.c

```
typedef struct point_st {
  int x, y;
} Point;

void DoubleXBroken(Point p)   {  p.x *= 2; }

void DoubleXWorks(Point* p) { p->x *= 2; }

int main(int argc, char** argv) {
  Point a = {1,1};
  DoubleXBroken(a);
  printf("(%d,%d)\n", a.x, a.y);   // prints: (  ,  )
  DoubleXWorks(&a);
  printf("(%d,%d)\n", a.x, a.y);   // prints: (  ,  )
  return EXIT_SUCCESS;
}
```

Returning Structs

- Exact method of return depends on calling conventions
  - Often in `%rax` and `%rdx` for small structs
  - Often returned in memory for larger structs

```
// a complex number is a + bi
typedef struct complex_st {
  double real;     // real component
  double imag;     // imaginary component
} Complex;

Complex MultiplyComplex(Complex x, Complex y) {
  Complex retval;

  retval.real = (x.real * y.real) - (x.imag * y.imag);
  retval.imag = (x.imag * y.real) - (x.real * y.imag);
  return retval;  // returns a copy of retval
}
```

complexstruct.c

Pass Copy of Struct or Pointer?

STYLE TIP

- Value passed: passing a pointer is cheaper and takes less space unless struct is small
- Field access: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize
- For small stucts (like `struct complex_st`), passing a copy of the struct can be faster and often preferred if function only reads data; for large structs use pointers

Check-In Activity

- Write out a C snippet that:
  - Defines a struct for a linked list node that holds (1) a character pointer and (2) a pointer to an instance of this struct
  - Typedefs the struct as `Node`

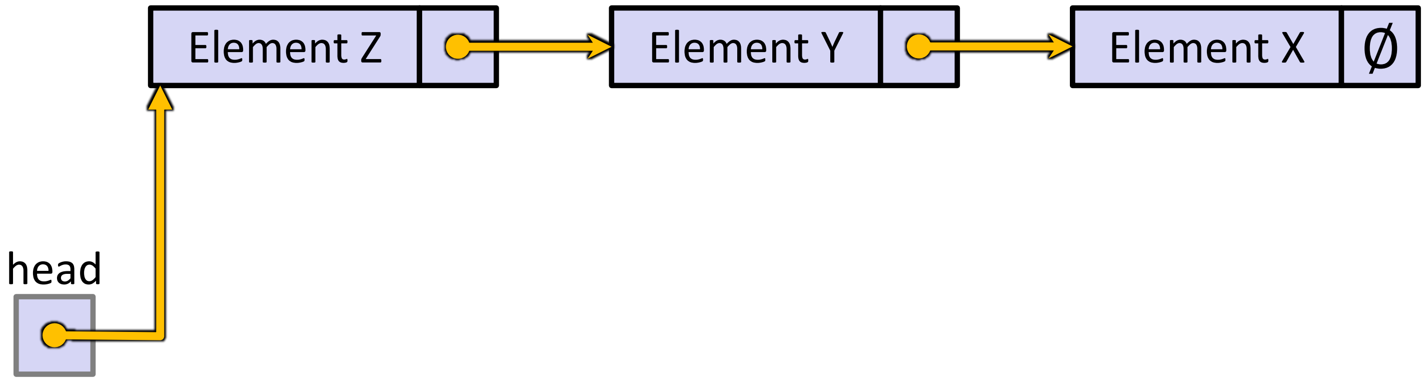
- Write out the prototype for a function **`Pop`** that takes the head of a linked list of `Node`, then removes and returns the first node:

Lecture Outline

- `struct`s and `typedef`
- **Generic Data Structures in C**
- Modules & Interfaces

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

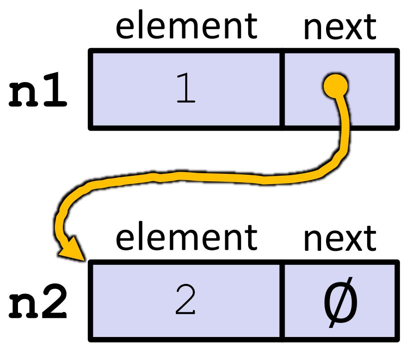
- Let's represent a linked list node with a struct
  - For now, assume each element is an `int`

```
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;
}
```

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 EXIT_SUCCESS;
}
```

push_list.c

(main) list ∅

Push Onto List

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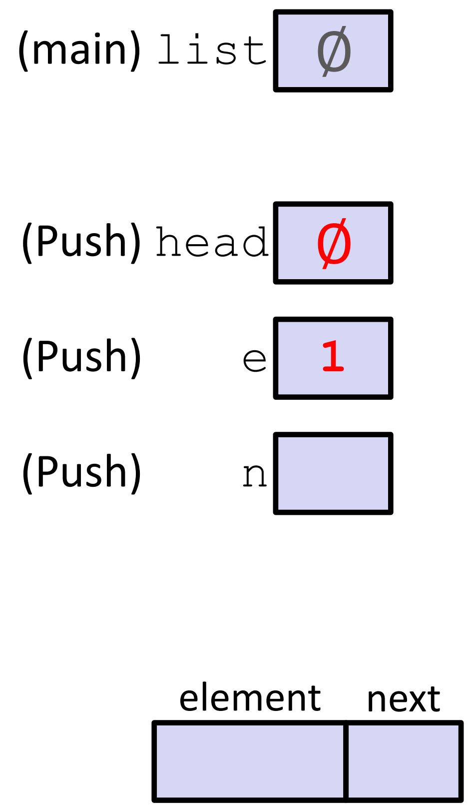
  list = Push(list, 2);
  return EXIT_SUCCESS;
}
```



push_list.c

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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 EXIT_SUCCESS;
}
```

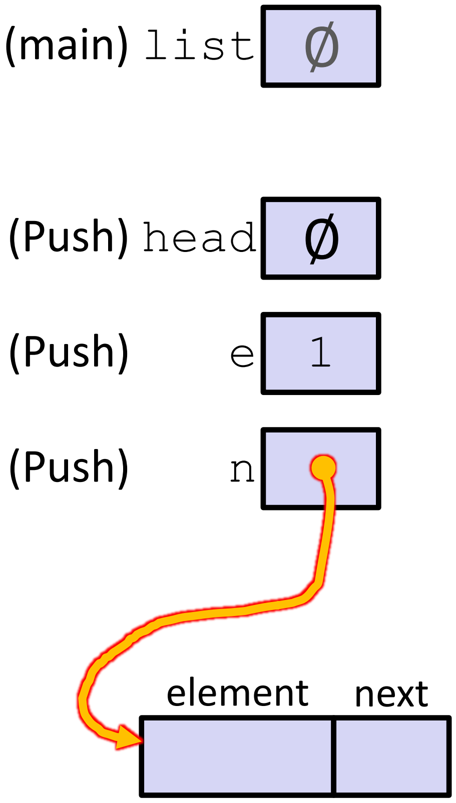

push_list.c

Push Onto List

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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) {
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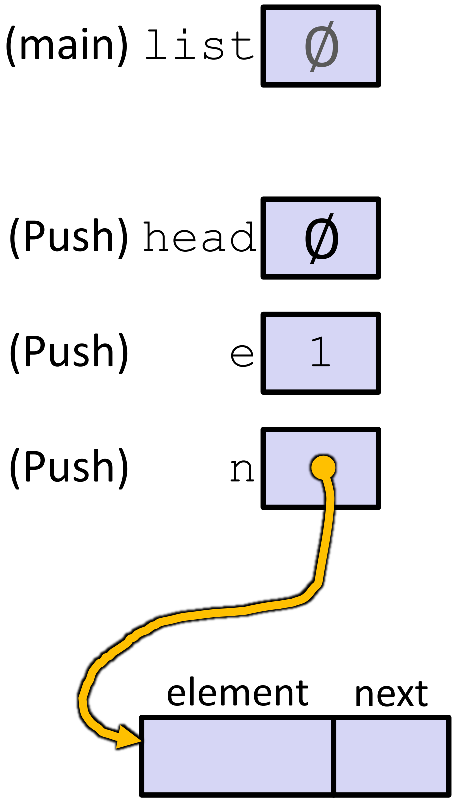
}
```

push_list.c



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  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;
}
```

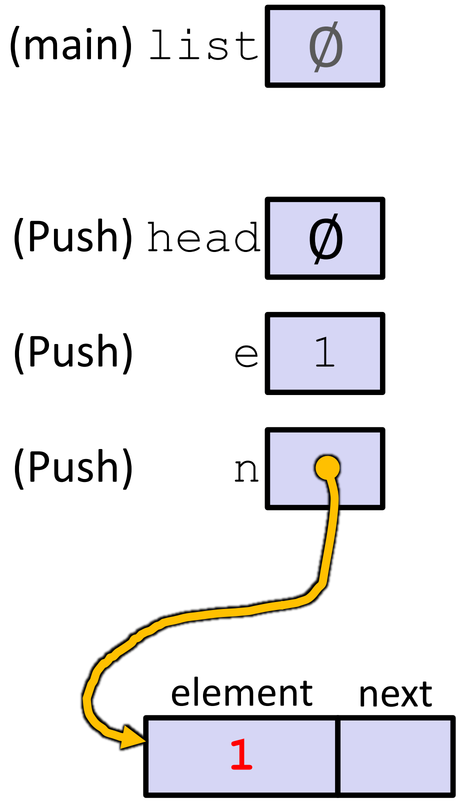

push_list.c

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} Node;

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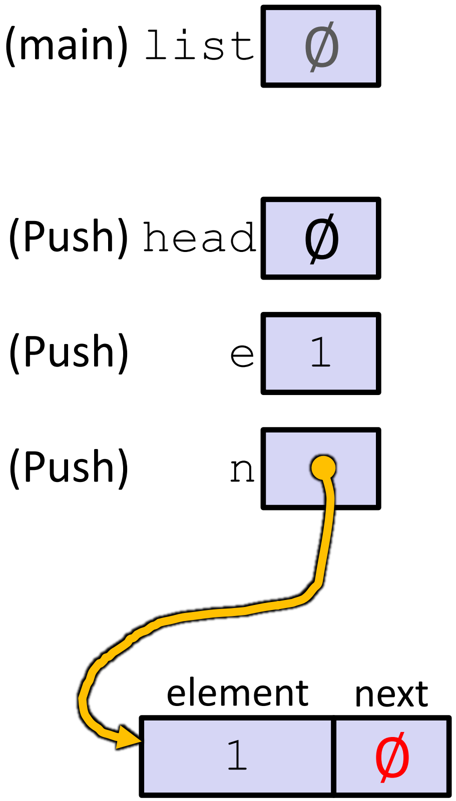
  Node* n = (Node*) malloc(sizeof(Node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}

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



push_list.c

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  n->next = head;
  return n;
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  return EXIT_SUCCESS;
}
```
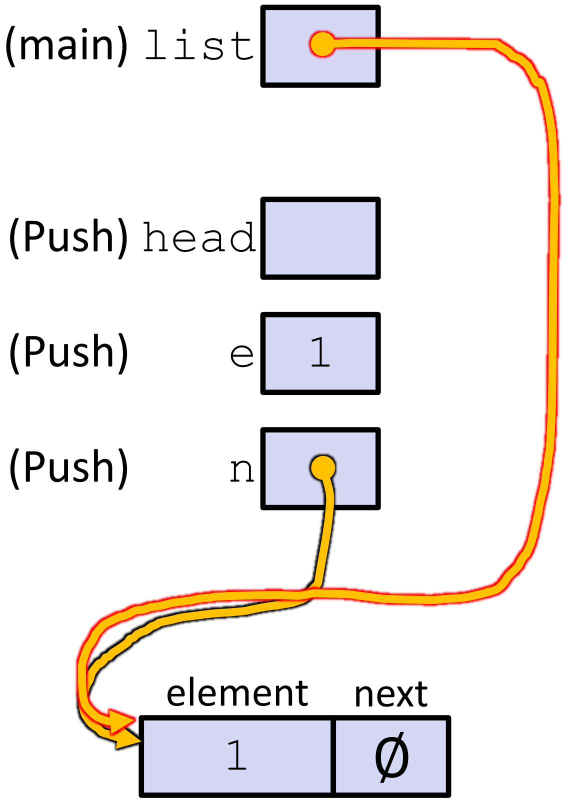

push_list.c



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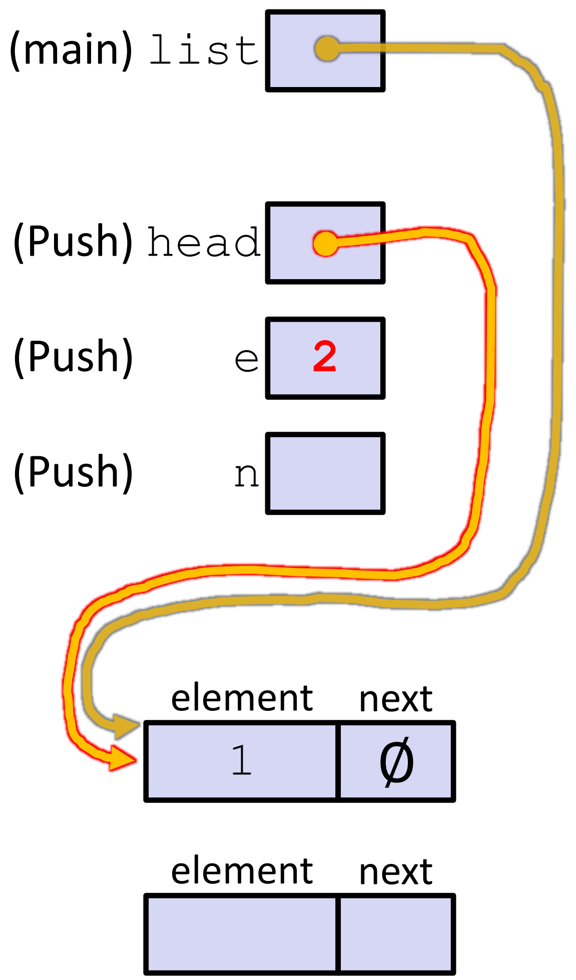
  Node* list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return EXIT_SUCCESS;
}
```

push_list.c



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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);
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```
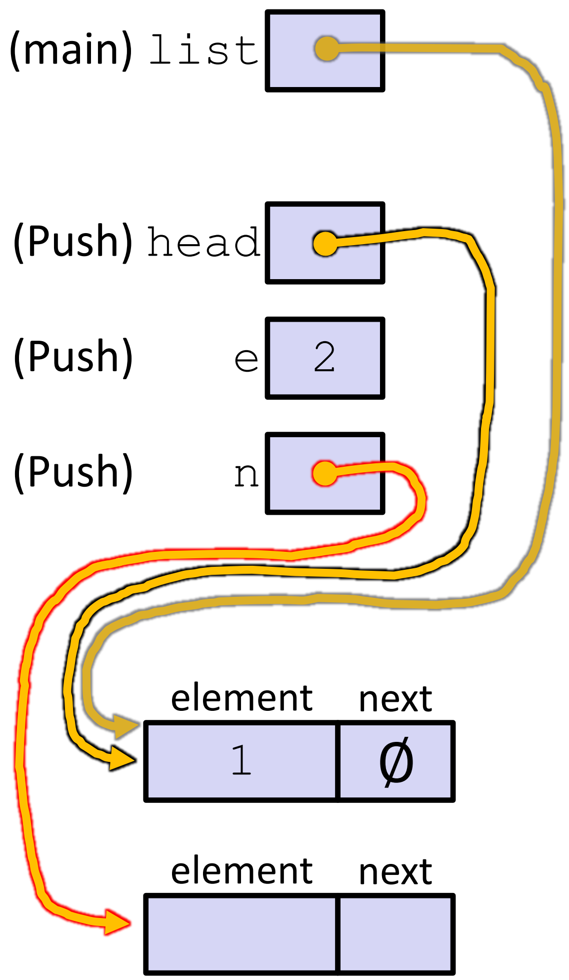

push_list.c



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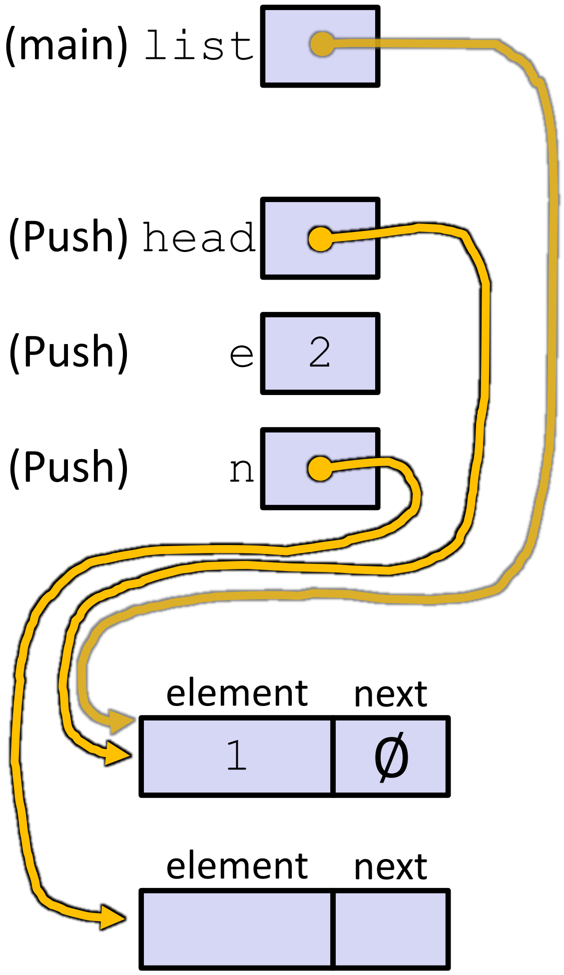
push_list.c



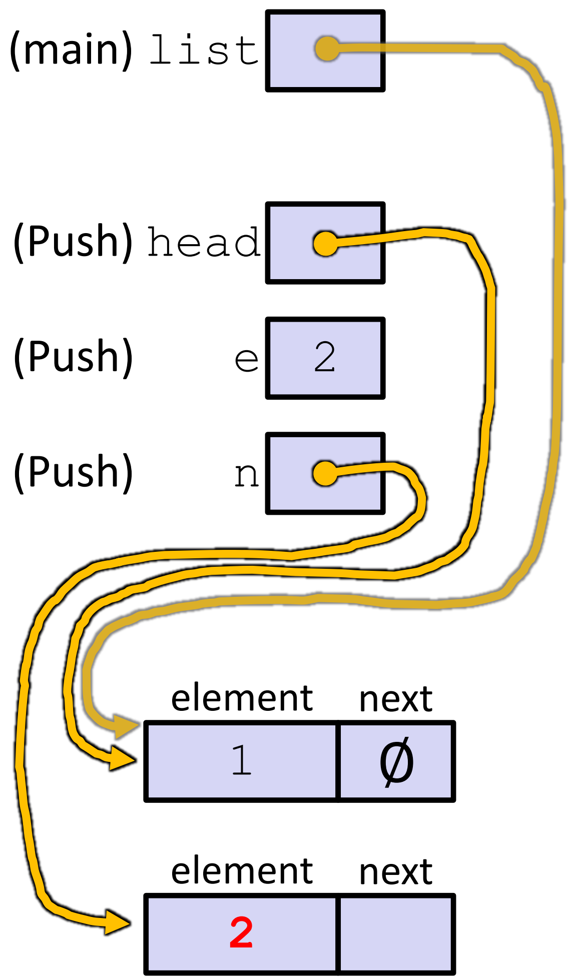
Push Onto List

Arrow points to *next* instruction.

```c
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 EXIT_SUCCESS;
}
```



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;
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  return n;
}

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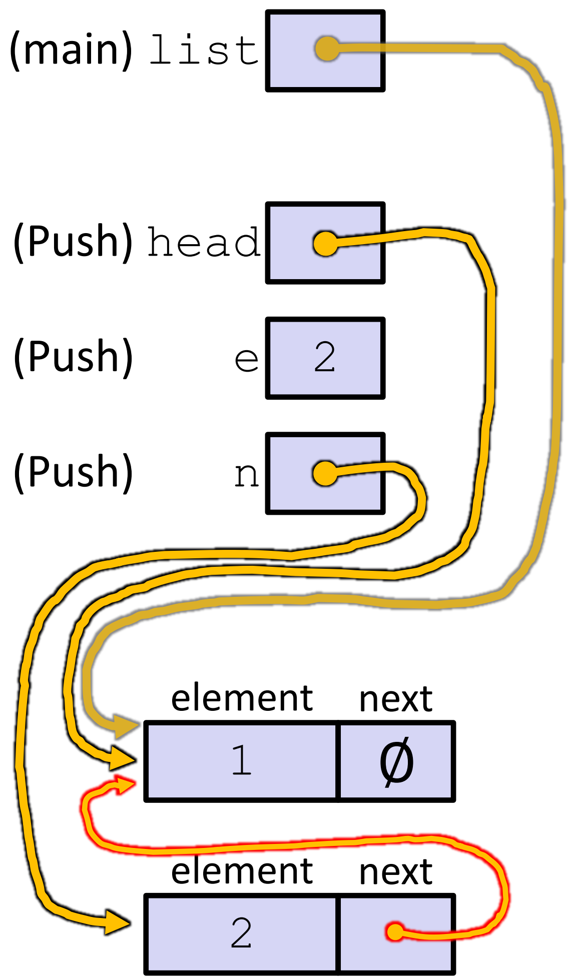
  return EXIT_SUCCESS;
}
```

push_list.c



Push Onto List

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

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

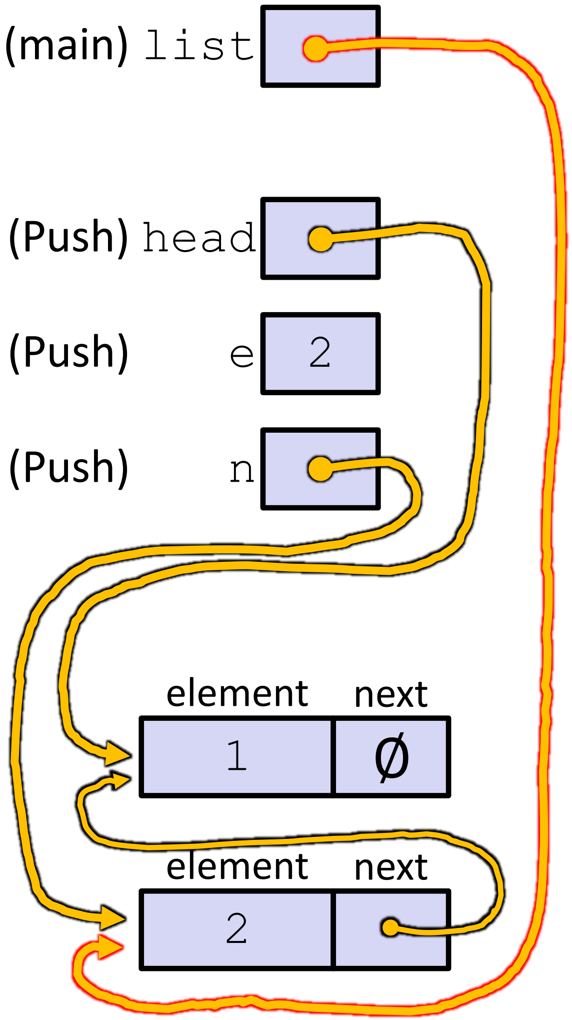

push_list.c

Push Onto List

Arrow points to *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 EXIT_SUCCESS;
}
```
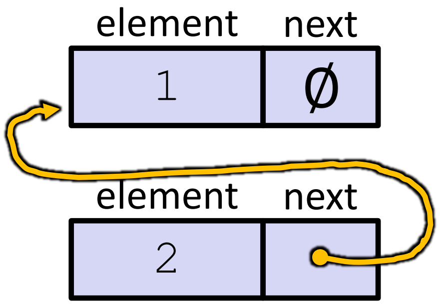
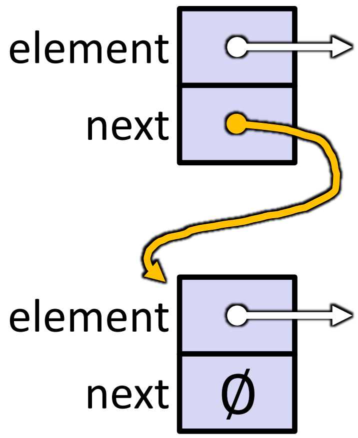

push_list.c



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;
}
```



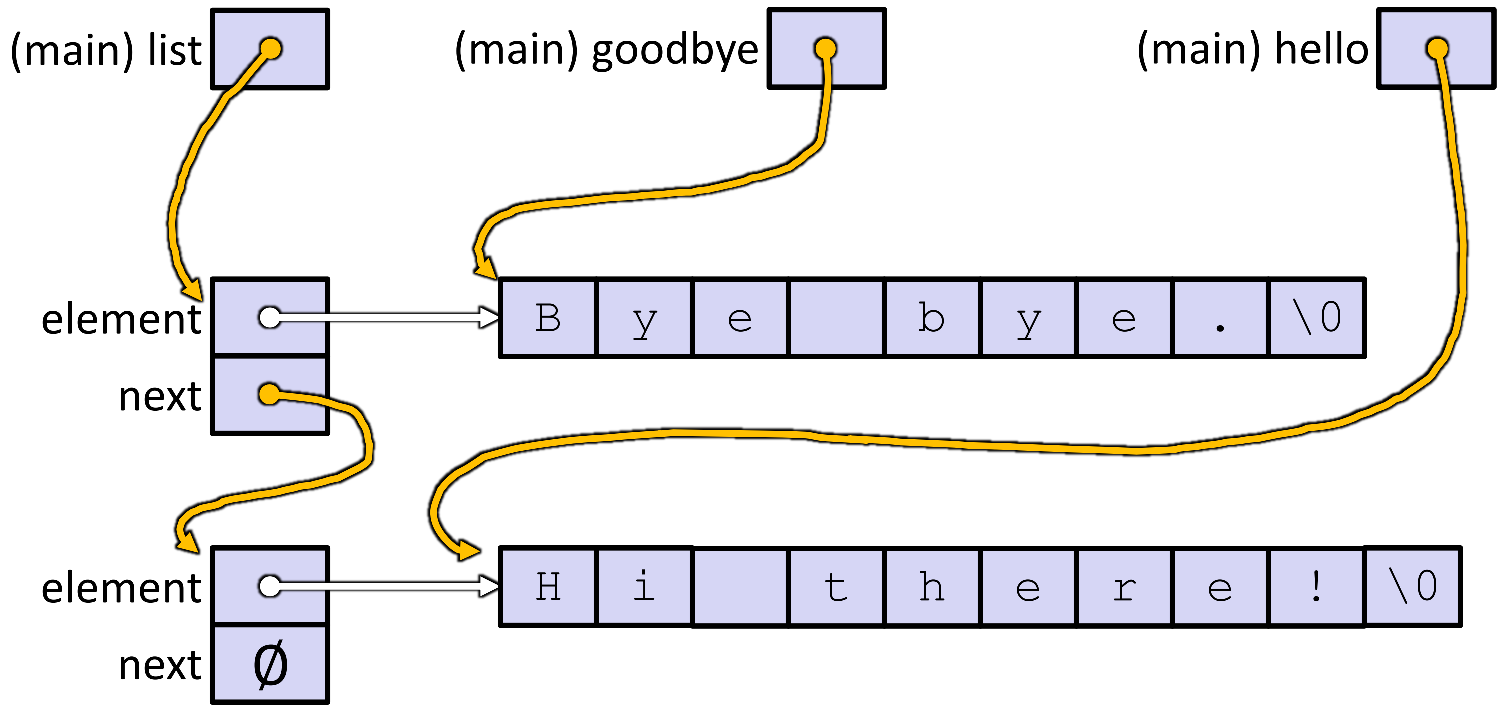
Using a Generic Linked List

- 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



What would happen if we execute `*(list->next) = *list`?

Something's Fishy...

- A (benign) memory leak!

```
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);
  return EXIT_SUCCESS;
}
```

- Try running with Valgrind:

```
$ gcc -Wall -g -o manual_list_void manual_list_void.c
$ valgrind --leak-check=full ./manual_list_void
```

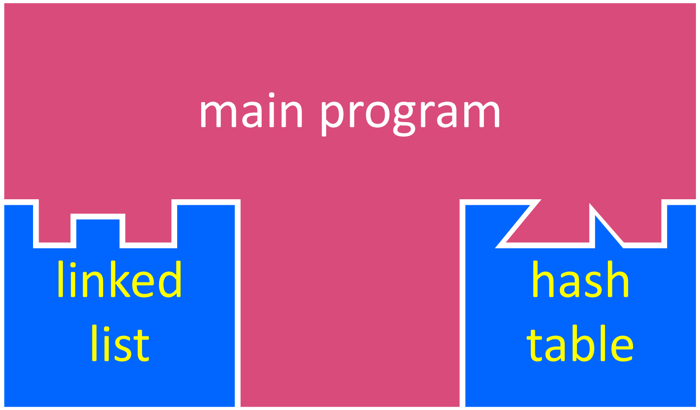
Lecture Outline

- `struct`s and `typedef`
- Generic Data Structures in C
- **Modules & Interfaces**

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
  - Can be developed independently and re-used in different projects

- The module's *interface* is its set of public functions, `typedef`s, and global variables



C Header Files

- Header: a 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
  - There are <system-defined> and "programmer-defined" headers

- 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 (1 of 2)

STYLE TIP

- File contents:
  - `.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
  - Public-facing functions are **`ModuleName_FunctionName`**`()` and take a pointer to "`this`" as their first argument
- Including:
  - ***NEVER*** `#include` a `.c` file – only `#include .h` files
  - `#include` all of headers you reference, even if another header (transitively) includes some of them
- Compiling:
  - Any `.c` file with an associated `.h` file should be able to be compiled (together via `#include`) into a `.o` file

C Module Conventions (2 of 2)

STYLE TIP

- Commenting:
  - 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*
    - Don't copy-paste the comment into the C file (don't want two copies that can get out of sync)
  - If prototype and implementation are in the same C file:
    - School of thought #1: Full comment on the prototype at the top of the file, no comment (or "declared above") on code
    - School of thought #2: Prototype is for the compiler and doesn't need comment; comment the code to keep them together

e.g., 333 project code

What the `#include`?

- We need function declarations before we can use them, but all we've been doing is `#include`'ing libraries and modules.
  - How do the declarations end up in our `.c` file/program?

- Before our code is compiled, the **C preprocessor** processes our code and replaces things like `#include` with the corresponding text content.

Extra Exercise #1

- Write a program that defines:
  - A new structured type Point
    - Represent it with `float`s for the x and y coordinates
  - A new structured type Rectangle
    - Assume its sides are parallel to the x-axis and y-axis
    - Represent it with the bottom-left and top-right Points
  - A function that computes and returns the area of a Rectangle
  - A function that tests whether a Point is inside of a Rectangle

Extra Exercise #2

- Implement `AllocSet()` and `FreeSet()`
  - AllocSet() needs to use malloc twice: once to allocate a new ComplexSet and once to allocate the "points" field inside it
  - FreeSet() needs to use free twice

```
typedef struct complex_st {
  double real;     // real component
  double imag;     // imaginary component
} Complex;

typedef struct complex_set_st {
  double   num_points_in_set;
  Complex* points;         // an array of Complex
} ComplexSet;

ComplexSet* AllocSet(Complex c_arr[], int size);
void FreeSet(ComplexSet* set);
```

Extra Exercise #3

- 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 #4

- Implement a Complex number module
  - `complex.c`, `complex.h`
  - Includes a typedef to define a complex number
    - a + bi, where a and b are `double`s
  - Includes functions to:
    - add, subtract, multiply, and divide complex numbers
  - Implement a test driver in `test_complex.c`
    - Contains `main()`