Data Structures

CSE 333 Winter 2020

Instructor: Justin Hsia

Teaching Assistants:

Andrew Hu
Austin Chan
Brennan Stein
Cheng Ni
Cosmo Wang
Diya Joy
Guramrit Singh
Mengqi Chen
Pat Kosakanchit
Rehaan Bhimar
Renshu Gu
Travis McGaha
Zachary Keyes

Administrivia

- ex0 grades released, ex3 released today
  - Regrade requests: open 24 hr after, close 72 hr after release
- We *highly* recommend doing the extra exercises
  - Also, can Google for "C pointer exercises"
  - You MUST master pointers quickly, or you'll have trouble the rest of the course (including hw1)
- hw0 due tonight *before* 11:59 pm (and 0 seconds)
  - Git: add/commit/push, then tag with `hw0-final`, then push tag
    - Then clone your repo somewhere totally different and do `git checkout hw0-final` and verify that all is well

Administrivia

- hw1 due Thursday, 1/23
  - You ***may not*** modify interfaces (`.h` files)
  - But ***do*** read the interfaces while you're implementing them(!)
  - New this qarter: maintain a bug journal
  - Suggestion: look at `example_program_{ll|ht}.c` for typical usage of lists and hash tables

- GitLab repo usage
  - Commit things regularly (not 1 massive commit on due date)
    - Newly completed units of work, milestones, project parts, etc.
  - Provides backup – can retrieve old versions of files ☺
  - Don't push `.o` and executable files or other build products (not portable)

Lecture Outline

- **Heap-allocated Memory**
  - **Memory leaks**
- `structs` and `typedef`
- Implementing Data Structures in C

Dynamic Allocation Function Review

- malloc: `var = (type*) malloc(size in bytes)`
  - Returns a `void*` to uninitialized heap memory
    - Returns `NULL` to indicate failure
  - Should use `sizeof()` and explicit cast; error check return value

- free: `free(pointer);`
  - Pointer *must* point to the first byte of heap-allocated memory
    - Will do nothing if passed `NULL`
  - Undefined behavior (often program crash) otherwise
  - Doesn't change the value of the pointer

Polling Question

- Which line below is first *guaranteed* to cause either an error or undefined behavior?
  - Vote at http://PollEv.com/justinh

A. Line 1
B. Line 4
C. Line 6
D. Line 7
E. We're lost…

```
int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

1 a[2] = 5;      <- write past end of array
2 b[0] += 2;     <- using garbage, didn't check for NULL
3 c = b+3;       <- pointer past allocated block
4 free(&(a[0])); <- free stack address
5 free(b);
6 free(b);       <- freeing previously-freed address
7 b[0] = 5;      <- using freed pointer

  return EXIT_SUCCESS;
}
```

Memory Corruption

- There are all sorts of ways to corrupt memory in C

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

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;    // assign past the end of an array
  b[0] += 2;   // assume malloc zeros out memory
  c = b+3;     // mess up your pointer arithmetic
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed pointer

  // any many more!
  return EXIT_SUCCESS;
}
```

memcorrupt.c

Memory Leak

- A memory leak occurs when code fails to deallocate dynamically-allocated memory that is no longer used
  - *e.g.* forget to `free` malloc-ed block, lose/change pointer to malloc-ed block

- What happens: program's VM footprint will keep growing
  - This might be OK for *short-lived* program, since all memory is deallocated when program ends
  - Usually has bad repercussions for *long-lived* programs
    - Might slow down over time (*e.g.* lead to VM thrashing)
    - Might exhaust all available memory and crash
    - Other programs might get starved of memory

Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks
- **`structs` and `typedef`**
- Implementing Data Structures in C

Structured Data

- 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};
```

type name

works even if fields are different types

Using structs

- 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

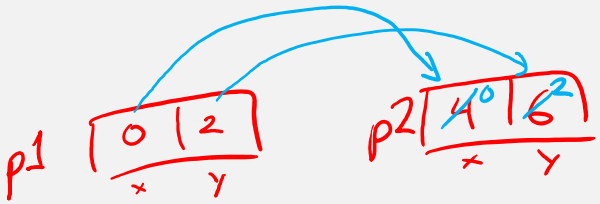
Copy by Assignment

- 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

- 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};
```

type

name

expands similarly to: unsigned int n, *p; ⟺ unsigned int n; unsigned int *p;

typedef struct point_st Point PointPtr

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, *ComplexPtr;

// note that ComplexPtr is equivalent to Complex*
ComplexPtr AllocComplex(double real, double imag) {
  Complex* retval = (Complex*) malloc(sizeof(Complex));
  if (retval != NULL) {
    retval->real = real;
    retval->imag = imag;
  }
  return retval;
}
```

these are equivalent

complexstruct.c

Structs as Arguments

- Structs are passed by value, like everything else in C
  - Entire struct is copied – where? if too large for register, then on Stack (argument build of caller)
  - To manipulate a struct argument, pass a pointer instead

structarg.c

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

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

void DoubleXWorks(PointPtr 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: (1,1)
  DoubleXWorks(&a);
  printf("(%d,%d)\n", a.x, a.y);    // prints: (2,1)
  return EXIT_SUCCESS;
}
```

only modifies local copy

modifies caller's data

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, *ComplexPtr;

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
}
```

OK to return local struct because values can be assigned to another struct

complexstruct.c

Pass Copy of Struct or Pointer?

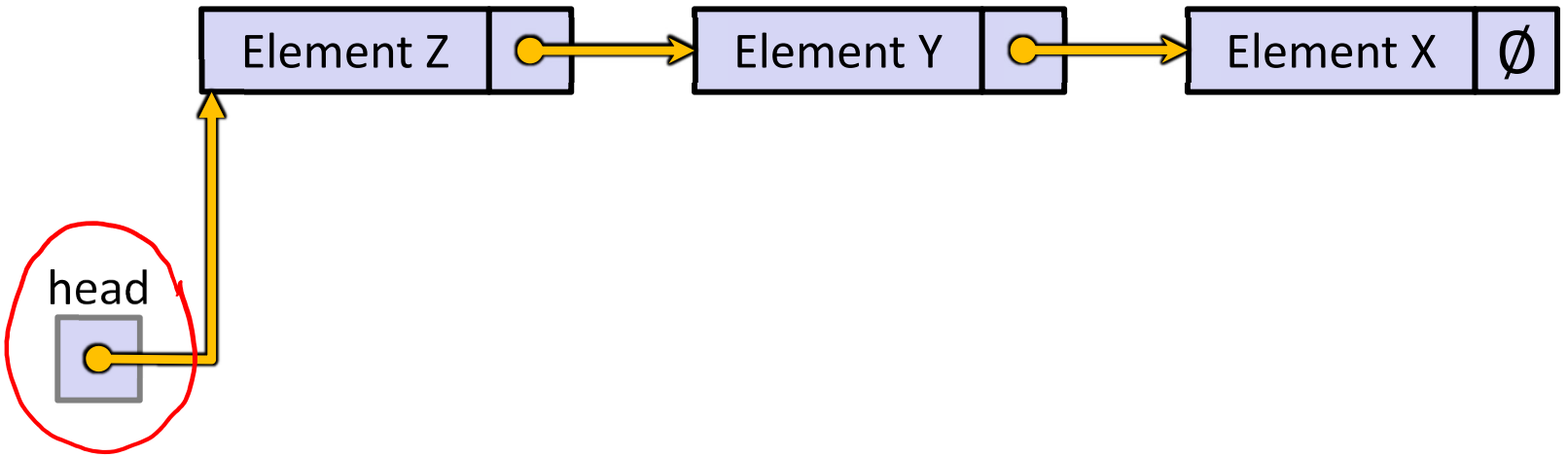
- Value passed: passing a pointer is cheaper and takes less space unless struct is small (≤ sizeof(void*))
- Field access: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize dereference = access memory
- For small stucts (like `struct complex_st`),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

Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks
- `structs` and `typedef`
- **Generic Data Structures in C**

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
  - Assume each element is an `int32_t`

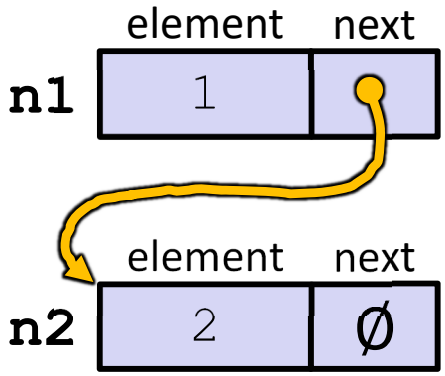
```
typedef struct node_st {
  int32_t element;
  struct node_st* next;
} Node;

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

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

tagname is necessary because pointer to it is part of struct definition

n1 ← on Stack



manual_list.c

Push Onto List

Arrow points to *next* instruction.

```
typedef struct node_st {
  int32_t element;
  struct node_st* next;
} Node;

                    NULL        1
Node* Push(Node* head, int32_t 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

push_list.c

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  return n;
}

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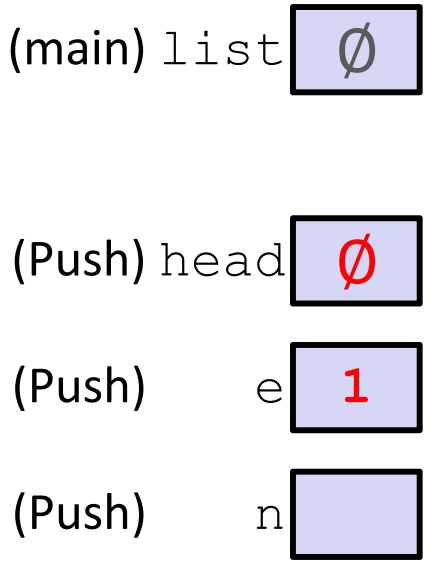
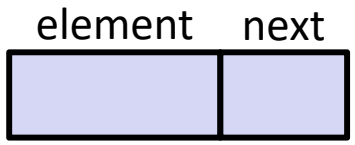
  list = Push(list, 2);
  return EXIT_SUCCESS;
}
```

push_list.c





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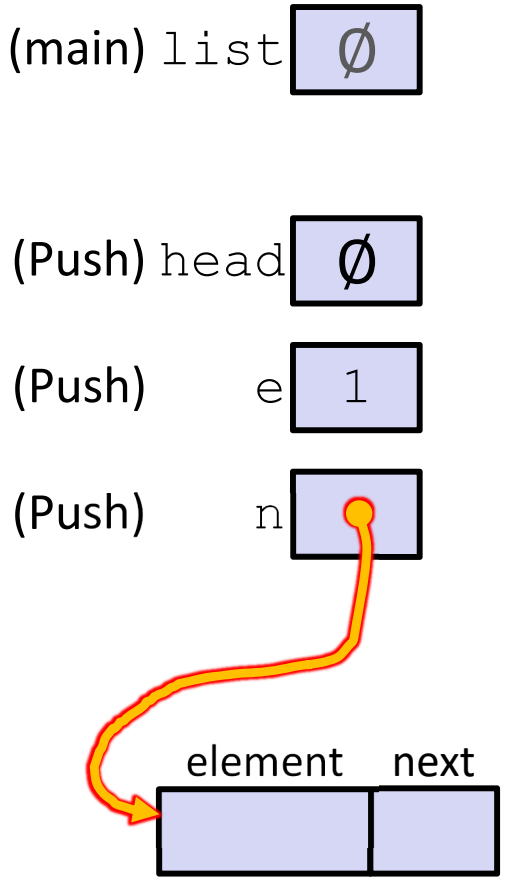
push_list.c



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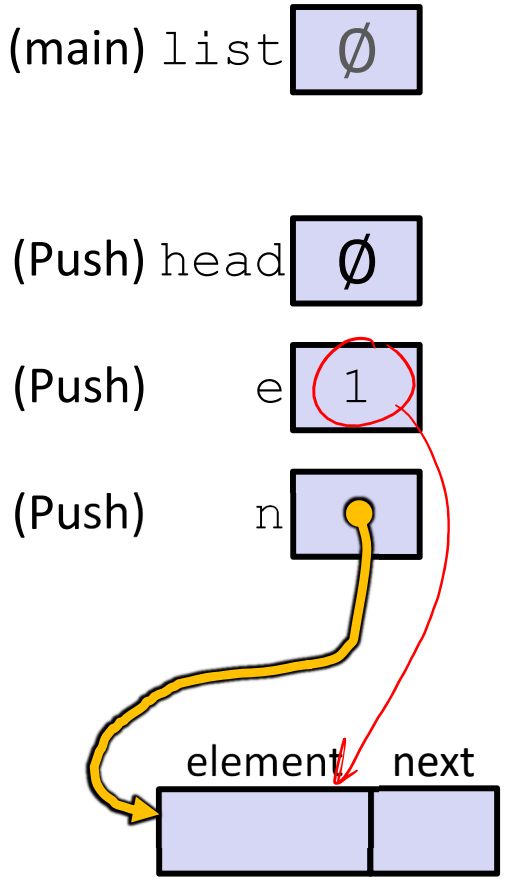
push_list.c



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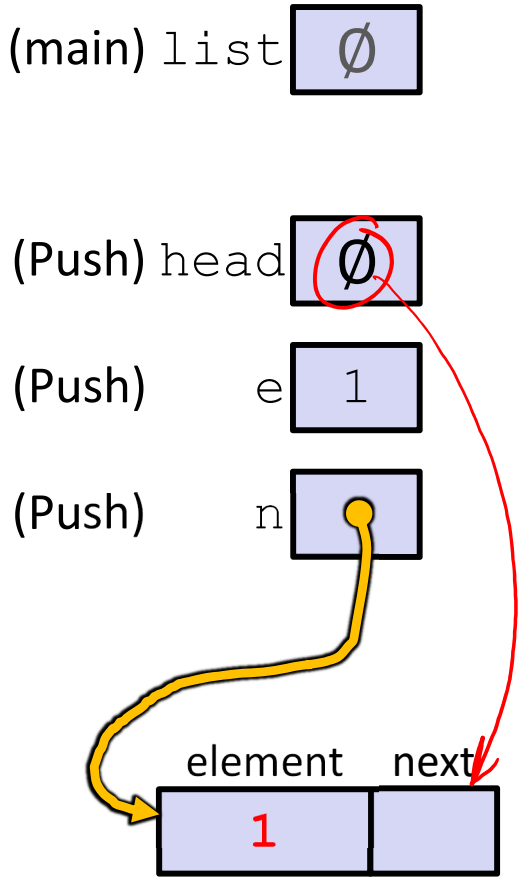
push_list.c



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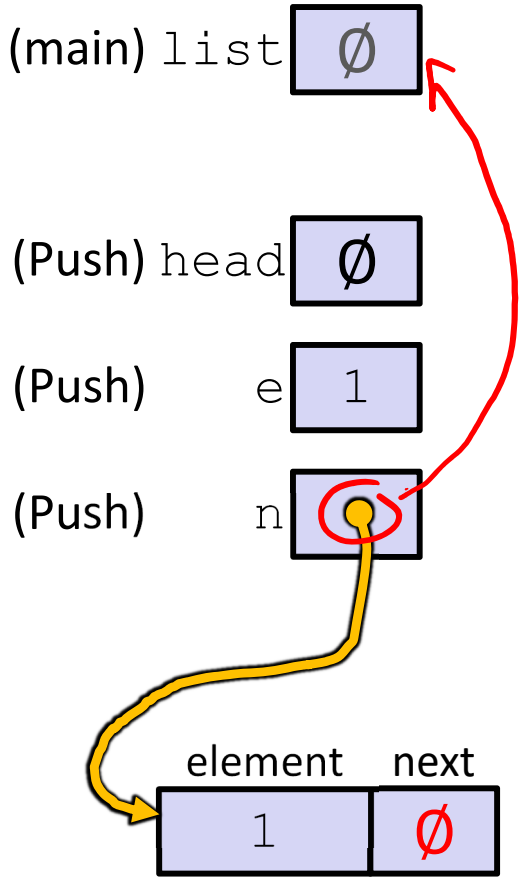

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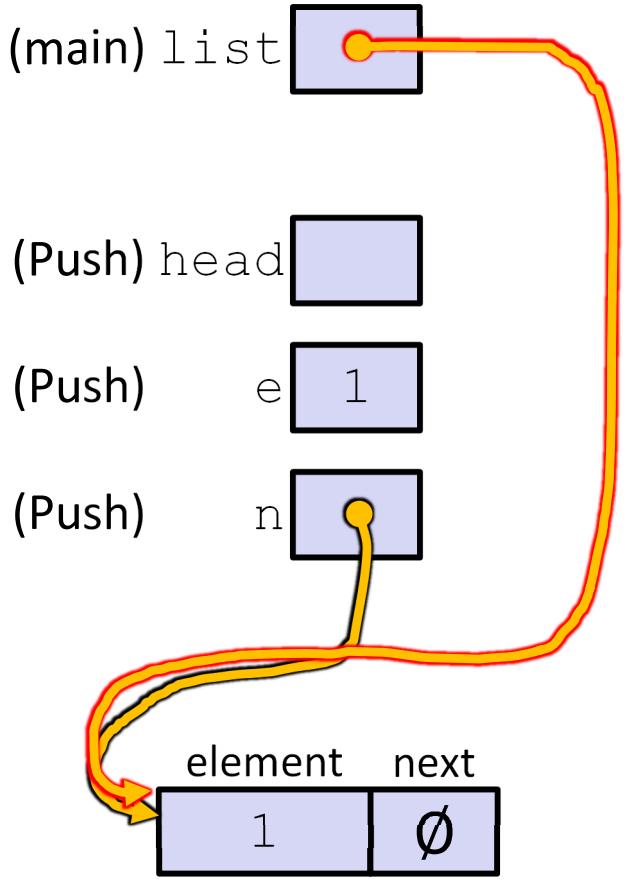

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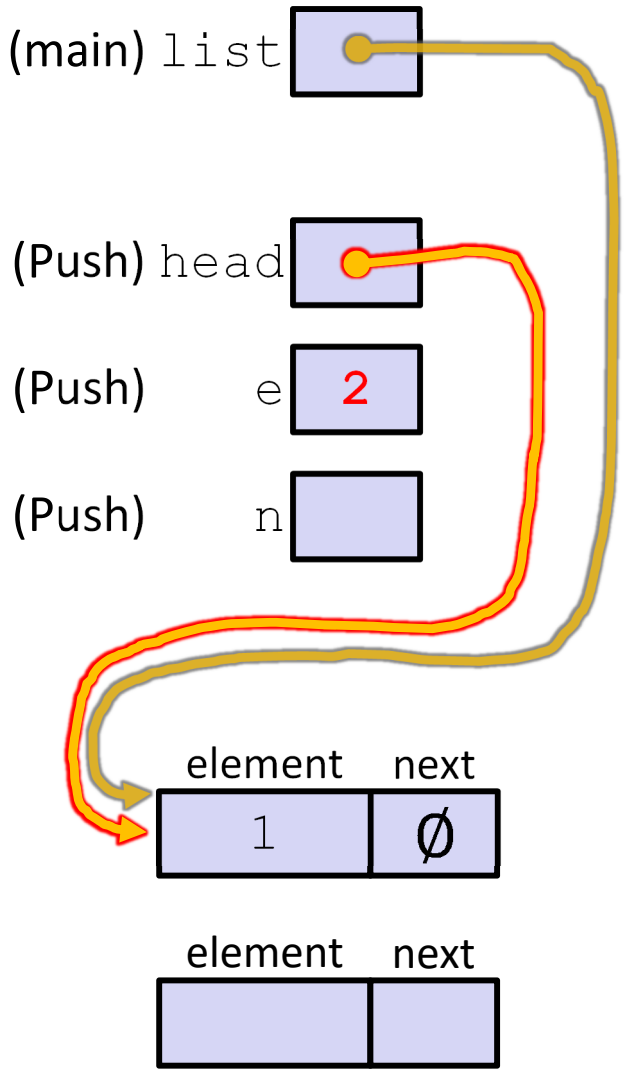

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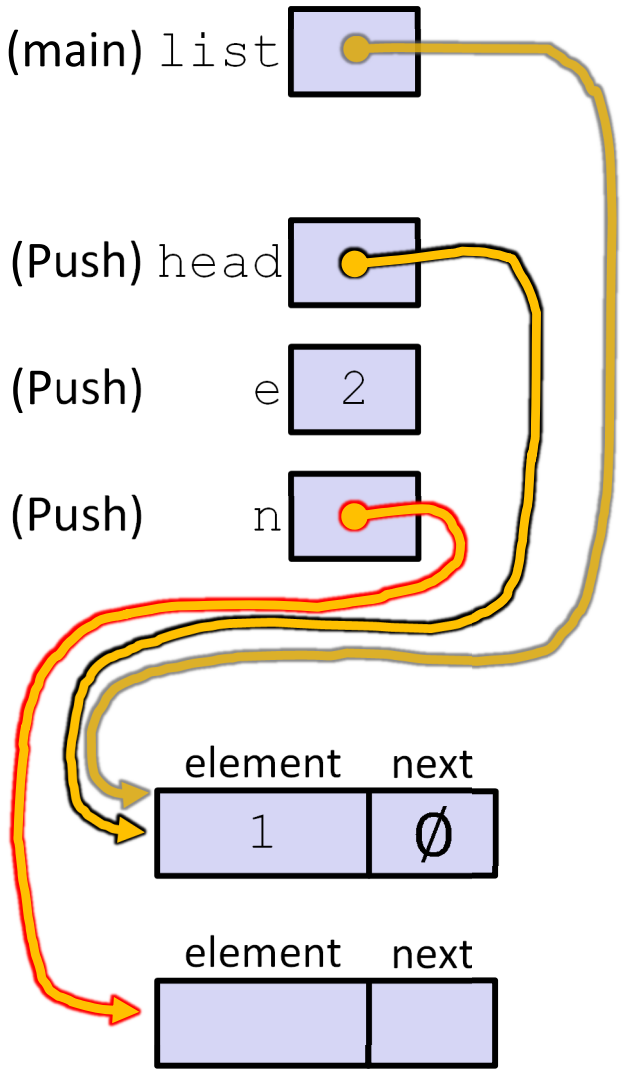

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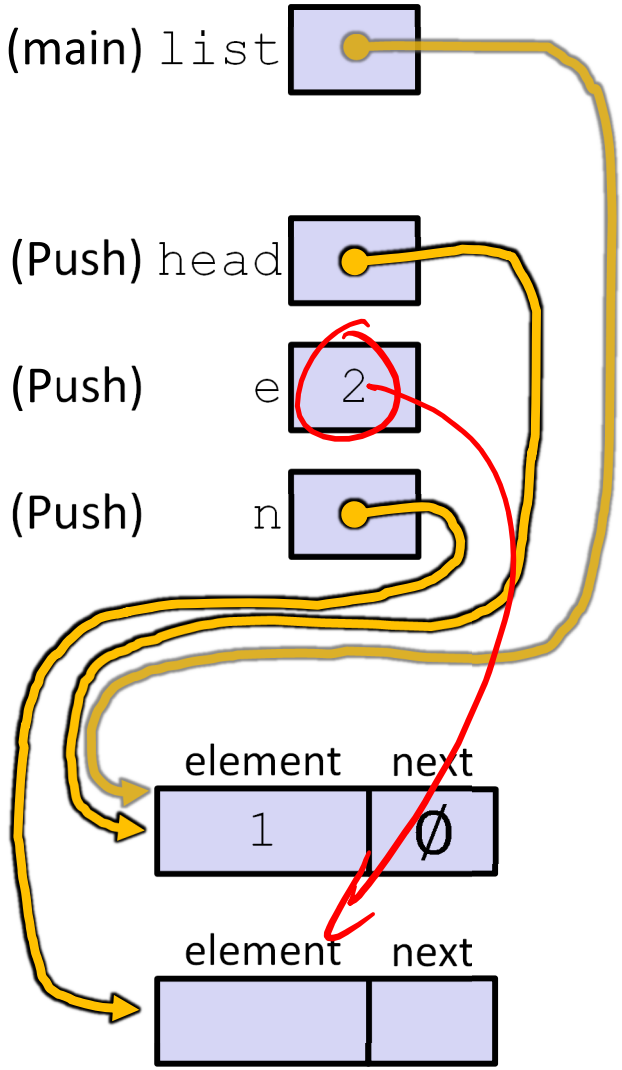

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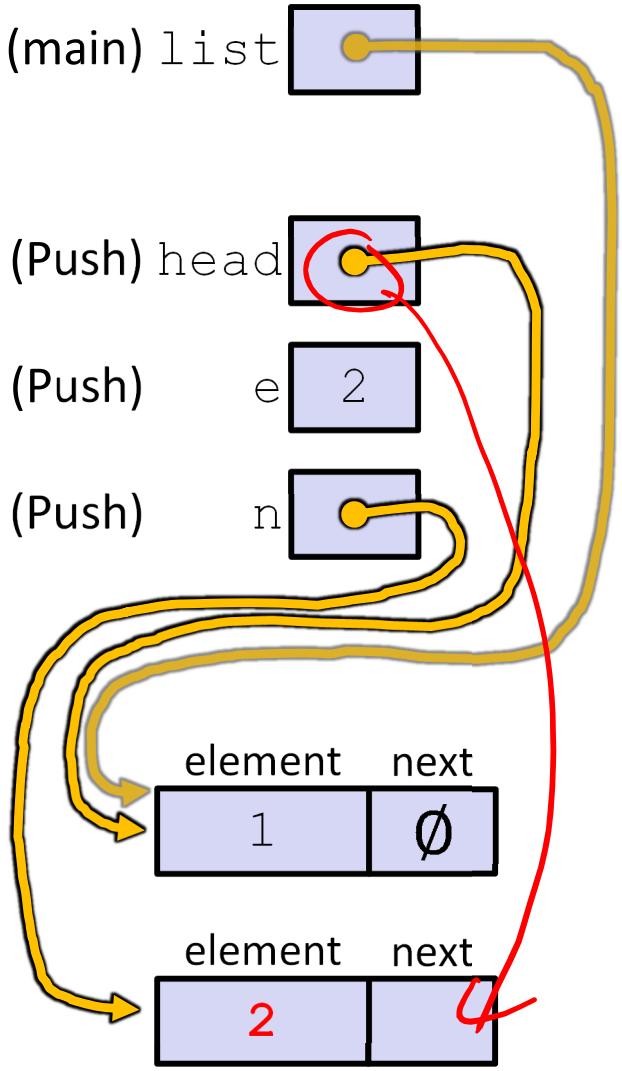

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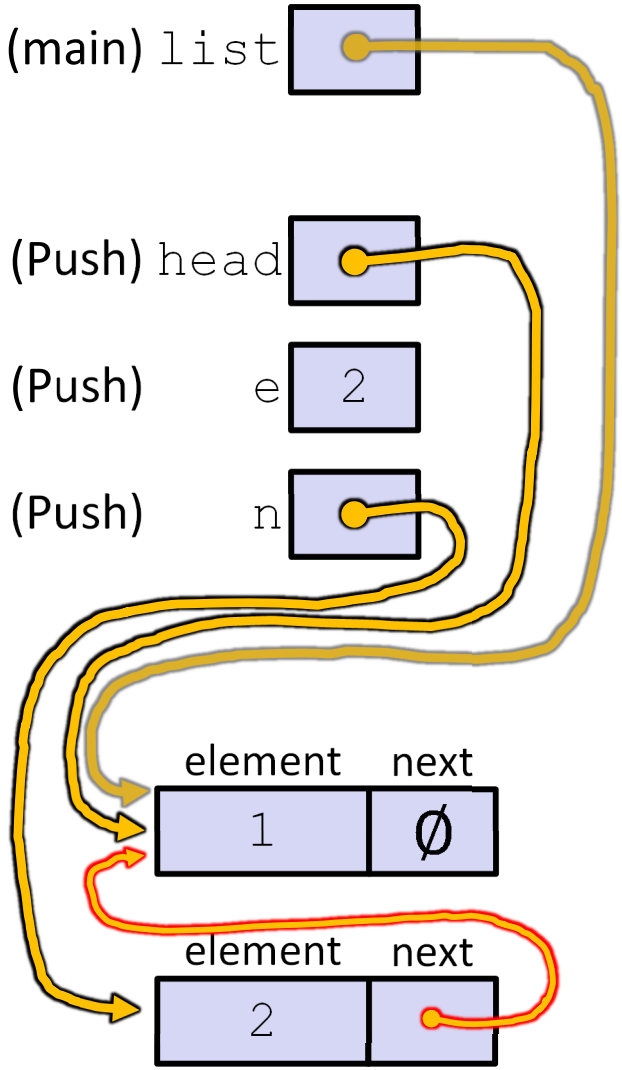

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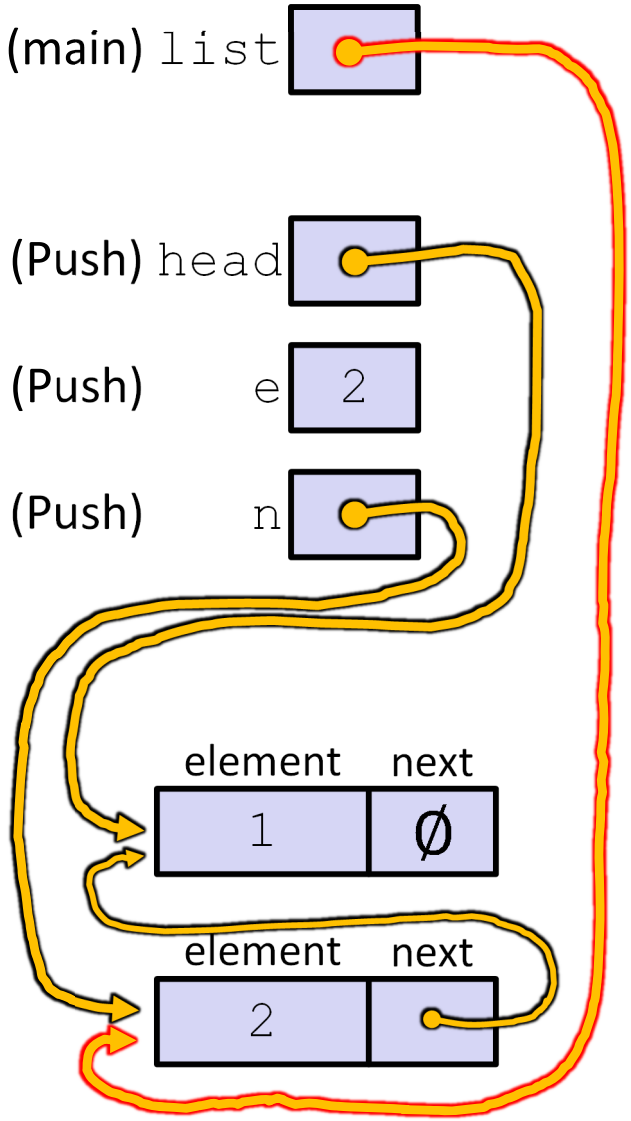

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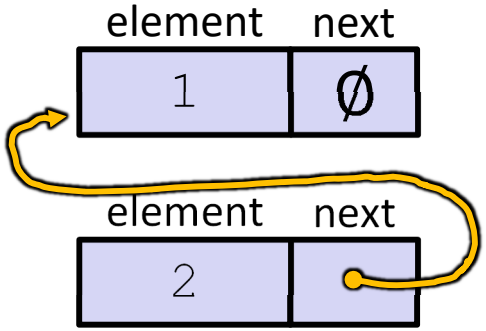
push_list.c

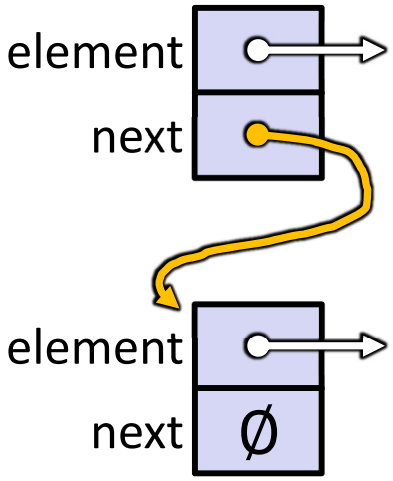


A Generic Linked List

- Let's generalize the linked list element type
  - Let customer decide type (instead of always `int32_t`)
  - 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

Extra Exercise #1

- Write a program that defines:
  - A new structured type Point
    - Represent it with `floats` 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

- 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