Structs, Modules
CSE 333 Winter 2023

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Relevant Course Information

❖ Exercise grades
  ▪ We will be giving “autograder correction” points
  ▪ Regrade requests: open 24 hr after, close 72 hr after release

❖ 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 for drawing memory diagrams and using your terminal
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:**

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

```c
// 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};

- Works even if fields are different types
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

```c
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!*

```c
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

```c
// 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

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

```c
// 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?

- **Value passed**: passing a pointer is cheaper and takes less space unless struct is small \( (\leq \text{sizeof}(\text{void}*)) \)

- **Field access**: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize 
  \[ \text{dereference} = \text{access memory} \]

- For small structs (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**
     ```c
     typedef struct ll_node_st {
     char* str;
     struct ll_node_st* next;
     } 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:
     ```c
     Node* Pop(Node* head);
     ```
Lecture Outline

- structs 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.
Let’s represent a linked list node with a struct

- For now, assume each element is an `int`

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

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

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

`manual_list.c`
**Push Onto List**

```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

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

The code snippet demonstrates how to push elements onto a list. Here is the implementation in C:

```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;
}
```

The `Push` function takes a `Node*` pointer and an integer `e` to push onto the list. The `assert` statement is used to ensure that the allocation is successful. Only use `assert` in testing code.

The output of the program is:
```
list
∅
∅
e
1
n
[1]
```

This shows the list being built with elements 1 and 2.
Push Onto List

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

```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*
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 Onto List

```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**

---

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
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

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

```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

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**

```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

```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`
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*`)

```c
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

```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 EXIT_SUCCESS;
}
```

`manual_list_void.c`
What would happen if we execute \(*(\text{list} \rightarrow \text{next}) = *\text{list}^*?\n
\textbf{ structs are copied by value }
Something’s Fishy...

❖ A (benign) memory leak!

```c
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.Void manual_list_void.c
$ valgrind --leak-check=full ./manual_list_void
```
Lecture Outline

- *structs 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 typedefs, and perhaps global variables, that customers can use
    - May have internal functions, typedefs, 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, typedefs, 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
  ```
  #include <stdio.h>
  #include "my_header.h"
  ```

❖ **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)

❖ 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)

- 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
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

```c
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
    - 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 doubles
  - Includes functions to:
    - add, subtract, multiply, and divide complex numbers
  - Implement a test driver in test_complex.c
    - Contains main()