COMP2521
Data Structures & Algorithms

Week 2.2
Abstract Data Types (ADTs)

In this lecture

Why?

- ADTs are a fundamental concept of writing robust software, and of being able to work with other people

What?

- ADT definition
- ADT usage
- ADT implementation
  - Set ADTs
    - array
    - sorted array
    - linked list

ADTs

What is a data type?

- Data type:
  - Set of values (atomic or structured)
  - Collection of operations on those values

- int
  - set of value(s): an integer
  - operations: addition, subtraction, multiplication, etc.
- array:
  - set of values(s): a repeat of any data type (e.g. int)
  - operations: index lookup, index assignment, etc.

Abstraction

- **Abstraction**: Hiding details of a how a system is built in favour of focusing on the high level behaviours, or inputs and outputs, of the system

- Examples?
  - C abstracts away assembly/MIPS code.
  - Python abstract away pointer arithmetic and memory allocation.
  - Web browsers abstract away the underlying hardware that they're run on.

Abstract Data Type

- **ADT** is a description of a data type that focuses on it's high level behaviour, without regard for how it is implemented underneath.

- This means:
  - There is a separation of interface from implementations
  - Users of the ADT see only the interface
  - Builds of the ADT provide an implementation
  - Both parties need to agree on the ADTs interface
  - Interface allows people to agree at the start, and work separately.

Programming by Contract

- When we define our **interface**, we also need to include information about:
  - Pre-conditions: What conditions hold at the start of the function call
  - Post-conditions: What conditions will hold at the end of the function
- Add them via comments
- Can sanity check with asserts

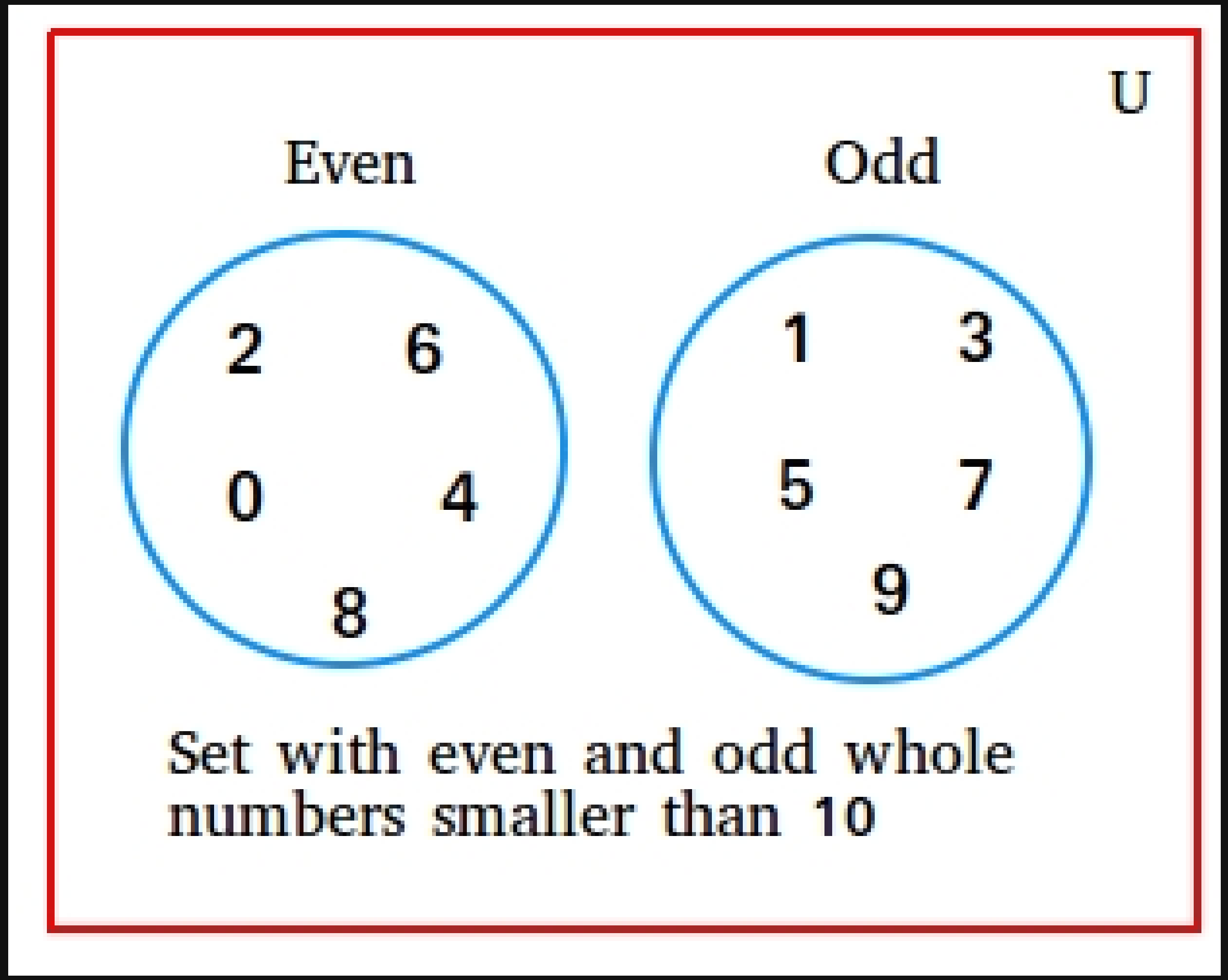
Abstract Data Type

- **Step 1:** Determine the interface of your ADT in a **.h** file
- **Step 2:** The "developer" builds a concrete implementation for the adt in a **.c** file
- **Step 3:** The "user" uses the abstract data type in their program
  - They have to compile with it, even though they might not understand how it is built underneath

Set ADTs (Step 1)

- **Set data type**: collection of unique integer values.

- What will we figure out first?
  - What **behaviour** does this ADT need? (interface)
  - ~~How are we going to code for it? (implementation)~~



Set ADTs (Step 1)

Let's brainstorm the **behaviour** of the "Set" ADT!

- **create** an empty collection
- **insert** one item into the collection
- **remove** one item from the collection
- **find** an item in the collection
- check the **size** of the collection
- **drop** the entire collection
- **display** the collection
- check if **unions** or **intersects** with another set

Set ADTs (Step 1)

- Now we start to write this as C code!
- Notice that we aren't implementing anything yet?

```c
Set SetCreate() // create a new set
void SetInsert(Set, int) // add number into set
void SetDelete(Set, int) // remove number from set
int SetMember(Set, int) // set membership test
int SetCard(Set) // size of set
Set SetUnion(Set, Set) // union
Set SetIntersect(Set, Set) // intersection
void SetDestroy(Set) // destroy a created set
```

Set ADTs (Step 1)

- Three key principles of ADTs in C:
  - When we write .h files, we use header guards to prevent re-definition
  - The "Set" (or equivalent) is usually a pointer of some sort
  - That pointer is usually the first argument in every ADT function

```c
#ifndef SET_H
#define SET_H

#include <stdio.h>
#include <stdbool.h>

typedef struct SetRep *Set;

// ADT functions go here

#endif
```

Set.h

- Notice how we haven't defined "struct SetRep"? That's not our job.

Set ADTs (Step 1)

```c
// Set.h ... interface to Set ADT

#ifndef SET_H
#define SET_H

#include <stdio.h>
#include <stdbool.h>

typedef struct SetRep *Set;

Set SetCreate();             // create new empty set
void SetDestroy(Set);        // free memory used by set
void SetInsert(Set,int);     // add value into set
void SetDelete(Set,int);     // remove value from set
bool SetMember(Set,int);     // set membership
Set SetUnion(Set,Set);       // union
Set SetIntersect(Set,Set);   // intersection
int SetCard(Set);            // cardinality

// others
Set SetCopy(Set);            // make a copy of a set
void ShowSet(Set);           // display set on stdout

#endif
```

Completed Set.h

But what's missing?

Programming by contract

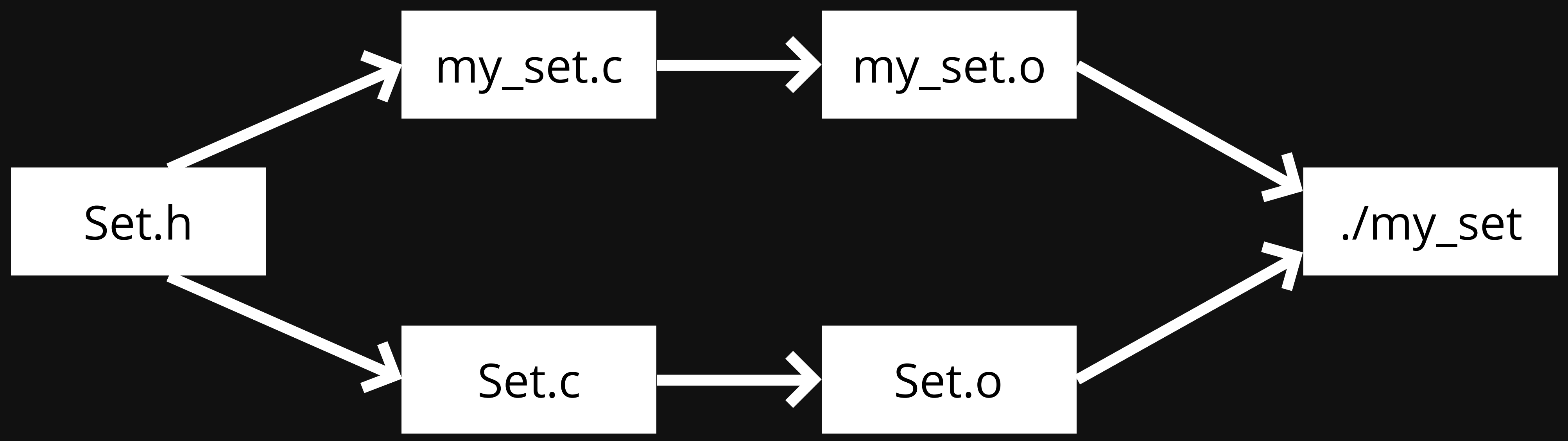
Set ADTs (Step 1)

- Pre and post conditions (i.e., comments) now added.
- Helps both developers and users manage expectations

```
// create new empty set
// pre:
// post: Valid set returned, set is empty
Set SetCreate();

// add value into set
// pre: Valid set provided
// post: New element "n" is now in set s
void SetInsert(Set s, int n);

// pre: Valid set provided for s1 and s2
// post: ∀ n ∈ res, n ∈ s1 or n ∈ s2
Set SetUnion(Set s1, Set s2);

// cardinality
// pre: Valid set provided for s
// post: Response is the number of elements in the set
int SetCard(Set s);
```

Set Usage (Step 3)

- How do we actually work with a set though?
  - We write our "main" file, and compile it with the set library that the ADT developer has implemented.
  - While we need their .c file to build with, we never need to look at it or make sense of it, because we have the ADT (i.e., .h file)
  - In fact, we could even just work with the .o file!



Set Usage (Step 3)

```c
#include "Set.h"

#include <stdio.h>

int main() {
    Set s = SetCreate();
    // Could use Scanf instaed
    for (int i = 1; i < 26; i += 2) {
        SetInsert(s,i);
    }
    SetShow(s);
    printf("\n");
}
```

testSet1.c

Set Implementation (Step 2)

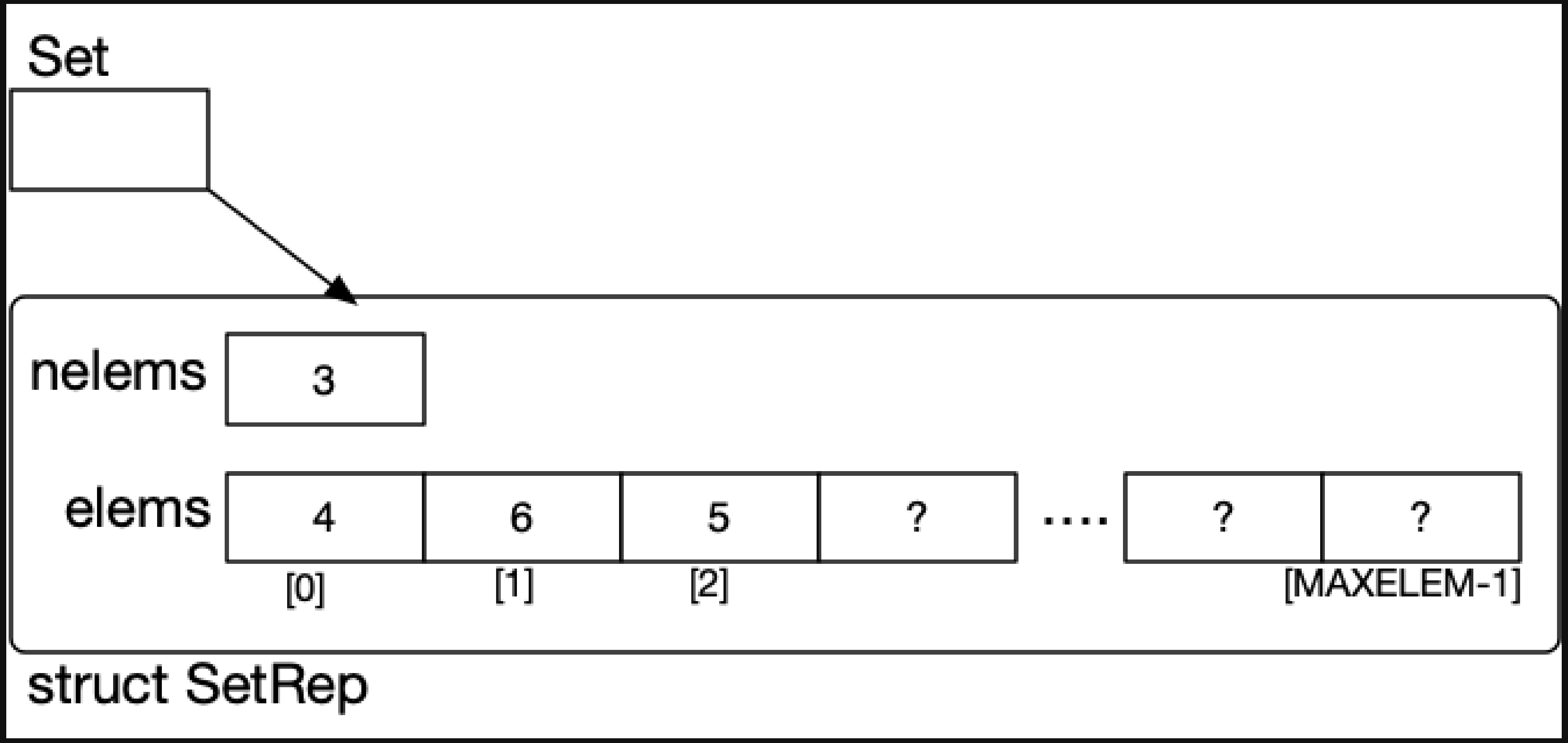
- It's time to implement the set! The "user" of our set doesn't need to worry about this.

    - We will implement 3 different types of sets:

        1. That uses an unsorted array
        2. That uses a sorted array
        3. That uses a linked list

Set Implementation (unsorted array)

- We can represent this set using an array (unsorted).
- This means we do have to do upper and lower bounds checks because there will be a theoretical limit on the size of the set.




```c
#define MAX_ELEMS 10000

// concrete data structure
struct SetRep {
    int elems[MAX_ELEMS];
    int nelems;
};

Set SetCreate(int) { ... }
void SetInsert(Set, int) { ... }
void SetDelete(Set, int) { ... }
int SetMember(Set, int) { ... }
int SetCard(Set) { ... }
Set SetUnion(Set, Set) { ... }
Set SetIntersect(Set, Set) { ... }
void SetDestroy(Set) { ... }
```

Set-array.c

Set Implementation (unsorted array)

A sample of the implemented set

```c
// create new empty set
Set SetCreate()
{
    Set s = malloc(sizeof(struct SetRep));
    if (s == NULL) {
        fprintf(stderr, "Insufficient memory\n");
        exit(1);
    }
    s->nelems = 0;
    // assert(isValid(s));
    return s;
}

// set membership test
int SetMember(Set s, int n)
{
    // assert(isValid(s));
    int i;
    for (i = 0; i < s->nelems; i++) {
        if (s->elems[i] == n) {
            return TRUE;
        }
    }
    return FALSE;
}
```

Set Implementation (unsorted array)

- Let's look at the time and space complexities:
  - n: Number of elements in the set
  - m: Number of elements in another set
  - E: Maximum number of items able to be in set

Data Structure	insert (time)	delete (time)	member (time)	union or intersection (time)	storage (space)
unsorted array	O(n)	O(n)	O(n)	O(n * m)	O(E)

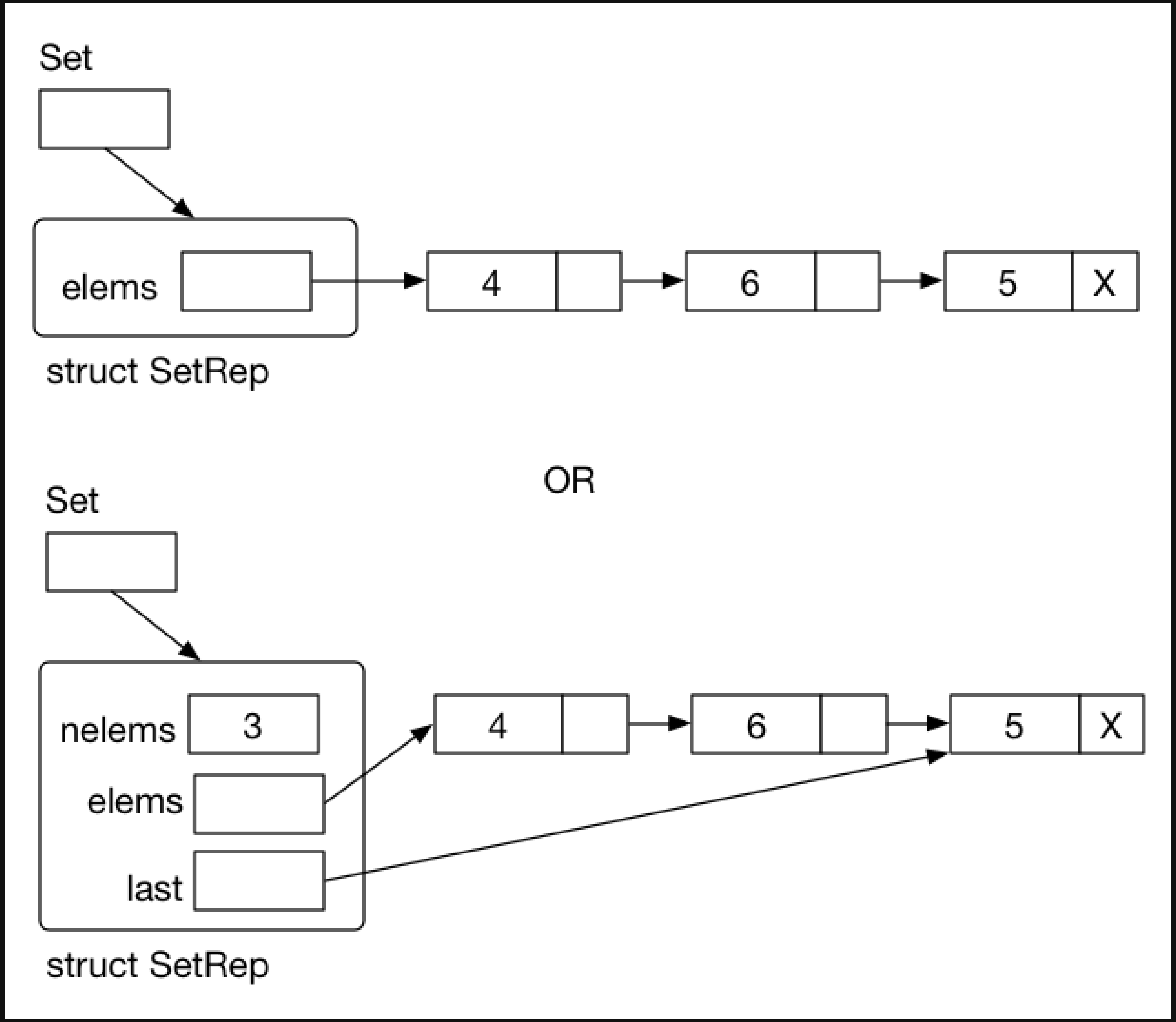
Set Implementation (sorted array)

- Same data structure as for unsorted array.
- **Differences**:
  - membership test -> can use binary search
  - insertion -> binary search and then shift up and insert
  - deletion -> binary search and then shift down

Set Implementation (sorted array)

Data Structure	**insert (time)**	**delete (time)**	**member (time)**	**union or intersection (time)**	**storage (space)**
unsorted array	O(n)	O(n)	O(n)	O(n * m)	O(E)
sorted array	O(log(n) +n) =O(n)	O(log(n) +n) =O(n)	O(log(n))	O(n * m)	O(E)

Set Implementation (linked list)




```c
typedef struct Node {
   int  value;
   struct Node *next;
} Node;

struct SetRep {
   Node *elems;   // pointer to first node
   int nelems;    // number of nodes
};

Set SetCreate() { ... }
void SetInsert(Set, int) { ... }
void SetDelete(Set, int) { ... }
int SetMember(Set, int) { ... }
int SetCard(Set) { ... }
Set SetUnion(Set, Set) { ... }
Set SetIntersect(Set, Set) { ... }
void SetDestroy(Set) { ... }
```

Set-list.c

Set Implementation (linked list)

```
// create new empty set
Set newSet()
{
   Set s = malloc(sizeof(struct SetRep));
   if (s == NULL) {...}
   s->nelems = 0;
   s->elems = s->last = NULL;
   return s;
}

// set membership test
int SetMember(Set s, int n)
{
   // assert(isValid(s));
   Node *cur = s->elems;
   while (cur != NULL) {
      if (cur->value == n) return true;
      cur = cur->next;
   }
   return false;
}
```

Set Implementation (linked list)

Data Structure	insert (time)	delete (time)	member (time)	union or intersection (time)	storage (space)
unsorted array	O(n)	O(n)	O(n)	O(n * m)	O(E)
sorted array	O(log(n) + n) =O(n)	O(log(n) + n) =O(n)	O(log(n)) =O(n)	O(n * m)	O(E)
unsorted linked list	O(n + 1) =O(n)	O(n + 1) =O(n)	O(n)	O(n * m)	O(n)
sorted linked list	O(n + 1) =O(n)	O(n + 1) =O(n)	O(n)	O(n * m)	O(n)

Direct access - issues?

- What happens if we try to access elements of the implementation directly?
- We might receive a "**dereferencing pointer to incomplete type**" error

```
gcc -Wall -Werror -g   -c -o bst.o bst.c
bst.c: In function ‘main’:
bst.c:44:3: error: dereferencing pointer to incomplete type ‘struct BSTNode’
  t->value;
   ^~
make: *** [<builtin>: bst.o] Error 1
```

ADT Summary

- ADT **interface**:
  - A user-view of the data structure
  - Functions for all operations
  - Explanations of those operations
  - Any guarantees it provides ("Contract")
- ADT **implementation**:
  - Concrete definition of the data structures
    - List, tree, graph, array, etc.
  - Definition of functions that operate on the data structure

ADT Summary

- Why abstract the data structure?
  - Allows future iterations to remove or upgrade a data structure
  - Allows things like lists to actually have more intelligent implementations underneath