# Ve 280

## Programming and Introductory Data Structures

**Abstract Data Types**

**Learning Objectives:**

Understand what is an abstract data type (ADT)

Understand the usefulness of an ADT

Know how to define an ADT in C++

# Outline

- Introduction to Abstract Data Types
- Class in C++: A Trivial Example
- More Details on Class
- Another Class Example: a Mutable Set of Integers (IntSet)
- Improve the Efficiency of IntSet

# Types

- The role of a type:
  - The set of values that can be represented by items of the type
  - The set of operations that can be performed on items of the type.

- Example
  - C++ string values:

    operations:

# Struct Types

- Struct types have the following feature:
  - **Every detail** of the type is known to all users of that type.
  - This is sometimes called the **concrete implementation**.

- Example: the `struct Grades` talked before.

```
struct Grades {
  char name[9];
  int  midterm;
  int  final;
};
```

# Struct Types

```
struct Grades {
  char name[9];
  int  midterm;
  int  final;
};
```

- Every function knows the details of exactly how `Grades` are represented.
- A change to the `Grades` definition (for example, change C-string for `name` to a C++-String) requires that we **make changes throughout the program** and recompile everything using this struct.

# Abstract Data Types

## Introduction

- Contrast the property of struct types with that of the functions
  - A function written by others shows **what** the function does, but not **how** it does it

- For function, if we find a faster way to implement, we can just replace the old implementation with the new one
  - No other components of the program calling the function need to change

# Abstract Data Types

## Introduction

- To solve the problem for struct type, we'll define **abstract data types**, or **ADTs**.
- An ADT provides an **abstract description** of **values** and **operations**.
- The definition of an ADT must combine **both** some notion of **what** values that type represents, and **what** operations on values it supports.
  - However, we can leave off the details of **how**.
- Example: mobile phone
  - Type: a portable telephone that can make and receive calls
  - Operations: turn on/off, make/receive call, text message

We don't know details!

# Abstract Data Types

## Introduction

- Abstract data types provide the following two advantages:

1. Information hiding: we don't need to know the details of how the **object** is **represented**, nor do we need to know how the **operations on those objects** are **implemented**.
2. Encapsulation: the objects and their operations are defined in the same place; the ADT combines both data and operation in one entity.

# Abstract Data Types

## Example

- `list_t`:
  - Information Hiding: In the `list_t` data type, you never knew the precise implementation of the `list_t` structure (except by looking in `recursive.cpp`).
  - Encapsulation: The definitions of the operations on lists (`list_print`, `list_make`, etc.) were found in the same header file as the type definition of `list_t`.

# Abstract Data Types

## Benefits

- Abstract data types have several benefits like we had with functional abstraction:
  - ADTs are **local**: the implementation of other components of the program does not depend on the **implementation** of ADT.
    - To realize other components, you only need to focus **locally**.
  - ADTs are **substitutable**: you can change the implementation and no users of that type can tell.

# Abstract Data Types

## Introduction

- Someone still needs to know/access the details of how the type is implemented.
  - I.e., how the values are represented and how the operations are implemented
  - This is referred to as the "**concrete representation**" or just the "**representation**"

- Question: Who can access the representation?
- Answer: **only** the operations defined for that type should have access to the representation.
  - Everyone else may access/modify this state only **through** operations.

# Abstract Data Types

## On to Classes

- C++ "class" provides a mechanism to give **true** encapsulation.

- The basic idea behind a class is to provide **a single entity** that both defines:
  - The **value** of an object.
  - The **operations** available on that object. These operations are sometimes also called **member functions** or **methods**.

# Outline

- Introduction to Abstract Data Types
- Class in C++: A Trivial Example
- More Details on Class
- Another Class Example: a Mutable Set of Integers (IntSet)
- Improve the Efficiency of IntSet

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: a trivial class to get/set a
    //           single integer value
    int    v;
public:
    int    get_value();
           // EFFECTS: returns the current
           //          value
    void   set_value(int newValue);
           // MODIFIES: this
           // EFFECTS: sets the current value
           // equal to newValue
};
```

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: a trivial class to get/set a
    //           single integer value
    int    v;
  public:
    int    get_value();
           // EFFECTS: returns the current
           //          value
    void   set_value(int newValue);
           // RME: Omitted for space
};
```

- There are a few things to notice about this definition:
  - There is a single OVERVIEW specification that describes the class as a whole.

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: Omitted for space
    int     v;
  public:
    int     get_value();
        // EFFECTS: returns the current value
    void    set_value(int newValue);
        // RME: Omitted for space
};
```

- There are a few things to notice about this definition:
  - The declaration includes both data elements (`int v`) and member functions/methods (`get_value` and `set_value`).

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: Omitted for space
    int    v;
  public:
    int    get_value();
           // EFFECTS: returns the current
           //          value
    void   set_value(int newValue);
           // MODIFIES: this
           // EFFECTS: sets the current value
           // equal to arg
};
```

- There are a few things to notice about this definition:
  - Each function that is declared must have a corresponding specification.

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: Omitted for space
    int    v;
  public:
    int    get_value();
          // EFFECTS: returns the current value
    void   set_value(int newValue);
           // MODIFIES: this
           // EFFECTS: sets the current value
           // equal to arg
};
```

- There are a few things to notice about this definition:
  - `set_value` says it MODIFIES `this`. This is the generic name for "**this object**".

# Outline

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# Abstract Data Types

## Classes – More Details

- By default, every member of a class is **`private`**.
    - Members = data members + function members
- A private member is visible **only** to **other members** of this class.
    - `int v` was a private member in the class `anInt`.
    - "Private" hides the implementation of the type from the user.

# Abstract Data Types

## Classes – More Details

- However, if everything were private, the class wouldn't be particularly useful!
- So, the `public` keyword is used to signify that some members are **visible** to anyone who sees the class declaration, not just visible to other members of this class.
  - Everything **after** the `public` keyword is **visible** to others.

# Abstract Data Types

## Classes – A trivial example

```
class anInt {
    // OVERVIEW: a trivial class to get/set a
    //           single integer value
    int    v;
  public:
    int    get_value();
           // EFFECTS: returns the current
           //          value
    void   set_value(int newValue);
           // MODIFIES: this
           // EFFECTS: sets the current value
           // equal to arg
};
```

# Abstract Data Types

## Classes – A trivial example

**This declaration, as it is, is incomplete. We have not yet defined the bodies of the member functions.**

```
class anInt {
    // OVERVIEW: a trivial class to get/set a
    //           single integer value
    int    v;
  public:
    int    get_value();
          // EFFECTS: returns the current
          //          value
    void   set_value(int newValue);
          // MODIFIES: this
          // EFFECTS: sets the current value
          // equal to arg
};
```

# Abstract Data Types

## Classes – Defining member functions

```
class anInt {
    // OVERVIEW: a trivial class to get/set a
    //           single integer value
```

**Note: You can actually define the functions within the class definition, but this "exposes" information, which is best left hidden!**

```
int anInt::get_value() {
  return v;
}
void anInt::set_value(int newValue) {
  v = newValue;
}
```

The definitions of member functions are usually put in the .cpp file;
You should include .h in the .cpp now!

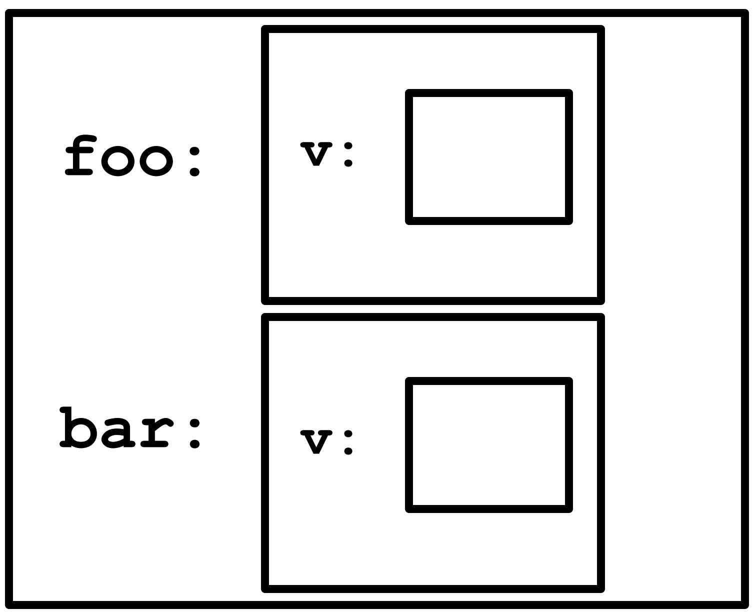
# Abstract Data Types

## Classes – Declaring class objects

- We can declare **objects** of type `anInt` as you would expect:

```
anInt     foo;
anInt     bar;
```

- This produces an environment with two objects:




**These values are still undefined (i.e. there is no initial value). We'll see several ways to set an initial value for data members later.**

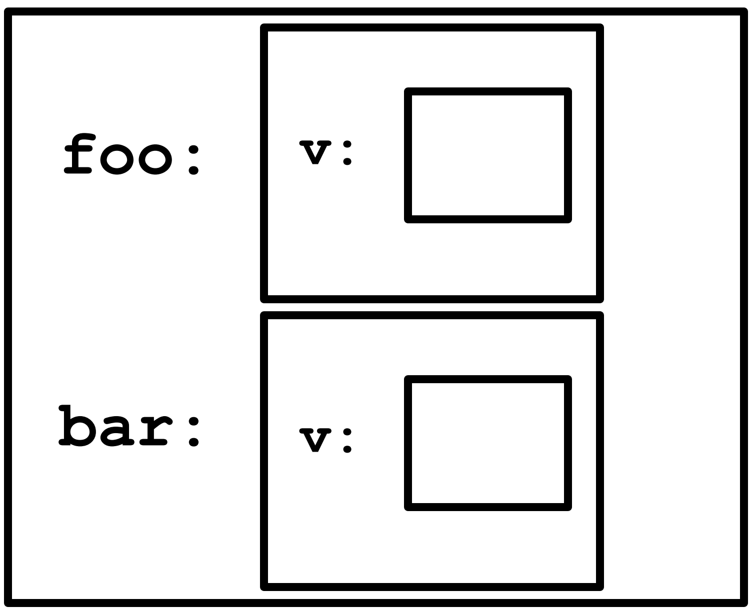
# Abstract Data Types

## Classes – Establishing data member values

- We can call the set_value member function to establish a value:

```
foo.set_value(1);
```

This calls foo's set_value() method.



# Abstract Data Types

## Classes – Establishing data member values

- There is one very important difference between normal function calls and **member** function calls:
  - The **other** members of the object are **also visible** to the function members!
  - For example, `v` is visible to the function `set_value()`

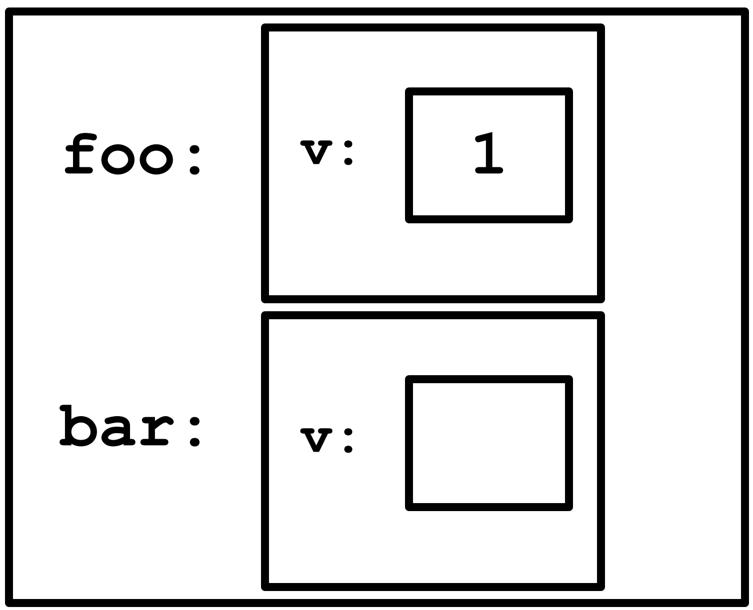
```
void anInt::set_value(int newValue) {
  v = newValue;
}
```

# Abstract Data Types

## Classes – Establishing data member values

- So, set value changes **`foo`**'s `v`:

```
foo.set_value(1);
```



# Abstract Data Types

## Classes – Accessing data member values

- We can't access v directly:

```
cout << foo.v; // Compile-time error
```

because `v` is **private**!

- However, we can use the get_value() method to do so for us:

```
cout << foo.get_value(); // OK.
```

because `get_value()` is **public**!

- Finally, class objects can be passed just like anything else.
- Like everything else (except arrays), they are passed by value.

# Abstract Data Types

## Class Example: Classes

- What is the result of the following?

```
void add_one(anInt i) {
    i.set_value(i.get_value()+1);
}
int main() {
    anInt foo;
    foo.set_value(0);
    add_one(foo);
    cout << foo.get_value() << endl;
    return 0;
}
```

# Abstract Data Types

## Classes – Passing by reference

- To pass a class object by reference, you use either a pointer argument or a reference argument, i.e.:

```
void add_one(anInt *ip) {
  ip->set_value(ip->get_value() + 1);
}
```

- This version would change the class object passed to it!

# Which Statements Are Correct?

- **A.** A C++ class defines a type.
- **B.** The information stored in an object of a class is accessible to any one.
- **C.** A class defines all the basic operations that are possible on objects of that class.
- **D.** All member functions of a class are accessible to any one.

# Outline

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- Improve the Efficiency of IntSet

# Abstract Data Types

## Using Classes

- Suppose we wanted to build an abstraction that held a **mutable** set of integers.

- This is a **set** in the mathematical sense:
  - A collection of zero or more integers, with **no duplicates**.

- The set is "mutable" because we can insert values into and remove objects from the set.

# Abstract Data Types

## Using Classes

- Suppose we wanted to build an abstraction that held a **mutable** set of integers.

- There are four **operations** on this set that we will define:
  1. Insert a value into the set.
  2. Remove a value from the set.
  3. Query to see if a value is in the set.
  4. Count the number of elements in the set.

# Abstract Data Types

## Using Classes

- Here is an **incomplete** definition of a class implementing such an ADT:

```
class IntSet {
    // OVERVIEW: a mutable set of integers

  public:
    void insert(int v);
      // MODIFIES: this
      // EFFECTS: this = this + {v}
    void remove(int v);
      // MODIFIES: this
      // EFFECTS: this = this - {v}
    bool query(int v);
      // EFFECTS: returns true if v is in this,
      //          false otherwise
    int  size();
      // EFFECTS: returns |this|.
};
```

# Abstract Data Types

## Using Classes

```
class IntSet { // omitted OVERVIEW for space
  public:
    void insert(int v); // omitted RME for space
    void remove(int v); // omitted RME for space
    bool query(int v); // omitted RME for space
    int  size(); // omitted RME for space
};
```

- The class is incomplete because we haven't chosen a **representation** for sets.
- Choosing a representation involves two things:
  - Deciding what **concrete** data elements will be used to **represent the values** of the set.
  - Providing an **implementation** for each **method**.

# Abstract Data Types

## Using Classes

```
class IntSet { // omitted OVERVIEW for space
  public:
    void insert(int v); // omitted RME for space
    void remove(int v); // omitted RME for space
    bool query(int v); // omitted RME for space
    int  size(); // omitted RME for space
};
```

- Despite not having a representation for a set, the (incomplete) definition above is all that a **customer** of the `IntSet` abstraction needs to know since it has:
  - The general overview of the ADT.
  - The specification of each method.

# Abstract Data Types

## Using Classes

- Start with a representation for the set itself:
  - Use an array.
  - Represent a set of size N as an **unordered** array of integers with no duplicates, stored in the first N slots of the array.
  - `int numElts`: maintains the number of elements currently in the array.

rep invariant

- These last two statements are called **representation invariants** or **rep invariants** (more on this later).
- This invariant is a rule that the representation must obey both **immediately before** and **immediately after** any method's execution.

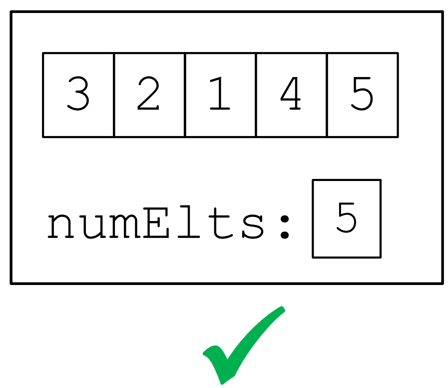
# Abstract Data Types

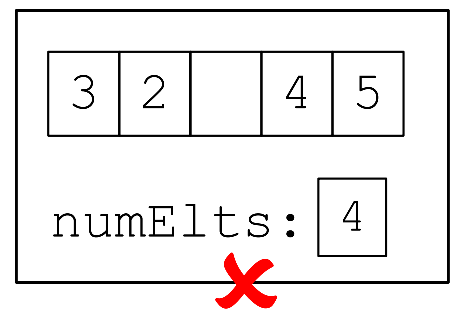
## Using Classes

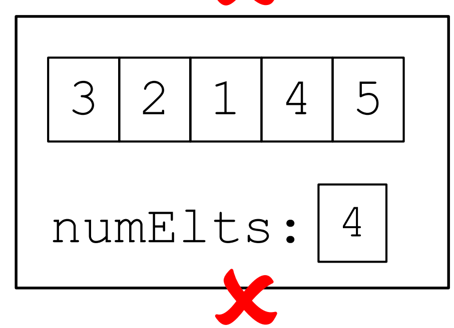
- Start with a representation for the set itself:
  - Use an array.
  - Represent a set of size N as an **unordered** array of integers with no duplicates, stored in the first N slots of the array.
  - `int numElts`: maintains the number of elements currently in the array.

rep invariant

```
class IntSet {
  int elts[100];
  int numElts;
  …
};
```



# Abstract Data Types

## Using Classes

- Since this is an array, and arrays have maximum sizes, we have to choose a maximum size and modify the `OVERVIEW`:

```
// OVERVIEW: a mutable set of
//           integers, |set| <= 100
```

- We also have to change the `EFFECTS` clause of `insert`:

```
// EFFECTS: this = this + {v} if
//          room available, throws int
//          100 otherwise
```

100 is arbitrary. What is a better way to specify such size?

# Abstract Data Types

## Using Classes

```
const int MAXELTS = 100;
class IntSet {
    // OVERVIEW: a mutable set of integers, |set| <= MAXELTS
    int         elts[MAXELTS];
    int         numElts;
  public:
    void insert(int v);
      // MODIFIES: this
      // EFFECTS: this = this + {v} if room,
      //          throws int MAXELTS otherwise
    void remove(int v);
      // MODIFIES: this
      // EFFECTS: this = this - {v}
   bool query(int v);  // RME omitted for space
    int  size();        // RME omitted for space
};
```

Use a global constant like we have talked about.

# Abstract Data Types

## Using Classes

Given this representation, and the representation invariants, we can write the methods.

```
const int MAXELTS = 100;
class IntSet { // OVERVIEW omitted for space
    int      elts[MAXELTS];
    int      numElts;
  public:
    void insert(int v); // RME omitted for space
    void remove(int v); // RME omitted for space
    bool query(int v);  // RME omitted for space
    int  size();        // RME omitted for space
};
```

```
int IntSet::size() {
  return numElts;
}
```

Because our rep invariant says that `numElts` is always the size of the set, we can return it directly.

# Abstract Data Types

## Using Classes

- Next, consider the three final routines:
  - query: search the array looking for a specific number.
  - remove: search the array for a number; if it exists, remove it.
  - insert: search the array for a number; if it doesn't exist, add it.

- All three of these have "search" in common.
- One might be tempted to just write `insert` and `remove` in terms of `query`, will this work?
  - Hint: think about `remove`.
- `query` only tells us **whether** the element exists, not **where** – we need one more method…

# Abstract Data Types

## Using Classes

```
const int MAXELTS = 100;
class IntSet { // OVERVIEW omitted for space
   int        elts[MAXELTS];
   int        numElts;
   int indexOf(int v);
     // EFFECTS: returns the index of
     //          v if it exists in the
     //          array, MAXELTS otherwise.
  public:
    void insert(int v);
    void remove(int v);
    bool query(int v);
    int  size();
};
```

__Note__: This member function must be **private**. This is because it exposes details about the concrete representation. It is inappropriate to expose these details to a user of this class.

# Abstract Data Types

## Using Classes

```
const int MAXELTS = 100;
class IntSet { // OVERVIEW omitted for space
    int       elts[MAXELTS];
    int       numElts;
    int indexOf(int v); // RME omitted for space
  public:
    void insert(int v);  void remove(int v); // RME omitted
    bool query(int v);   int  size();        // RME omitted
};
```

```
int IntSet::indexOf(int v) {
  for (int i = 0; i < numElts; i++) {
    if (elts[i] == v) return i;
  }
  return MAXELTS;
}
```

# Abstract Data Types

## Using Classes

```
const int MAXELTS = 100;
class IntSet { // OVERVIEW omitted for space
    int       elts[MAXELTS];
    int       numElts;
    int indexOf(int v); // RME omitted for space
  public:
    void insert(int v);  void remove(int v); // RME omitted
    bool query(int v);   int  size();        // RME omitted
};
```

With `indexOf`, `query` is trivial…

```
bool IntSet::query(int v)      {
  return (indexOf(v) != MAXELTS);
}
```

# How to Implement `insert(v)`?

Select all the correct answers.

- **A.** We can first search `v` to check if it is already there with `indexOf(v)`
- **B.** If `v` is not present, we then add `v`
- **C.** If we add `v`, it should be added as `elts[numElts-1]` before we increment `numElts`
- **D.** If `v` is added, we need to increment `numElts`

# Abstract Data Types

## Using Classes

- The code for `insert` is not much more difficult than query:
  - First look for the `indexOf` the element to insert.
  - If it doesn't exist, we need to add this element to the **end** of the array.
  - What is the index of the current "end" ?
  - Place the element in the next slot and **update** `numElts`.
  - The only exception to this is if `numElts` already equals `MAXELTS`.

# Abstract Data Types

## Using Classes

```
const int MAXELTS = 100;
class IntSet { // OVERVIEW omitted for space
    int       elts[MAXELTS];
    int       numElts;
    int indexOf(int v); // RME omitted for space
  public:
    void insert(int v);  void remove(int v); // RME omitted
    bool query(int v);   int  size();        // RME omitted
};
```

```
void IntSet::insert(int v) {
  if (indexOf(v) == MAXELTS) {
    if (numElts == MAXELTS) throw MAXELTS;
    elts[numElts++] = v;
  }
}
```

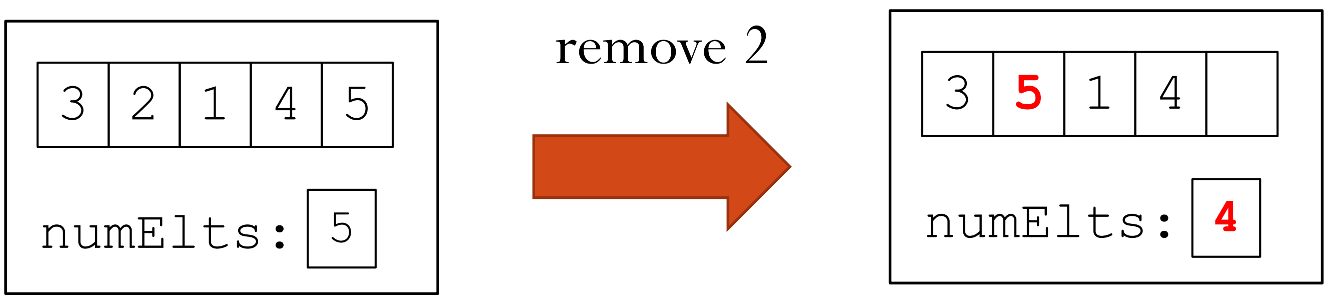
# How about Remove?

- If the element (its index is called the `victim`) is in the array, we have to remove it leaving a "hole" in the array.

- What representation invariants are violated?
  - How can we fix them?

# How about Remove?

- Instead of moving each element after the `victim` to the left by one position, pick up the current "last" element and move it to the hole.
- This also breaks the invariant on `numElts`, so we must fix it.



# Abstract Data Types

## Using Classes

```
void IntSet::remove(int v) {
  int victim = indexOf(v);
  if (victim != MAXELTS) {
    elts[victim] = elts[numElts-1];
    numElts--;
  }
}
```

# Abstract Data Types

## Using Classes

- Question: There is one problem with our implementation. What is it?

- Hint: Consider the newly-created set:

```
IntSet s;
```

What does the computer actually create when we declare `s`?

# Abstract Data Types

## Using Classes

- <u>Question</u>: There is one problem with our implementation. What is it?
- <u>Answer</u>: On creation, `s`'s data members are **uninitialized**!
- This means that the value of `numElts` could be a random value, but our representational invariant says it must be zero!
- How can we fix this?

# Abstract Data Types

## Automatically Initializing Classes

- Using **constructor**!
- The constructor (really, the **default** constructor) has the following type signature:

```
class IntSet { // OVERVIEW omitted for space
    …
  public:
    IntSet();
      // EFFECTS: creates an empty IntSet
    …
};
```

# Abstract Data Types

## Automatically Initializing Classes

```
IntSet();
  // EFFECTS: creates an empty IntSet
```

- **The name of the function is the same as the name of the class.**
- **This function doesn't have a return type.**
- **It also does not take an argument in this case.**
- It is guaranteed to be the **first** function called immediately after an object is created.
- It builds a "blank" uninitialized `IntSet` and makes it satisfy the rep invariant.

# Abstract Data Types

## Automatically Initializing Classes

```
IntSet();
  // EFFECTS: creates an empty IntSet
```

- Here's how it's written:

```
IntSet::IntSet(): numElts(0)
{
}
```

# Abstract Data Types

## Automatically Initializing Classes

```
IntSet::IntSet()
        : numElts(0)
{
}
```

```
Class_T::Class_T(): anInt(0),
    aDouble(1.2),
    aString("Yes")
{
}
```

- This syntax is called "initialization syntax".
- Each data member is initialized this way.
- **Note**: The order in which elements are initialized is the order they **appear in the definition**, NOT the order in the initialization list.  It is a good practice to keep them in the same order to avoid confusion.

# Abstract Data Types

## Automatically Initializing Classes

- Alternatively, we could write this function as follows, but this is not considered as a good way!

```
IntSet::IntSet()
{
    numElts = 0;
}
```

# Abstract Data Types

## A Benefit of Classes

- Now, instead of writing this:

```
void add_one (int a[], int elts);
```

and having to worry about the number of elements in the array. All we have to write is this:

```
void add_one (IntSet& set);
```

and we no longer have to worry about the array and its count being separated.

# Const Member Functions

- A slight change to the class definition:

```
const int MAXELTS = 100;
class IntSet {
   int elts[MAXELTS];
   int numElts;
   int indexOf(int v) const;

public:
    void insert(int v);
    void remove(int v);
    bool query(int v) const;
    int  size() const;
};
```

# Const Member Functions

`int size() const;`

- Each member function of a class has an extra, implicit parameter named **`this`**.
  - "**`this`**" is a pointer to the current instance on which the function is invoked.
- **`const`** keyword modifies the implicit **`this`** pointer: **`this`** is now a pointer to a **const instance**.
  - Means: the member function **`size()`** cannot change the object on which **`size()`** is called.
  - By its definition, **`size()`** shouldn't change the object! Adding **`const`** keyword prevents any accidental change.
  - It is a good practice to add **`const`** keyword when possible!

# Const Member Functions

- Implement **`size()`**

```
int IntSet::size() const {
   return numElts;
}
```

The function body is the same as before.

- A **const** object can only call its **const** member functions!

```
const IntSet is;
cout << is.size(); ✓
is.insert(2); ✗
```

# Const Member Functions

- If a const member function calls other **member** functions, they must be **const** too!

```
void A::g() const { f(); }
```

```
void A::f() {...}
```

✘

```
void A::f() const {...}
```

✓

# Outline

- Introduction to Abstract Data Types
- Class in C++: A Trivial Example
- More Details on Class
- Another Class Example: a Mutable Set of Integers (IntSet)
- Improve the Efficiency of IntSet

# How many elements of the array must `indexOf` examine?

```
int IntSet::indexOf(int v) {
  for (int i = 0; i < numElts; i++) {
    if (elts[i] == v) return i;
  }
  return MAXELTS;
}
```

- **A.** In the best case, 1 element
- **B.** In the worst case, `numElts` elements
- **C.** In the worst case, `MAXELTS` elements
- **D.** None of the above

# Abstract Data Types

## Improving Efficiency

- We say the time for `indexOf` grows **linearly** with the size of the set.

- If there are N elements in the set, we have to examine all N of them **in the worst case**. For large sets that perform lots of queries, this is too expensive!

- Luckily, we can replace this implementation with a different one that can be more efficient. The only change we need to make is to the **representation (implementation)** – the abstraction can stay precisely the same.

# Abstract Data Types

## Improving Efficiency

- Still use an array to store the elements of the set and the values will still occupy the first `numElts` slots.

- However, now we'll keep the elements in **sorted** order.

# Question: What Parts of the Class Should Be Changed?

```
const int MAXELTS = 100;
class IntSet {
    // OVERVIEW: a mutable set of integers
    int elts[MAXELTS];
    int numElts;
    int indexOf(int v) const;
  public:
    IntSet();
    void insert(int v);
    void remove(int v);
    bool query(int v) const;
    int  size() const;
};
```

# Abstract Data Types

## Improving Efficiency

- The constructor and size methods don't need to change at all since they just use the `numElts` field.

- `query` also doesn't need to change.

```
bool IntSet::query(int v)  {
    return (indexOf(v) != MAXELTS);
}
```

- `indexOf` also doesn't need to change.

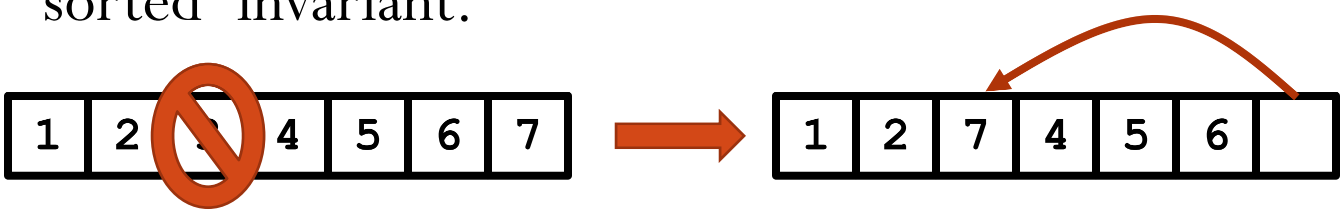
- However, `insert` and `remove` do need to change.

# Abstract Data Types

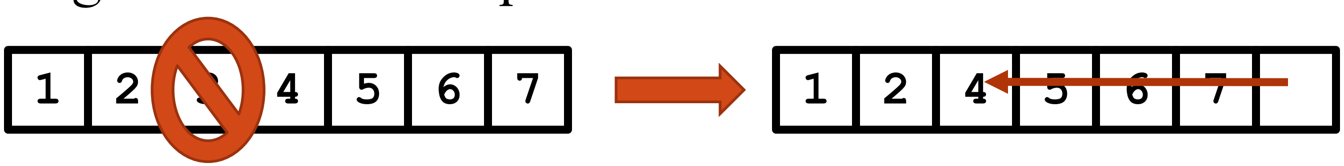
## Improving Efficiency

- We'll start with the easiest one: `remove`.

- Recall the old version that moved the last element from the end to somewhere in the middle, this will break the new "sorted" invariant.




- Instead of doing a swap, we have to "squish" the array together to cover up the hole.



# Abstract Data Types

## Improving Efficiency

- How are we going to do the "squish"?
  - Move the element next to the hole to the left leaving a new hole.
  - Keep moving elements until the hole is "off the end" of the elements.

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 4 | 6 | 7 | |

remove 4

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | | 6 | 7 | |

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 6 | | 7 | |

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 6 | 7 | | |

  - We'll reuse the variable `victim` as a loop variable.
  - `victim`'s invariant is that it always points at the hole in the array.

# Abstract Data Types

## Improving Efficiency

```
void IntSet::remove(int v) {
  int victim = indexOf(v);
  if (victim != MAXELTS) {
      // victim points at hole
    numElts--; // one less element
    while (victim < numElts) {
      // ..hole still in the array
      elts[victim] = elts[victim+1];
      victim++;
    }
  }
}
```

# Abstract Data Types

## Improving Efficiency

- We also have to change `insert` since it currently just places the new element at the end of the array. This will also break the new "sorted" invariant.

# Abstract Data Types

## Improving Efficiency

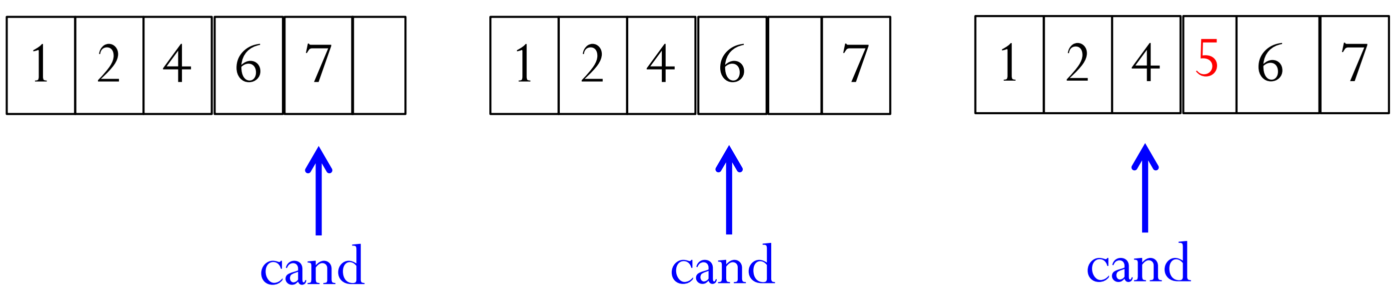
- How are we going to do the insert?
  - Start by moving the last element to the right by one position.
  - Repeat this process until the correct location is found to insert the new element.
  - Stop if the start of the array is reached or the element is sorted.
  - We'll need a new loop variable called `cand`(idate) to track this movement.
  - It's invariant in that it always points to the next element that **<u>might</u>** have to move to the right.

# Abstract Data Types

## Improving Efficiency

```
void IntSet::insert(int v) {
  if (indexOf(v) == MAXELTS) { // duplicate not found
    if (numElts == MAXELTS) throw MAXELTS; // no room
    int cand = numElts-1; // last element
    while ((cand >= 0) && elts[cand] > v) {
      elts[cand+1] = elts[cand];
      cand--;
    }
    // Now, cand points to the left of the "gap".
    elts[cand+1] = v;
    numElts++; // repair invariant
  }
}
```

insert 5



# Abstract Data Types

## Improving Efficiency

```
void IntSet::insert(int v) {
  if (indexOf(v) == MAXELTS) { // duplicate not found
    if (numElts == MAXELTS) throw MAXELTS; // no room
    int cand = numElts-1; // last element
    while ((cand >= 0) && elts[cand] > v) {
      elts[cand+1] = elts[cand];
      cand--;
    }
    // Now, cand points to the
    elts[cand+1] = v;
    numElts++; // repair invar
  }
}
```

<u>Note</u>: We are using the "short-circuit" property of &&. If cand is not greater than or equal to zero, we never evaluate the right-hand clause.

# Abstract Data Types

## Improving Efficiency

```
void IntSet::insert(int v) {
  if (indexOf(v) == MAXELTS) { // duplicate not found
    if (numElts == MAXELTS) throw MAXELTS; // no room
    int cand = numElts-1; // largest (last) element
    while ((cand >= 0) && elts[cand] > v) {
      elts[cand+1] = elts[cand];
      cand--;
    }
    // Now, cand points to the left of the "gap".
    elts[cand+1] = v;
    numElts++; // repair invariant
  }
}
```

Question: What is the situation when the loop terminates due to `cand < 0`? Is our implementation correct?

# Abstract Data Types

## Improving Efficiency

- **<u>Question</u>**: Do we have to change `indexOf`?

```
int IntSet::indexOf(int v) {
  for (int i = 0; i < numElts; i++) {
    if (elts[i] == v) return i;
  }
  return MAXELTS;
}
```

# Abstract Data Types

## Improving Efficiency

- **<u>Question</u>**: Do we have to change `indexOf`?
- **<u>Answer</u>**: No, but it can be made more efficient with the new representation.
- **<u>How?</u>**

Using **binary search**! (The array is sorted)

```
int IntSet::indexOf(int v) {
  for (int i = 0; i < numElts; i++) {
    if (elts[i] == v) return i;
  }
  return MAXELTS;
}
```

# Abstract Data Types

## Complexity

| | Unsorted | Sorted |
|---|---|---|
| query | O(N) | ? |
| insert | ? | ? |
| remove | ? | ? |

# Abstract Data Types

## Complexity

| | Unsorted | Sorted |
|---|---|---|
| `query` | `O(N)` | `O(log N)` |
| `insert` | `O(N)` | `O(N)` |
| `remove` | `O(N)` | `O(N)` |

`insert` and `remove` are still **linear**, because they may have to "swap" an element to the beginning/end of the array.

# Abstract Data Types

## Complexity

| | `Unsorted` | `Sorted` |
|---|---|---|
| `query` | `O(N)` | `O(log N)` |
| `insert` | `O(N)` | `O(N)` |
| `remove` | `O(N)` | `O(N)` |

- If you are going to do more searching than inserting/removing, you should use the "sorted array" version, because `query` is faster there.

- However, if `query` is relatively rare, you may as well use the "unsorted" version. It's "about the same as" the sorted version for `insert` and `remove`, but it's MUCH simpler!

# References

- **Problem Solving with C++ (8th Edition)**
  - Chapter 10.3 Abstract Data Types
  - Chapter 10.2 Classes and constructors

- **C++ Primer, 4th Edition**
  - Chapter 7.7.1 const Member Function