Ve 280

Programming and Introductory Data Structures

ADT Example: IntSet;

Improve ADT Efficiency;

Introduction to Subtypes

Midterm

- 4:00 pm – 5:40 pm, July 1st, 2016
- Find your seat on Sakai (to be posted later)
- Closed book and closed notes
- No electronic devices are allowed
  - These include laptops and cell phones
  - We will show a clock on the screen

Midterm

- Written exam
  - A number of questions which only require you to provide a very short answer
  - A few questions which require you to write code on the paper

- Abide by the **Honor Code**!

Midterm Topics

- Linux Commands
- Compiling and Developing Program on Linux
- C++ Basics: Pointers, References
- Procedural Abstraction and Specification Comments
- Recursion
- Function Pointers
- const Qualifier
- enum Type
- Program Taking Arguments
- I/O Streams
- Testing/Debugging
- Exception
- Class Basics

Lecture 1-12 (this one)

Outline

- A Class Example: a **Mutable** Set of Integers (IntSet)
- Improve the Efficiency of IntSet
- Introduction to Subtypes

Review: IntSet

```
const int MAXELTS = 100;
class IntSet {
    // OVERVIEW: a mutable set of integers, |set| <= MAXELTS
    int         elts[MAXELTS];    representation
    int         numElts;          invariant
    int         indexOf(int v); // return index or MAXELTS
  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);  // return whether v in this
    int  size();       // return |this|
};
```

Abstract Data Types

Using Classes

- <u>Question</u>: There is one problem with our implementation. What is it?

- <u>Hint</u>: Consider the newly-created set:

```
IntSet s;
```

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

Abstract Data Types

Using Classes

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

- Answer: 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.
- **<u>Note</u>**: 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**.
  - <u>Means</u>: 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

- A Class Example: a **Mutable** Set of Integers (IntSet)

- Improve the Efficiency of IntSet

- Introduction to Subtypes

Abstract Data Types

Class Exercise

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

- **<u>Question</u>**: How many elements of the array must `indexOf` examine in the **worst case** if there are 10 elements? If there are 90 elements?

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.

- <u>However, now we'll keep the elements in **sorted** order</u>.

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.

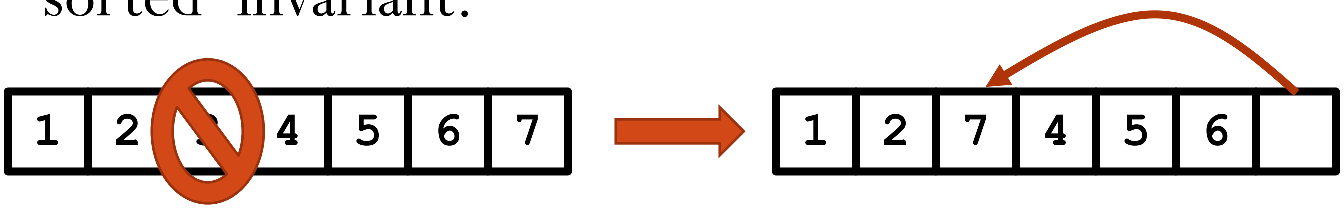
- However, `insert` and `remove` do need to change.

Abstract Data Types

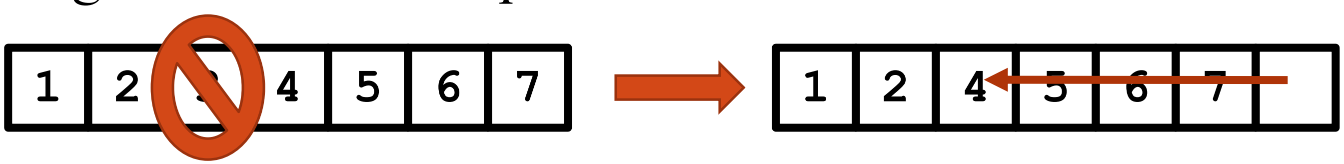
Improving Efficiency

- 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 also will break the new "sorted" invariant.

Abstract Data Types

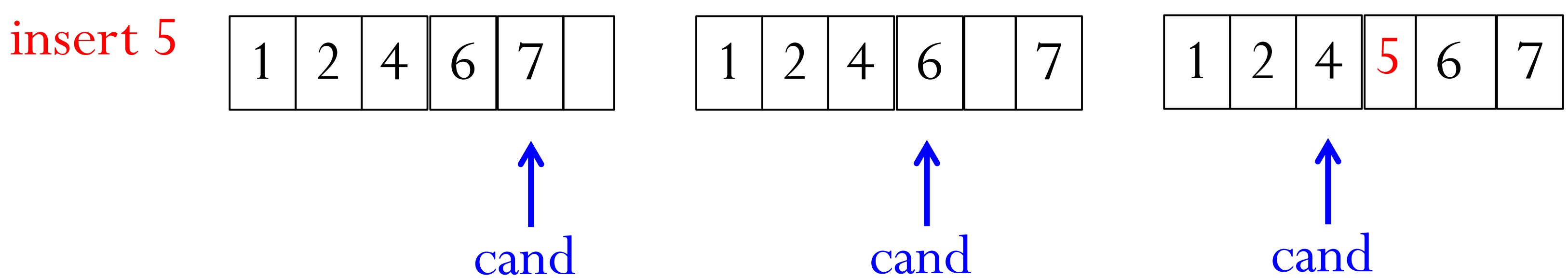
Improving Efficiency

- 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 to track this movement called `cand`(idate).
  - It's invariant in that it always points to the next element that might 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
  }
}
```



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
  }
}
```

Note: 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

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

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!

Outline

- A Class Example: a **Mutable** Set of Integers (IntSet)
- Improve the Efficiency of IntSet
- Introduction to Subtypes

Subtypes

Introduction

- Suppose we have two types, S and T.
- S is a **subtype** of T, written "$S <: T$", if:
  - For any instance where an object of type T is expected, an object of type S can be supplied without changing the correctness of the **original** computation.
  - In other words, code written to correctly use T is still correct if it uses S.
- This is called the "substitution principle".
- If $S <: T$, then we also say that "T is a **supertype** of S".

Subtypes

Example

- Supertype: Number
- Subtypes: Integer, rational number, real number, …

```
Number double_val(Number x) {
    return x*2;
}
```

Subtypes

Example

- Consider the following where `inFile` has been declared as an `ifstream` and opened:

```
 void add(istream &source) {
    int n1, n2;
    source >> n1 >> n2;
    cout << n1+n2;
 }
add(inFile);
```

- The function call `add(inFile)` is valid and works because `ifstream` is a **subtype** of `istream`
- `ifstream` can be supplied (substituted for `istream`) without changing the correctness.

Subtypes

Introduction

- Subtypes are different from the notion of "type-convertible".
  - For example, in any computation that expects a `double`, you can use an `int`.
  - However, the object isn't an `int` when it is used.
  - It is first "converted" to a `double` and its physical representation changes!

- However, if you use a subtype where a supertype is expected, it is **not converted** to the supertype
- Instead, it is used as-is.

References

- Constructor
  - Problem Solving with C++, 8th Edition, Chapter 10.2
- const Member Function
  - C++ Primer, 4th Edition, Chapter 7.7.1