

# Ve 280

## Programming and Elementary Data Structures

### **Dynamic Resizing**

#### **Learning Objectives:**

Learn a basic strategy for managing a dynamic storage using arrays

Learn some basics of complexity analysis

# Dynamic Resizing

## Modifying `Insert()`

- We have modified `IntSet` to allow a client to specify the **capacity** of an `IntSet`.
- However, this doesn't really get around the “big instance” problem, since the caller itself might not know how big the set will grow.
- So, what we **really** want to do is to create an `IntSet` that can **grow** as big as it needs to.
- To do this, we only need to modify the `insert()` method.

# Dynamic Resizing

## Modifying `Insert()`

- We will use the unsorted representation. We will focus on the action of **resizing**, not the action of inserting.

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

We want to modify  
`throw sizeElts`

# Dynamic Resizing

## Modifying `Insert()`

- Rather than throw an exception if the array is at maximum capacity, we will instead **grow** the array.

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

# Dynamic Resizing

Modifying `Insert()`

- The `grow` method won't take any arguments or return any values.
- It should **never** be called from outside of the class, so add it as a **private** method taking no arguments and returning void.

```
class IntSet {  
    // data members ...  
    void grow();  
    // EFFECTS: enlarge the elts array,  
    //           preserving current contents  
public:  
    // ...  
};
```

# Dynamic Resizing

Modifying `Insert()`

- `grow` will look like the assignment operator.
- It must perform the following steps:
  1. Allocate a bigger array.
  2. Copy the smaller array to the bigger one.
  3. Destroy the smaller array.
  4. Modify `elts/sizeElts` to reflect the new array.

Note the order of allocation can destroy. Can we switch this order?

# Dynamic Resizing

Modifying `Insert()`

```
void grow() {  
    int *tmp = new int[sizeElts + 1];  
    for (int i = 0; i < numElts; i++) {  
        tmp[i] = elts[i];  
    }  
    delete [] elts;  
    elts = tmp;  
    sizeElts += 1;  
}
```

1. Allocate a bigger array.
2. Copy the smaller array to the bigger one.
3. Destroy the smaller array.
4. Modify `elts/sizeElts` to reflect the new array.



An `IntSet` is created with a capacity of 1 and  $N > 0$  elements are inserted. How many times can `grow()` be called?

Select all the correct answers.

- **A.** Zero times.
- **B.** Zero to  $N$  times.
- **C.** One to  $N$  times.
- **D.** None of the above.





# Dynamic Resizing

## Group Exercise – Modifying `Insert()`

- Unfortunately, we might end up doing a lot of copying.
- Suppose a client creates an `IntSet` of capacity 1, and then inserts  $N$  elements into it.
- **Question**: What's the number of integer copies performed by the function `grow` in the worst case?

```
void grow() {  
    int *tmp = new int[sizeElts + 1];  
    for (int i = 0; i < numElts; i++) {  
        tmp[i] = elts[i];  
    }  
    delete [] elts;  
    elts = tmp;  
    sizeElts += 1;  
}
```

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

# Dynamic Resizing

## Group Exercise – Modifying `Insert()`

- Suppose a client creates an `IntSet` of capacity 1, and then inserts  $N$  elements into it. What's the number of integer copies in the worst case?

### Answer:

- The worst case happens when all the elements inserted are different!
- Before each new insertion, `numElts == sizeElts`.
- We need to call `grow` each time we insert a new element.
- When we grow an array of size  $k$  to one of size  $k+1$ , we copied  $k$  items.
- We did this for  $k$  from 1 to  $N-1$ .
- So the total number of copies is:

$$O(N^2)$$

$$1 + 2 + \dots + (N-2) + (N-1) = N(N-1)/2$$

# Dynamic Resizing

Group Exercise – Modifying `Insert()`

- Suppose a client creates an `IntSet` of capacity 1, and then inserts  $N$  elements into it. What's the number of integer copies in the worst case?

**Answer:**

- $N(N-1)/2$
- This is a quadratic function in  $N$ .
- This means that as the `IntSet` grows, the cost to build the `IntSet` grows much faster.
- **How can we make this better?**

# Dynamic Resizing

Optimizing `grow()`

- How can we make **`grow()`** better?
- The intuition is that we aren't buying enough room each time we copy the array:
  - We copy  $N$  things, but only buy room for one more slot.
- Instead, we'd like to buy more slots for each  $N$  things we copy.
- The new version is only **slightly** different from the old version.
- However, it has **very** different performance characteristics.

# Dynamic Resizing

Optimizing `grow()`

```
void grow() {  
    int *tmp = new int[sizeElts * 2];  
    for (int i = 0; i < numElts; i++) {  
        tmp[i] = elts[i];  
    }  
    delete [] elts;  
    elts = tmp;  
    sizeElts *= 2;  
}
```

Instead of growing the array by one, we double it.



An `IntSet` is created with a capacity of 1 and  $N > 0$  elements are inserted. How many times can `grow()` be called?

Select all the correct answers.

- A. Up to  $N$  times.
- B. Up to  $N/2$  times.
- C. Up to  $\text{floor}(\log_2(N))$  times.  $\text{floor}(\log_2(N-1))+1$
- D. None of the above.

1	0
2	1
3	2
4	2
5	3



# Dynamic Resizing

## Group Exercise – Optimizing `grow()`

- Suppose a client creates an `IntSet` of capacity 1, and then inserts  $N$  elements into it using the new version of `grow()`.
- **Question**: What's the number of integer copies performed by the function `grow` in the worst case?

```
void grow() {  
    int *tmp = new int[sizeElts * 2];  
    for (int i = 0; i < numElts; i++) {  
        tmp[i] = elts[i];  
    }  
    delete [] elts;  
    elts = tmp;  
    sizeElts *= 2;  
}
```

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

# Dynamic Resizing

Group Exercise – Optimizing `grow()`

## Answer:

- After the first `grow`, the capacity is 2. We copy 1 item.
- After the second `grow`, the capacity is 4. We copy 2 items.
- After the  $k$ -th `grow`, the capacity is  $2^k$ . We copy  $2^{k-1}$  items.
  
- Suppose  $2^m < N \leq 2^{m+1}$
- How many times we need to call `grow`?
  - $m+1$  times
- How many copies we perform?
  - $T = 1 + 2 + 4 + \dots + 2^m = 2^{m+1} - 1 < 2N$



# Dynamic Resizing

Group Exercise – Optimizing `grow()`

## Answer:

- $T$  (the number of copies)  $< 2N$
- So, instead of copying almost  $(N-1)N/2$  elements, we copy fewer than  $2N$  of them.

# Dynamic Resizing

Group Exercise – Optimizing `grow()`

## Answer:

- Here's a little table showing what this means:

# elements	$(N-1)N/2$	$2N$
1	0	2
8	28	16
64	2016	128
512	130816	1024
2048	2096128	4096

- The "double" implementation is **much** better than the "by-one" implementation.

# Reference

- **Problem Solving with C++ (8<sup>th</sup> Edition)**, by *Walter Savitch*, Addison Wesley Publishing (2011)
  - Chapter 11.4 **Classes and Dynamic Arrays**