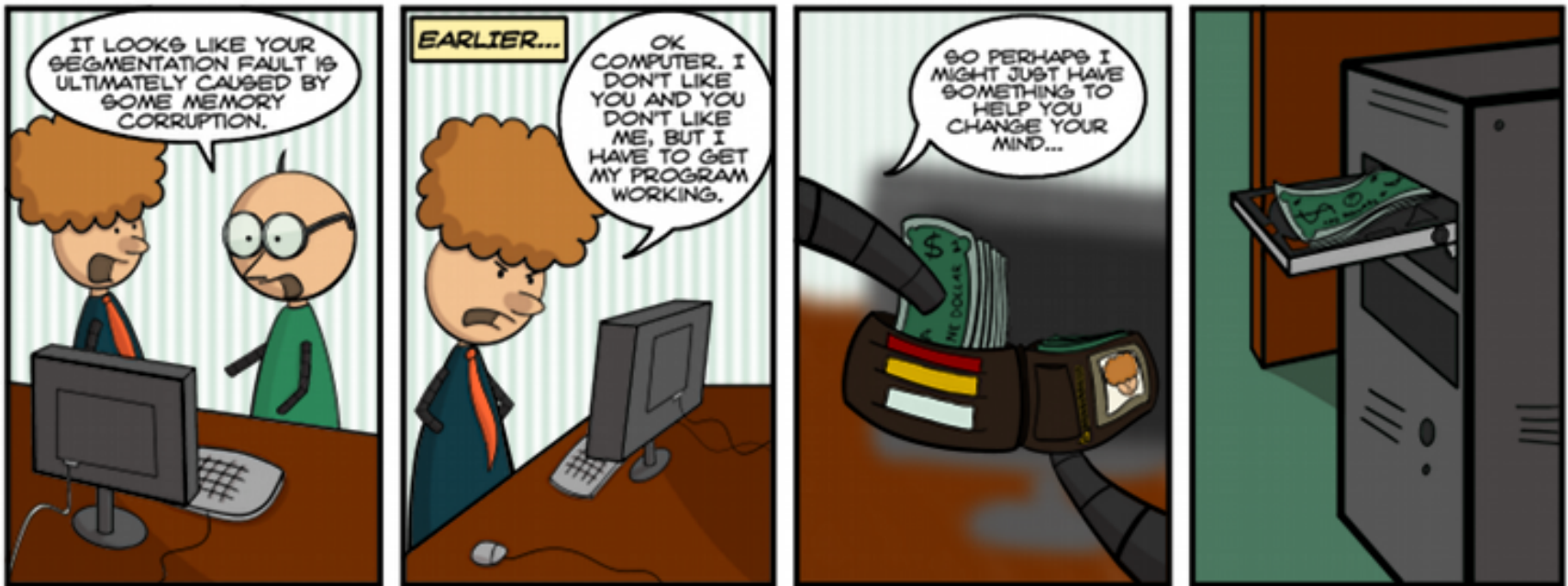


VE280 Programming and Elementary Data Structures

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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 IntSet::grow() {
```

```
① int *tmp = new int[sizeElts + 1];
```

```
② { for (int i = 0; i < numElts; i++) {  
    tmp[i] = elts[i];  
}
```

```
③ delete [] elts;
```

```
④ { 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.

zero to N-1 times

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:

$$\underline{1} + \underline{2} + \dots + (N-2) + (N-1) = N(N-1)/2 = \overset{\downarrow}{O}(N^2)$$

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.
- **D.** None of the above.

$$\text{ceil}(\log_2(N)) \rightarrow \lceil \log_2(N) \rceil$$

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?
 - $T = 1 + 2 + 4 + \dots + 2^m = 2^{m+1} - 1 \leq 2N$

v	size	elts
✓ 1	1	
x 2	2	1
x 3	4	2^2
✓ 4	4	3
x 5	8	2^3
...
N		

after resizing

2nd
3rd
insertion

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:

N ↓ # elements	↓ (N-1) N/2	↓ 2N
1	0	2
8	28	16
64	2016	128
512	130816	1024
→ 2048	<u>2096128</u> ~ 35 mins	<u>4096</u> ~ 4 secs

→ 1 copy ~ 1ms

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

Reference

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