Introduction

Data Structures

This course

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Lectures usually twice a week:

- Wednesdays 13-15, room EA
- Fridays 13-15, room EC

But check TimeEdit in case of exceptions!

Labs

Three labs and one hand-in

- Please submit them in English
- Do them in pairs if possible

Part of the course examination

- Copying strictly forbidden!

Lab supervision (again, check TimeEdit for exceptions):

- Tuesday 13-15, 15-17
- Friday 10-12

All in 3354/3358, starting after Easter

Exercises

Optional (but helpful) exercises

One set a week

- Answers also available on website

No formal exercise sessions, but you can ask Alexander for help at the lab sessions

There is

NO

course book

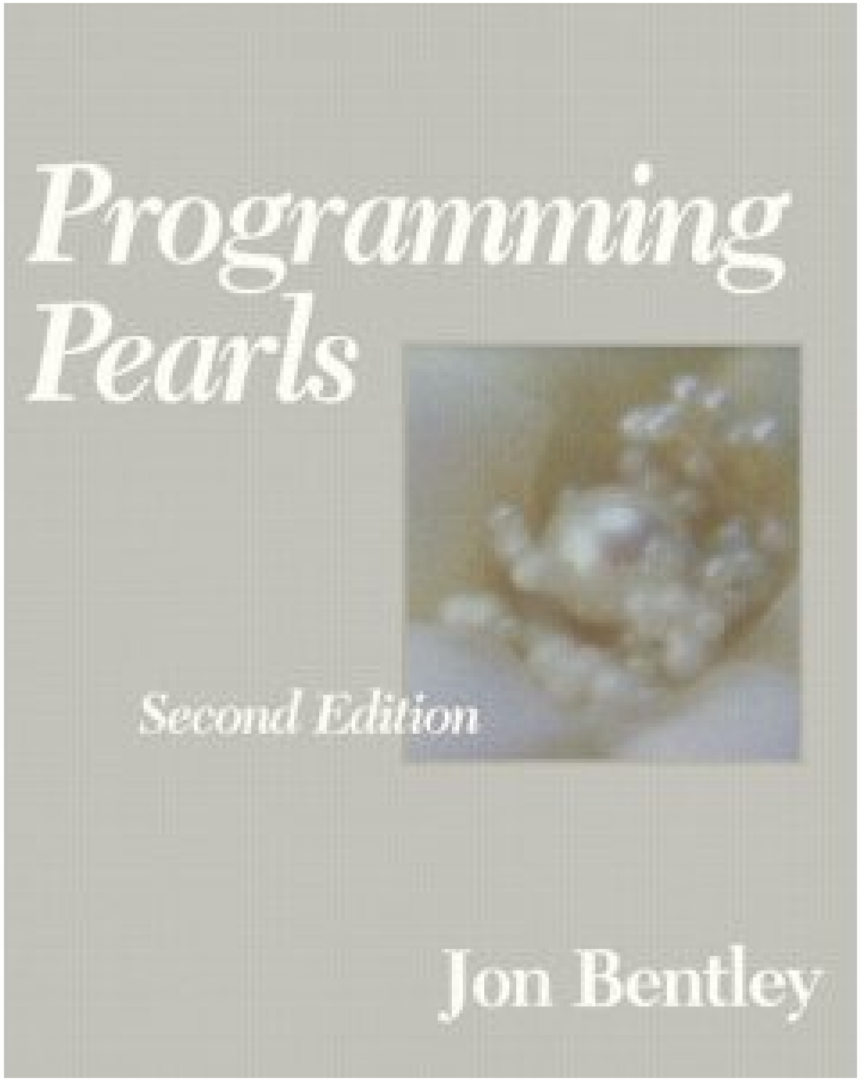
...here are some interesting books instead

Not the course book

- Robert Sedgewick: Algorithms
- Covers most of what's in the course
- Very well-written
- Buy it if you would rather have a textbook anyway

Not the course book

- Jon Bentley: Programming Pearls
- A classic computer science book – imaginative solutions to various programming problems
- A fun read (I think)
- Short and cheap!



A simple problem

Suppose we want to write a program that reads a file, and then outputs it, twice

Idea: read the file into a string

```
String result = “”;
Character c = readChar();
while(c != null) {
    result += c;
    c = readChar();
}
System.out.print(result);
System.out.print(result);
```

A simple problem

Suppose we want [illegible] e a program that reads a file, [illegible] ts it twice

Idea: re [illegible] ng

```
String res[illegible]
Charac[illegible]
while(c ![illegible]
    resu[illegible]
    c = rea[illegible];
}
System.out.print(result);
System.out.print(result);
```

This program is *amazingly slow*!

The right way to solve it?

Use a StringBuilder instead

```
StringBuilder result = new StringBuilder();
Character c = readChar();
while(c != null) {
    result.append(c);
    c = readChar();
}
System.out.print(result);
System.out.print(result);
```

…but: **why is there a difference?**

Behind the scenes

A string is basically an *array of characters*

- String s = “hello” ↔ char[] s = {'h','e','l','l','o'}

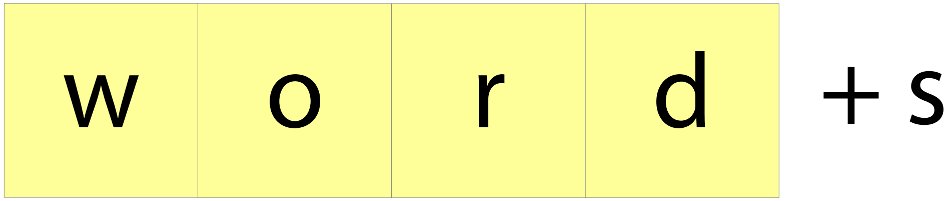
This little line of code…

```
  result = result + c;
```

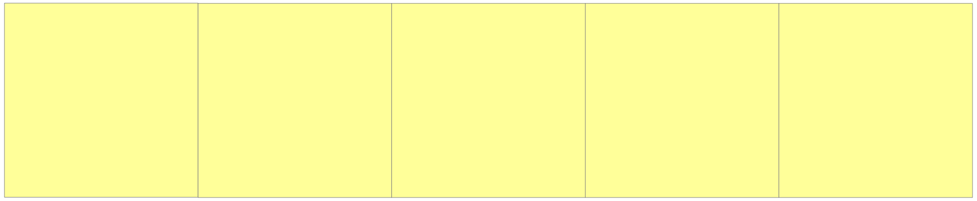
is:

- Creating a new array one character longer than before
- Copying the original string into the array, one character at a time
- Storing the new character at the end

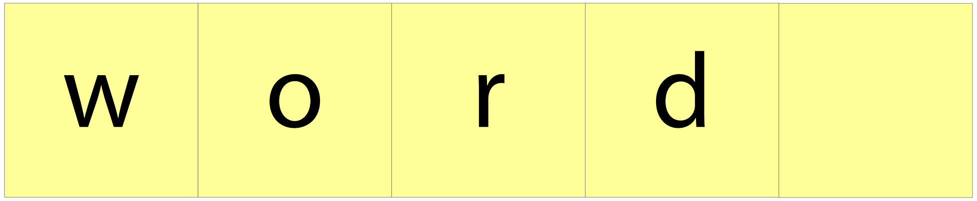
(See CopyNaive.java)



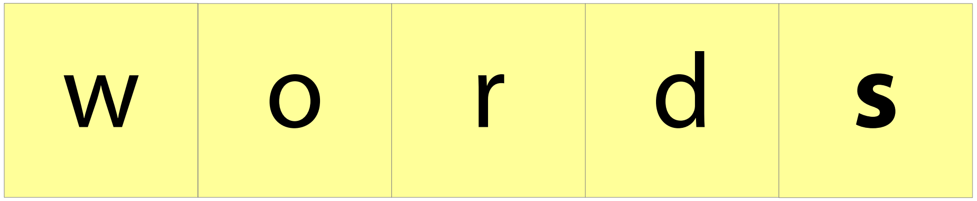
1. Make a new array



2. Copy the old array there



3. Add the new element



Well, is it really so bad?

Appending a single character to an string of length *i* needs to copy *i* characters

Imagine we are reading a file of length *n*

- …we append a character *n* times
- …the string starts off at length 0, finishes at length *n*
- …so average length throughout is *n/2*
- total: $n \times n/2 = n^2/2$ characters copied

For "War and Peace", n = 3600000

so 1800000 × 3600000 = **6,480,000,000,000** characters copied!

No wonder it's slow!

Improving it (take 1)

It's a bit silly to copy the whole array every time we append a character

Idea: add some slack to the array

- Whenever the array gets full, make a new array that's (say) 100 characters bigger
- Then we can add another 99 characters before we need to copy anything!
- Implementation: array+variable giving size of *currently used* part of array

(See Copy100.java)

h	e	l	l	o		w	o	r	l

Add an element:

h	e	l	l	o		w	o	r	l
d									

Add an element:

h	e	l	l	o		w	o	r	l
d	**!**								

Improving it (take 1)

Does this idea help?

We will avoid copying the array 99 appends out of 100

In other words, we will copy the array **1/100th** as often…

…so instead of copying **6,480,000,000,000** characters, we will copy only **64,800,000,000!**
(Oh. That's still not so good.)

Improving it (take 2)

Another idea: whenever the array gets full, **double** its size

That way, we need to copy the array *less and less often* as it gets bigger

Does this work?

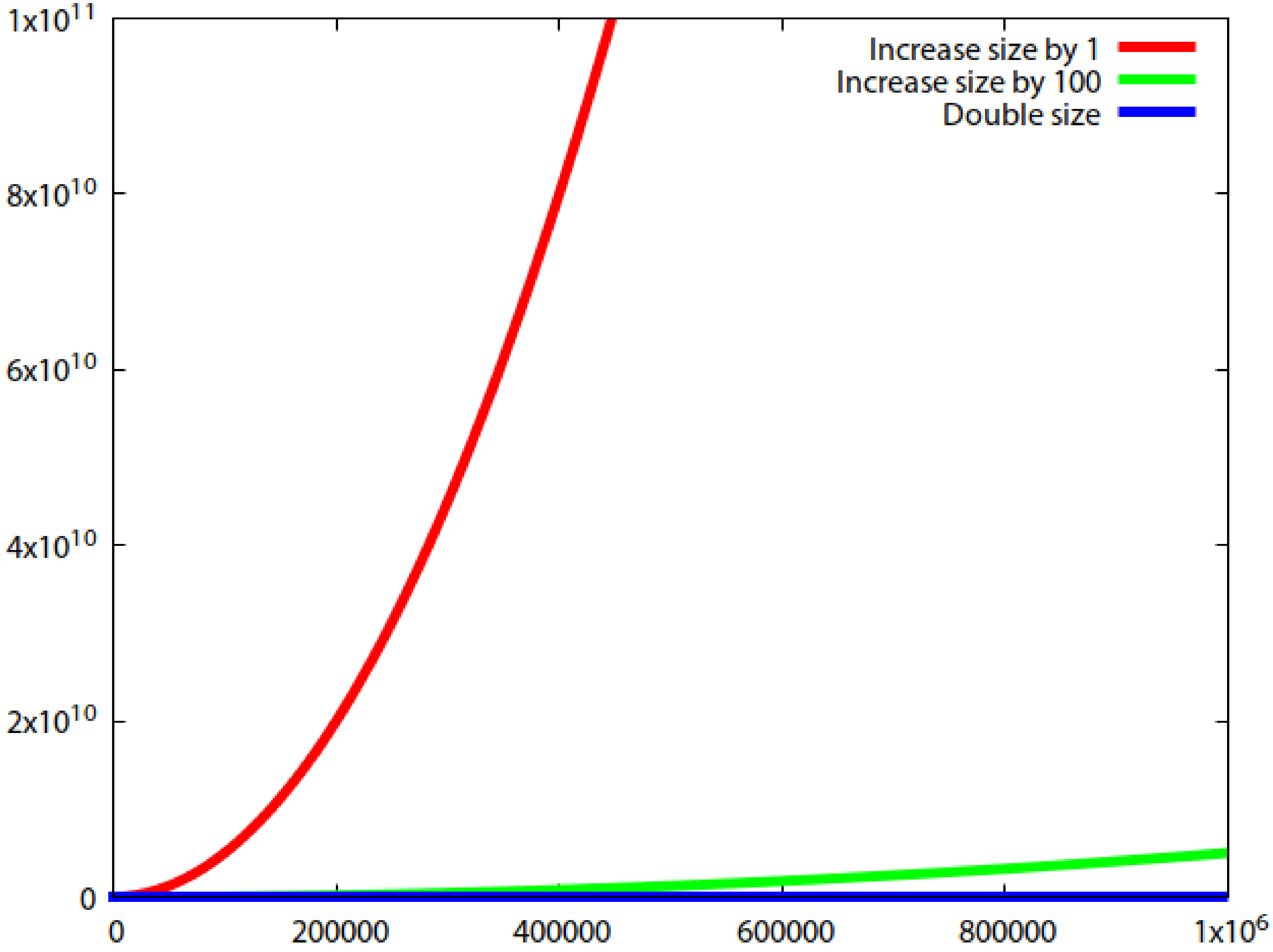
Improving it (take 2)

Let's calculate *how many characters are copied per character appended to the string*

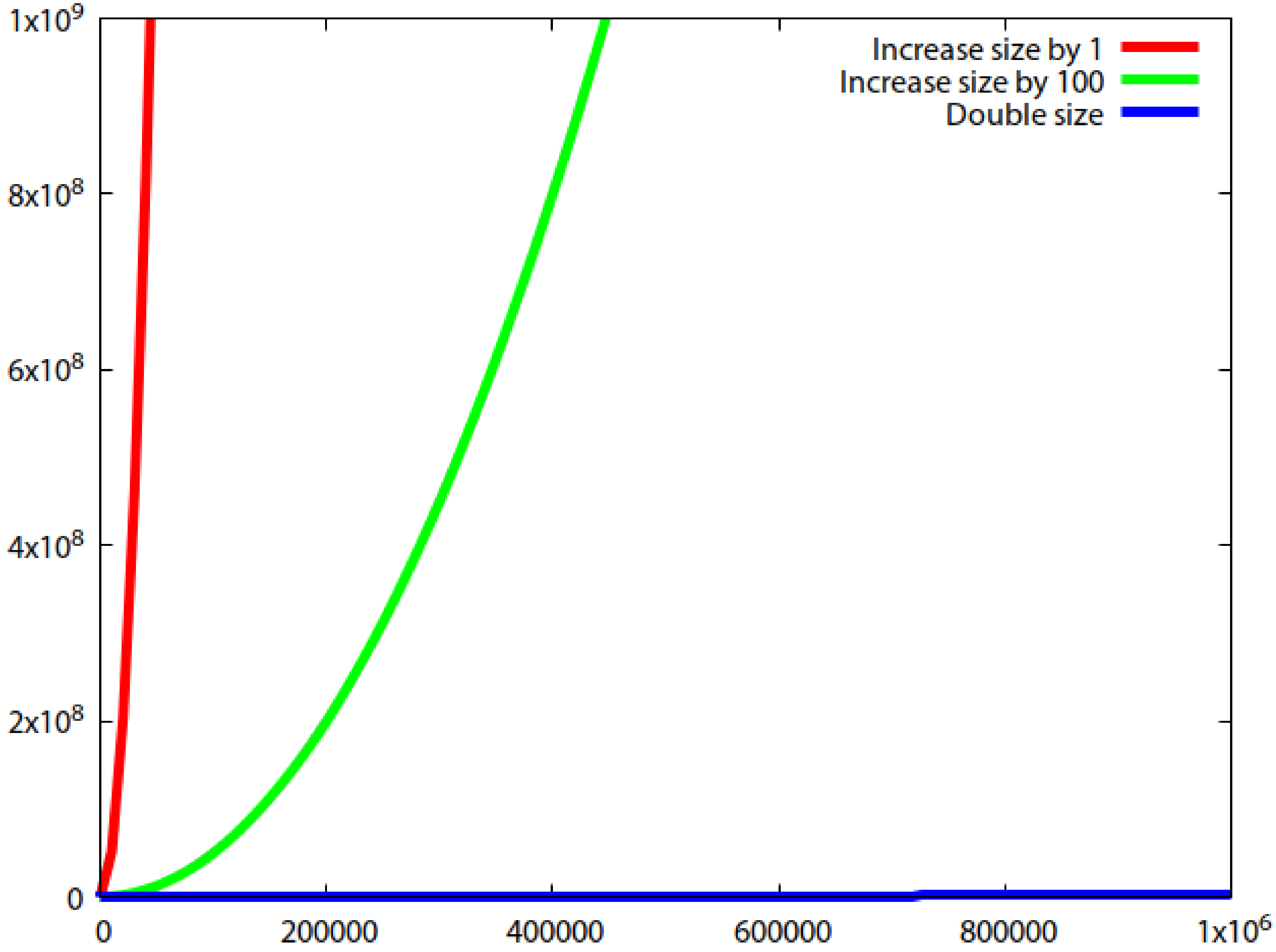
- Imagine we have just expanded the array
- It must have size *2n* and contain *n+1* characters
- The next *n-1* appends don't copy anything
- The next append after that copies *2n* characters
- *n* characters appended, *2n* characters copied: average of 2 characters copied per append

For “War and Peace”, we copy **~7,200,000** characters. A million times less than the first version!

Performance – a graph

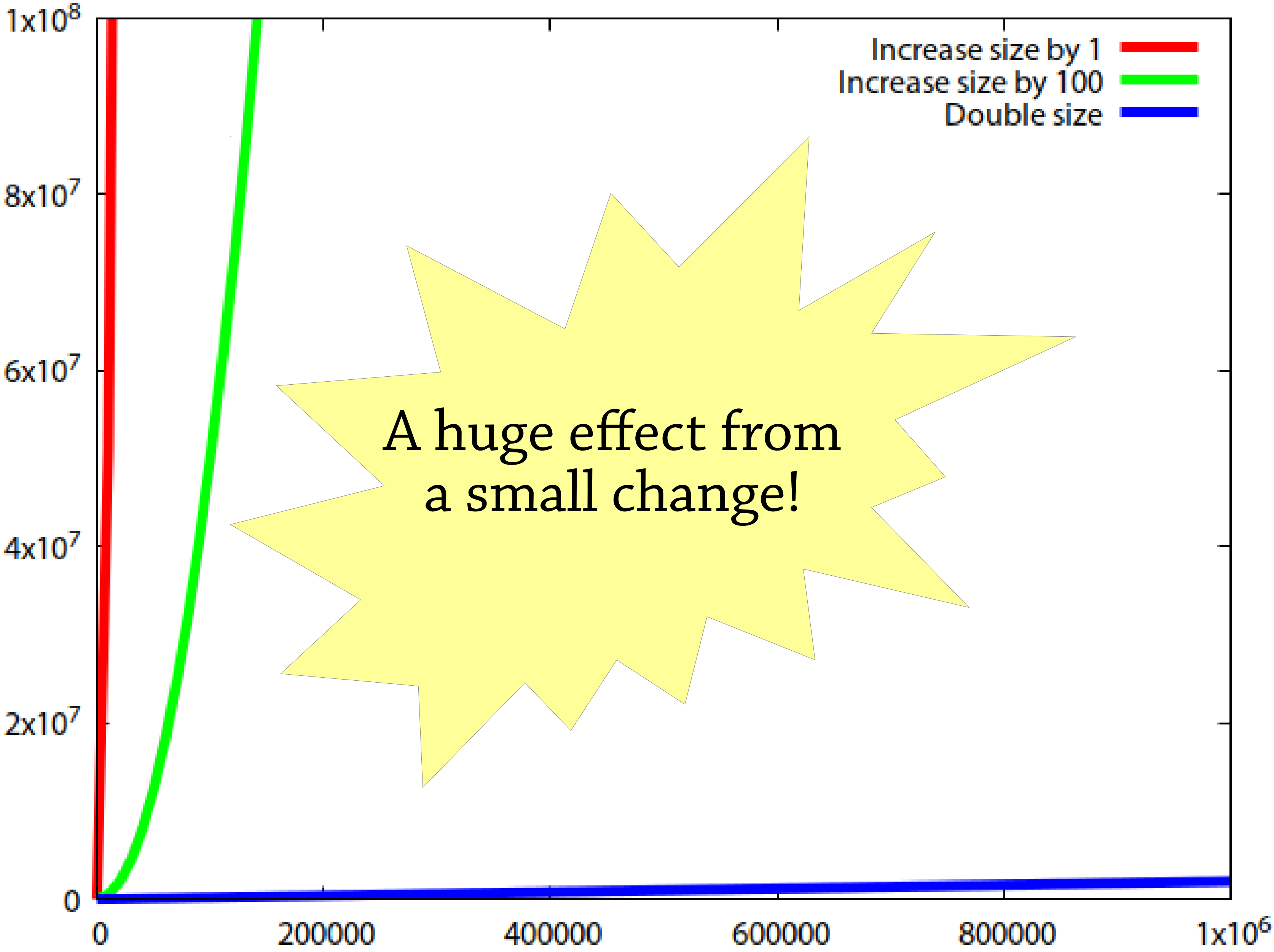


Zoom in!



1x10^9
8x10^8
6x10^8
4x10^8
2x10^8
0
0
200000
400000
600000
800000
1x10^6
Increase size by 1
Increase size by 100
Double size

Zoom in!



A huge effect from a small change!

Why does it work really?

The important property:

- After resizing the array, the new array is no more than half full
- For every "expensive" step of copying *2n* characters, there are *n* "cheap" steps with no copying => constant cost of 2 characters copied per step

Also works if we e.g. increase array size by 50% instead of doubling!

Dynamic arrays

A dynamic array is like an array, but can be resized – very useful data structure:

- `E get(int i);`
- `void set(int i, E e);`
- `void add(E e);`

Implementation is just as in our file-reading example:

- An array
- A variable storing the size of the used part of the array
- `add` copies the array when it gets full, but doubles the size of the array each time

Called `ArrayList` in Java

About strings and StringBuilder

String: array of characters

- Fixed size
- Immutable (can't modify once created)

StringBuilder: *dynamic* array of characters

- Can be resized and modified efficiently

Why can't the String class use a dynamic array?

A puzzle

Suppose we want to also be able to delete the last element from our dynamic array.

How should we implement it?

Think about:

- Memory use
  (we don't want e.g. an array of size 100000 with only 10 elements in it)
- Performance
  (it shouldn't be possible to make the operations start to run slowly)

A puzzle

Suppose we want to also be able to delete the last element from our dynamic array.

How should we implement it?

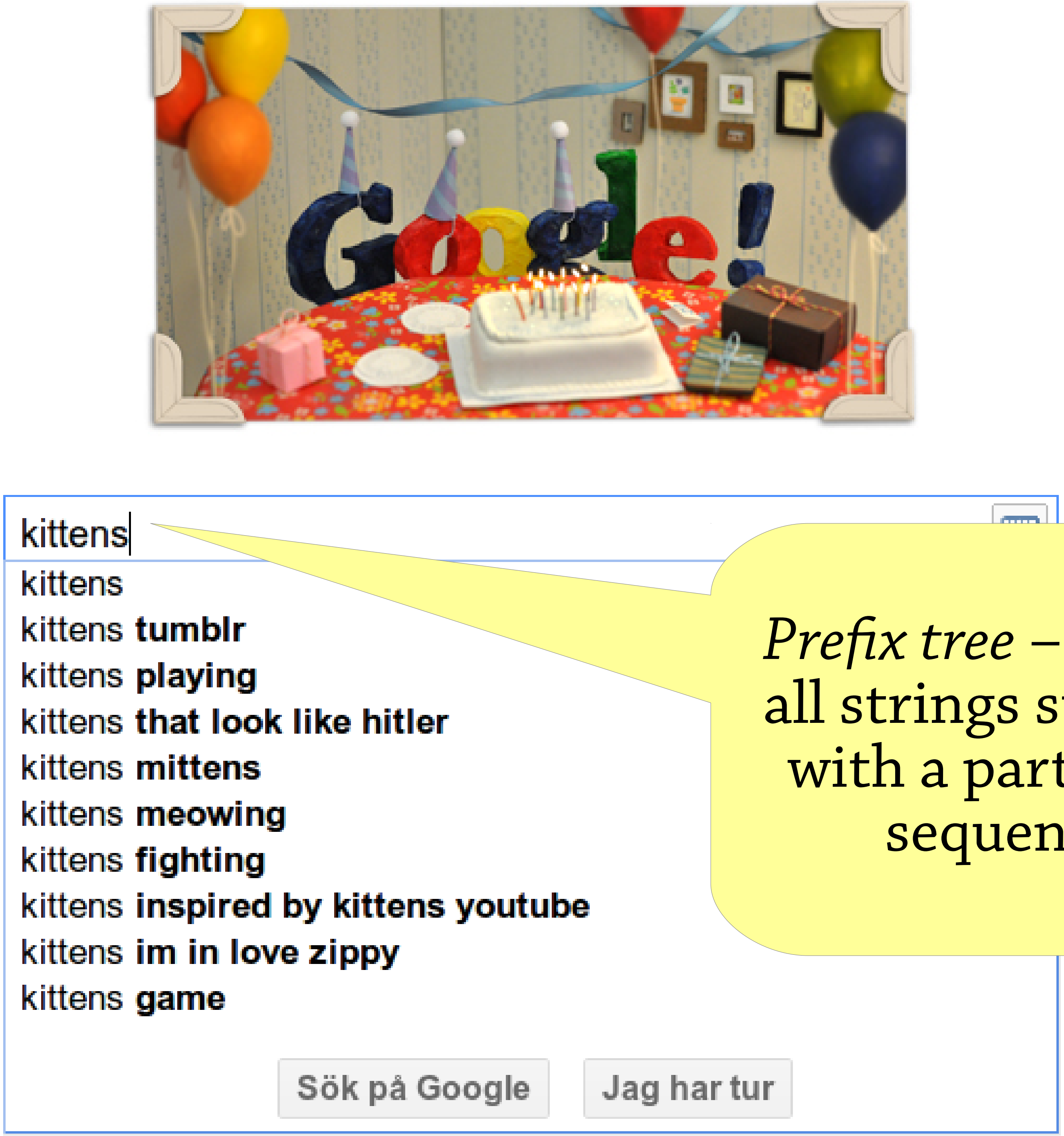
- Simply decrement the size variable?
  - Can also set write `null` to the deleted index, so the deleted element can be garbage collected
  - Wastes space
- Resize the array when it gets half full?
  - Gives bad performance! (Exercise: work out why)
- Resize the array when it gets a quarter full?
  - Good performance but wastes space

So what is a data structure anyway?

Vague answer: any way of organising the data in your program

A data structure always supports a particular set of *operations*:

- Arrays: get (`a[i]`), set (`a[i]=x`), create (`new int[10]`)
- Dynamic arrays: same as arrays plus `add/remove`
- Haskell lists: `cons`, `head`, `tail`
- Many, many more…



kittens

kittens
kittens **tumblr**
kittens **playing**
kittens **that look like hitler**
kittens **mittens**
kittens **meowing**
kittens **fighting**
kittens **inspired by kittens youtube**
kittens **im in love zippy**
kittens **game**

Prefix tree – return all strings starting with a particular sequence

Interface vs implementation

As a user, you are mostly interested in *what operations* the data structure supports, not how it works

Terminology:

- The set of operations is an *abstract data type (ADT)*
- The data structure *implements* the ADT
- Example: *map* is an ADT which can be implemented by a binary search tree, a 2-3 tree, a hash table, … (we will come across all these later)

Interface vs implementation

Why study how data structures work inside? Can't we just use them?

- As computer scientists, you ought to understand how things work inside
- Sometimes you need to *adapt* an existing data structure, which you can only do if you understand it
- The best way to learn how to *design your own* data structures is to study lots of existing ones

This course

- *How to design* data structures
  - Lectures and exercises
- *How to reason* about them
  - Lectures, exercises, hand-in
- *How to use them* and pick the right one
  - Labs and exercises

Big points

“Brute force” programming works up to a point

- After that you need to *think*!
- Using the right data structures makes your program *simpler* and *faster*

Most data structures are based on some simple idea

Reasoning helps to get things right

- Dynamic arrays work because the array is always half empty after resizing
- Identifying this helped us get deletion right

Next time: reasoning about performance