

# INF102

## Algorithms, Data Structures and Programming

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# INF102, practical stuff

- ▶ Lecturer: Marc Bezem; Team: see homepage
- ▶ Homepage: [INF102](#) (hyperlinks in red)
- ▶ Also: [GitHub](#) (recommended); Dropbox: [slides](#), [schedule](#)
- ▶ Textbook: [Algorithms, 4th edition](#)
- ▶ Prerequisites: INF100 + 101 ( $\approx$  Ch. 1.1 + 1.2)
- ▶ Syllabus (pensum): Ch. 1.3 – 1.5, Ch. 2 – 4
- ▶ Exam: three compulsory exercises and a [written exam](#)
- ▶ Old exams: [2004–2013](#), [2014](#)
- ▶ [Table of Contents of these slides](#)

# Resources

- ▶ Good textbook, USA-style: many pages, exercises etc.
- ▶ Average speed must be ca 50 pages p/w
- ▶ Lectures (ca 24) focus on the essentials
- ▶ Slides (ca 120, dense!) summarize the lectures
- ▶ Prepare yourself by reading in advance
- ▶ Workshops: selected exercises
- ▶ Test yourself by trying some exercises in advance
- ▶ If you can do the exercises (incl. compulsory), you are fine
- ▶ Review of exercises on Friday morning

## Generic Bags, Queues and Stacks

- ▶ Generic programming in Java, example: **PolyPair.java**
- ▶ Bag, Queue and Stack are generic, iterable collections
- ▶ Queue and Stack: Ch. 9 in textbook INF100/1
- ▶ APIs include: `boolean isEmpty()` and `int size()`
- ▶ All three support adding an element
- ▶ Queue and Stack support removing an element (if any)
- ▶ FIFO Queue (en/dequeue), LIFO Stack (push/pop)
- ▶ Dijkstra's Two-Stack Expression Evaluation **Movie**
- ▶ Example:  $( 1 + ( ( 2 + 3 ) * ( 4 * 5 ) ) )$

## Implementations

- ▶ `ResizingArray_Stack.java`
- ▶ Arrays give direct access, but have fixed size
- ▶ Resizing takes time and space proportional to size
- ▶ `LinkedList_Stack.java`
- ▶ No fixed size, but indirect access
- ▶ Pointers take space and dereferencing takes time
- ▶ Programming with pointers: make a picture
- ▶ `LinkedList_Queue.java`

## Computation time and memory space

- ▶ Two central questions:
  - ▶ How long will my program take?
  - ▶ Will there be enough memory?
- ▶ Example: **ThreeSum.java**
- ▶ Inner loop (here  $a[i] + a[j] + a[k] == 0$ ) is important
- ▶ Sorting helps: **ThreeSumOptimized.java**
- ▶ Run some experiments: `1Kints.txt`, `2Kints.txt`, ...

## Methods of Analysis

- ▶ Empirical:
  - ▶ Run program with randomized inputs, measuring time & space
  - ▶ Run program repeatedly, doubling the input size
  - ▶ Measuring time: **StopWatch**
  - ▶ Plot, or log-log plot and **linear regression**
- ▶ Theoretical:
  - ▶ Define a cost model by abstraction (e.g., array accesses, comparisons, operations)
  - ▶ Try to count/estimate/average this cost as function of the input (size)
  - ▶ Use  $O(f(n))$  and  $f(n) \sim g(n)$

## ThreeSum, empirically

- ▶ Input sizes 1K, 2K, 4K, 8K take time 0.1, 0.8, 6.4, 51.1 sec
- ▶ The log's are 3, 3.3, 3.6, 3.9 and -1, -0.1, 0.8, 1.71
- ▶ Basis of the logarithm should be the same for both
- ▶ Linear regression gives  $y \approx 3x - 10$
- ▶  $\log(f(n)) = 3 \log(n) - 10$  iff

$$f(n) = 10^{\log(f(n))} = 10^{3 \log(n) - 10} = n^3 * 10^{-10}$$

- ▶ Conclusion: cubic in the input size, with constant  $\approx 10^{-10}$
- ▶ Strong dependence on input can be a problem
- ▶ Constant  $10^{-10}$  depends on computer, exponent 3 does not



## ThreeSum, theoretically

- ▶ Number of different picks of triples:  $g(n) = n(n-1)(n-2)/6$
- ▶ Inner loop  $a[i] + a[j] + a[k] == 0$  executed  $g(n)$  times
- ▶  $g(n) = n^3/6 - n^2/2 + n/3$
- ▶ Cubic term  $n^3/6$  wins for large  $n$
- ▶ Computational model # array accesses:  $3 * n^3/6 = n^3/2$
- ▶ Cost array access  $t$  sec: time  $t * n^3/2$  sec
- ▶ Cost models are abstractions! (NB cache)

## Big Oh, and $\sim$

- ▶ Q: 'wins for large  $n$ ' uhh???
- ▶ A: Big Oh, and  $\sim$  will clear this up
- ▶ Costs are positive quantities, so  $f, g, \dots : \mathbb{N} \rightarrow \mathbb{R}^+$
- ▶ MNF130:  $f(n)$  is  $O(g(n))$  if there exist  $c \in \mathbb{R}^+$ ,  $N \in \mathbb{N}$  such that  $f(n) \leq cg(n)$  for all  $n \geq N$  (that is,, for  $n$  large enough)
- ▶ Example:  $n^2$  and even  $99n^3$  are  $O(n^3)$ , but  $n^3$  is not  $O(n^{2.9})$
- ▶ INF102:  $f(n) \sim g(n)$  if  $1 = \lim f(n)/g(n)$
- ▶ If  $f(n) \sim g(n)$ , then  $f(n)$  is  $O(g(n))$  and  $g(n)$  is  $O(f(n))$
- ▶ Big Oh and  $\sim$  aim to capture 'order of growth'
- ▶ Big Oh abstracts from constant factors,  $\sim$  does not
- ▶ Large constant factors are important!

## Important orders of growth

- ▶ constant:  $c$ ,  $f(n) = c$  for all  $n$
- ▶ linear:  $n$  (compare all for  $n = 20$  sec)
- ▶ linearithmetic:  $n \log n$
- ▶ quadratic:  $n^2$
- ▶ cubic:  $n^3$
- ▶ exponential:  $2^n$
- ▶ general form:  $an^b(\log n)^c$

## Logarithms and Exponents

- ▶ Definition:  $\log_x z = y$  iff  $x^y = z$  for  $x > 0$
- ▶ Inverses:  $x^{\log_x y} = y$  and  $\log_x x^y = y$
- ▶ Exponent:  $x^{(y+z)} = x^y x^z$ ,  $x^{(yz)} = (x^y)^z$
- ▶ Logarithm:  $\log_x(yz) = \log_x y + \log_x z$ ,  $\log_x z = \log_x y \log_y z$
- ▶ Base of logarithm: the  $x$  in  $\log_x$
- ▶ Various bases:  $\log_2 = \lg$ ,  $\log_e = \ln$ ,  $\log_{10} = \log$
- ▶ Double exponent: e.g.  $2^{(2^n)}$  (not used in INF102)
- ▶ Double logarithm:  $\log(\log n)$  (not used in INF102)

## Examples

- ▶ Worst case: guaranteed, independent of input
- ▶ Average case: not guaranteed, dependent of input *distribution*
- ▶ Linked list implementations of Stack, Queue and Bag: all operations take constant time in the worst case
- ▶ Resizing array implementations of Stack, Queue and Bag: adding and deleting take linear time in the worst case (easy)
- ▶ Amortized: worst-case cost *per operation*. E.g., each 10-th operation has cost  $\leq 21$ , all others cost 1, amortized  $\leq 3$  p/o.
- ▶ Resizing arrays: adding and deleting take constant time *per operation* in the worst case (proof is difficult)
- ▶ Special case of resizing array that is only growing:  
 $1(2)2(4)3(8)4(16)5(32)6(64)7(128)8(256)9 \dots 16(32) \dots$ , with  $(n)$  the new size.  
 Resizing to  $(n)$  costs  $2n$  array accesses, so in total  
 $(1+4)+(1+8)+(2+16)+(4+32)+(8+64) \dots$ , so 9 p/push.

## Staying Connected

- ▶ MNF130: relation  $E \subseteq V \times V$  is an *equivalence* if
  - ▶  $E$  is *reflexive*:  $\forall x \in V. E(x, x)$
  - ▶  $E$  is *symmetric*:  $\forall x, y \in V. E(x, y) \rightarrow E(y, x)$
  - ▶  $E$  is *transitive*:  $\forall x, y, z \in V. E(x, y) \wedge E(y, z) \rightarrow E(x, z)$
- ▶ We assume connectedness to be an equivalence
- ▶ Dynamic connectivity means that  $R$  can grow and shrink
- ▶ Example: if the 'Bergensbanen' is broken, Oslo and Bergen are no longer connected by rail
- ▶ We want efficient algorithms and datastructures for testing whether two objects are connected
- ▶ Clear relationship with paths in graphs, (connected) components (MNF130)
- ▶ We take  $V = \{0, \dots, N - 1\}$ .

## Union Find

- ▶ UF, idea: every component has an identifier ('hub'), which has edges ('spokes') to the elements of its component
- ▶ API: **UF**
- ▶ Implementations with `int[] id` containing the identifiers
  - ▶ **SlowUF.java**
  - ▶ **FastUF.java**
  - ▶ **WeightedUF.java**
- ▶ WeightedUF: log depth of tree (Proposition X)

# Sorting

- ▶ Sorting: putting objects in a certain order
- ▶ MNF130: relation  $R \subseteq V \times V$  is a *total order(ing)* if
  1.  $R$  is *reflexive*:  $\forall x \in V. R(x, x)$
  2.  $R$  is *transitive*:  $\forall x, y, z \in V. R(x, y) \wedge R(y, z) \rightarrow R(x, z)$
  3.  $R$  is *antisymmetric*:  $\forall x, y \in V. R(x, y) \wedge R(y, x) \rightarrow x = y$
  4.  $R$  is *total*:  $\forall x, y \in V. R(x, y) \vee R(y, x)$
- ▶ Natural orderings:
  - ▶ Numbers of any type: ordinary  $\leq$  and  $\geq$
  - ▶ Strings: lexicographic
  - ▶ Objects of a Comparable type:  $v.\text{compareTo}(w) < 0$



## Sorting (ctnd)

- ▶ Bubble sort: `ExampleSort.java`
- ▶ Certification: `assert isSorted(a)` in `main()`
- ▶ No guarantee against modifying the array (but `exch()` is safe)
- ▶ Costmodel 1: number of `exch()`'s and `less()`'s
- ▶ Costmodel 2: number of array accesses
- ▶ Pitfalls: cache misses, expensive `v.compareTo(w) < 0`
- ▶ Why studying sorting? (`java.util.Arrays.sort()`)
- ▶ Comparing sorting algorithms: `CompareSort.java`

## Selection Sort

- ▶ Bubble sort:  $\sim n^2/2$  compares, 0 . .  $\sim n^2/2$  exchanges
- ▶ Selection sort:
  - ▶ Find index of a minimal value  $a[1..n]$ , exchange with  $a[1]$
  - ▶ Find index of a minimal value  $a[2..n]$ , exchange with  $a[2]$
  - ▶ ... until  $n-1$
- ▶ Selection sort:  $\sim n^2/2$  compares,  $n-1$  exchanges

```
public static void sort(Comparable[] a) {  
    int N = a.length;  
    for (int i=0; i<N-1; i++){  
        int min=i;  
        for (int j=i+1; j<N; j++) if (less(a[j],a[min])) min=j;  
        exch(a,i,min);  
    }  
}
```

## Insertion sort

- ▶ Insertion sort:
  - ▶ Insert  $a[2]$  on its correct place in (sorted)  $a[1..1]$
  - ▶ Insert  $a[3]$  on its correct place in (sorted)  $a[1..2]$
  - ▶ ... until  $a[n]$
- ▶ Very good for partially sorted arrays, costs:
  - ▶ Best case:  $n-1$  compares and 0 exchanges
  - ▶ Worst case:  $\sim n^2/2$  compares and exchanges
  - ▶ Average case:  $\sim n^2/4$  compares and exchanges (distinct keys)

```
public static void sort(Comparable[] a) {  
    int N = a.length;  
    for (int i=1; i<N; i++){  
        for (int j=i; j>0 && less(a[j],a[j-1]); j--)  
            exch(a,j,j-1);  
    }  
}
```

## Shell sort

- ▶ Insertion sort:
  - ▶ Very good for partially sorted arrays
  - ▶ Slow in transport: step by step `exch(a,j,j-1)`
- ▶ Idea: h-sort, `a[i], a[i+h], a[i+2h], ...` sorted (any `i`)

```
public static void hsort(int h, Comparable[] a) {  
    int N = a.length;  
    for (int i=h; i<N; i++)  
        for (int j=i; j-h>=0 && less(a[j],a[j-h]); j-=h)  
            exch(a,j,j-h);  
}
```

- ▶ Insertion sort: `hsort(1,a)`
- ▶ Shell sort: e.g., `hsort(10,a); hsort(1,a)`

## Shell sort (ctnd)

- ▶ `hsort(10,a); hsort(1,a)` faster than just `hsort(1,a)` !
- ▶ Q: How is this possible?
- ▶ A: `hsort(10,a)` transports items in steps of 10, which would be done by `hsort(1,a)` in 10 steps of 1
- ▶ What about `hsort(100,a); hsort(10,a); hsort(1,a)`?
- ▶ To be expected: depends on the length N of the array
- ▶ Book:

# Mergesort

- ▶ Top-down (recursive) algorithm:
  - ▶ Mergesort left half, mergesort right half
  - ▶ Merge the results
- ▶ Using an auxiliary array: [TopDownMergeSort.java](#), [Movie](#)
- ▶ Bottom-up algorithm:
  - ▶ Merge  $a[0], a[1], a[2], a[3], a[4], a[5], \dots$
  - ▶ Merge  $a[0..1], a[2..3], a[4..5], a[6..7], \dots$
  - ▶ Merge  $a[0..3], a[4..7], a[8..11], a[12..15], \dots$
- ▶ Also using an auxiliary array: [BottomUpMergeSort.java](#)

## The complexity of sorting

- ▶ Mergesort uses between  $\sim (n/2) \lg n$  and  $\sim n \lg n$  compares
- ▶ Mergesort uses between  $\sim 6n \lg n$  array accesses
- ▶ Mergesort uses  $\sim 2n$  space (plus some var's)
- ▶ Q: How fast can compare-based sorting be?
- ▶ Book:

# Quicksort

- ▶ Top-down (recursive) algorithm:
  - ▶ Choose a (pivot value)  $v$  in the array
  - ▶ Partition the array in non-empty parts  $\leq v$  and  $\geq v$
  - ▶ Quicksort the two parts
- ▶ Pros: in-place, average computation time  $O(n \log n)$
- ▶ Cons: stack space for the recursion, worst-case  $O(n^2)$
- ▶ Implementation: **QuickSort.java**



## Quicksort, details

- ▶ Subtleties in `partition`:
  - ▶ Invariants  $l \leq h$  in the two inner loops
  - ▶ Postcondition after the two inner loops
  - ▶ Invariant of the `for(;;)` loop
  - ▶ Termination of the `for(;;)` loop
- ▶ Termination of recursive `quicksort`

## Quicksort, performance

- ▶ Compare Quicksort to other sorting methods ( $n = 10^2, 10^3, \dots$ )
- ▶ Quicksort runs in quadratic time if pivot is always smallest (largest)
- ▶ Randomization is important (choose pivot randomly, or shuffle array)
- ▶ If all keys are distinct and randomization is perfect, then quicksort uses on average  $\sim 2n \ln n$  compares (proof on blackboard)
- ▶ Similar result for exchanges holds (proof is complicated)
- ▶ Relevant improvements:
  - ▶ Cutoff to insertion sort for sizes  $\leq M$
  - ▶ Median-of-three pivot
  - ▶ Taking advantage of duplicate keys (3-way partitioning)
- ▶ Quicksort is generally very good, ... bucketsort

## ToC and topics of general interest

- ▶ Table of Contents on next slide (all items clickable)
- ▶ Practical stuff: slide 2

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