Part I

Overview
Organization

- Master CSE → compulsory
  Master BiomedComp → elective
  Master Informatics → “bridge” courses
- Extent: 2+2 SWS / 5 credits
- Lectures: Tuesday 10–12, 02.07.023, at first online
- Exercises/Tutorials (by Muqsit Azeem and Kush Grover): Tuesday and Thursday 16–18, at first online online
  Please register separately for the “Tutorials for Fundamental Algorithms (CSE) (IN2157)”
- Slides, tutorial sheets and announcements on the website
  https://www.in.tum.de/i07/lehre/ws21-22/fundamental-algorithms-cse/
Contents

Cormen, Leiserson, Rivest, Stein: Introduction to Algorithms. MIT Press

Topics:

- Fundamentals (Analysis, Complexity Measures)
- Sorting
- Parallel Algorithms
- Searching (hashing, search trees, . . . )
- Arithmetic problems (e.g. parallel matrix and vector operations)
- Graph problems
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Techniques: (more important!)

- Analysis of “fundamental” algorithms
  - Correct?
  - Efficient?
- Aim: get common basis for other lectures
Color Code for Headers

Blue Headers:

• for all slides with regular topics
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Green Headers:

• summarized details: will be explained in the lecture, but usually not as an explicit slide; “green” slides will only appear in the handout versions
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Orange Headers:
• advanced topics or outlook

Black Headers:
• repeat fundamental concepts that are probably already known, but are important throughout the lecture
Part II

Algorithms
What is an Algorithm? – Some Definitions

Definition (found on numerous websites)

An algorithm is a set of rules that specify the order and kind of arithmetic operations that are used on a specified set of data.
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**Definition (Wikipedia)**

An algorithm is an effective method expressed as a finite list of well-defined instructions for calculating a function.
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**Definition (Donald Knuth)**

An algorithm is a finite, definite, effective procedure, with some output.

**Definition (Britannica.com)**

Systematic procedure that produces – in a finite number of steps – the answer to a question or the solution of a problem.
Example Algorithm: Chocolate Chip Cookies

**Ingredients:**
- 1 cup butter, softened
- 1 cup white sugar
- 1 cup packed brown sugar
- 2 eggs
- 2 teaspoons vanilla extract
- 3 cups all-purpose flour
- 1 teaspoon baking soda
- 2 teaspoons hot water
- 1/2 teaspoon salt
- 2 cups semisweet chocolate chips
- 1 cup chopped walnuts

**Directions:**
1. Preheat oven to 350 degrees F (175 degrees C).
2. Cream together the butter, white sugar, and brown sugar until smooth. Beat in the eggs one at a time, then stir in the vanilla. Dissolve baking soda in hot water. Add to batter along with salt. Stir in flour, chocolate chips, and nuts. Drop by large spoonfuls onto ungreased pans.
3. Bake for about 10 minutes in the preheated oven, or until edges are nicely browned.
Problem vs. problem instance

Definition

*Problem*: Sorting

*Input*: A sequence of $n$ keys $a_1, \ldots, a_n$

*Output*: The permutation (reordering) $a'_1, \ldots, a'_n$ of the input sequence such that $a'_1 \leq a'_2 \leq \cdots \leq a'_{n-1} \leq a'_n$
Essential properties of an algorithm

- an algorithm is **finite**
  (w.r.t.: set of instructions, use of resources, time of computation)
- instructions are **precise** and **computable**
- instructions have a specified logical order, however, we can discriminate between
  - **deterministic** algorithms
    (every step has a well-defined successor)
  - **non-deterministic** algorithms
    (randomized algorithms, e.g.)
  - how about **parallel** algorithms?
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  - deterministic algorithms (every step has a well-defined successor)
  - non-deterministic algorithms (randomized algorithms, e.g.)
- how about parallel algorithms? (→ “logical order” can be parallel as well as non-deterministic)
- produce a result
Basic Questions About Algorithms

For each algorithm, we should answer the following basic questions:

- does it terminate?
- is it correct?
- is the result of the algorithm determined?
- how much resources will it use in terms of
  - memory? (and memory bandwidth?)
  - operations?
  - run-time?
  - . . . ?
Example: Fibonacci Numbers

Definition
The sequence \( f_j, j \in \mathbb{N} \), of the Fibonacci numbers is defined recursively as:

\[
\begin{align*}
    f_0 & := 1 \\
    f_1 & := 1 \\
    f_j & := f_{j-1} + f_{j-2} \quad \text{for} \quad j \geq 2
\end{align*}
\]

Origin: simple model of a rabbit population
- starts with one pair of rabbits (male and female)
- every month, each pair of rabbits gives birth to a new pair
- but: new-born rabbits need one month to become mature

(compare lecture in Scientific Computing)
A Recursive Algorithm for the Fibonacci Numbers

Fibonacci algorithm:

\[
\text{Fibo}(n : \text{Integer}) : \text{Integer} \{
\text{if } n = 0 \text{ then return } 1;
\text{if } n = 1 \text{ then return } 1;
\text{if } n > 1 \text{ then return } \text{Fibo}(n-1) + \text{Fibo}(n-2);
\}
\]

→ How many arithmetic operations does it take to compute \(f_j\)?

**Definition**

\(T_{\text{Fibo}}(n)\) shall be the number of arithmetic operations (here: additions) that the algorithm Fibo will perform with \(n\) as input parameter.
Number of Additions by Fibo

We observe that:

- \( T_{\text{Fibo}}(0) = T_{\text{Fibo}}(1) = 0 \)
  (both cases do not require any additions)

If the parameter \( n \) is larger than 1, then we have to:

- perform all additions of calling Fibo\((n-1)\) and Fibo\((n-2)\)
- and add the two results
- thus:
  \[
  T_{\text{Fibo}}(n) = T_{\text{Fibo}}(n - 1) + T_{\text{Fibo}}(n - 2) + 1
  \]
Number of Additions by Fibo

We observe that:

- $T_{Fibo}(0) = T_{Fibo}(1) = 0$
  (both cases do not require any additions)

If the parameter $n$ is larger than 1, then we have to:

- perform all additions of calling Fibo($n-1$) and Fibo($n-2$)
- and add the two results
- **No** → better:

$$T_{Fibo}(n) = T_{Fibo}(n-1) + T_{Fibo}(n-2) + 3$$

- because: we forgot to compute $n-1$ and $n-2$

We obtain a so-called **recurrence equation**
Number of Additions by Fibo (2)

Solving the recurrence: (in this example)
- first observation: recurrence looks a lot like Fibonacci recurrence, itself
- draw a table of $n$ vs. additions
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- Proof: by induction over \( n \)
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Estimate of the number of operations:

- algebraic formulation of the Fibonacci numbers:

\[
f_n = \frac{1}{\sqrt{5}} \left( \left( \frac{1 + \sqrt{5}}{2} \right)^{n+1} - \left( \frac{1 - \sqrt{5}}{2} \right)^{n+1} \right)
\]

- **exponential** growth of number of operations
- example: \( T_{\text{Fibo}}(100) \approx 10^{21} \)
  (requires more than 30,000 years, if we process one addition per nanosecond)
Why is Fibo so Slow?

Examine recursive calls:

→ Obviously, lots of numbers $f_j$ are computed multiple times!
An Iterative Algorithm for the Fibonacci Numbers

\begin{verbatim}
FibIt(n : Integer) : Integer {
    if n < 2 then return 1;
    else {
        last2 := 1;
        last1 := 1:
        for i from 2 to n do {
            f := last2 + last1;
            last2 := last1;
            last1 := f;
        }
        return last1;  // where last1 = f
    }
}
\end{verbatim}

Idea:

- keep the last two values $f_{i-2}$ and $f_{i-1}$ in last2 and last1
Is This Correct?

Only the loop is critical for correctness

- Basic idea for a correctness proof: use so-called **loop invariant** to prove properties about loop
- Statement of conditions that are valid for each loop execution
- Here, e.g.

  *before the loop body is executed:*
  
  *last1 and last2 contain \( f_{i-1} \) and \( f_{i-2} \), respectively*
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For loop invariants, we need to prove:

**Initialization:** It is true prior to first execution of loop (body)

**Maintenance:** If it is true before iteration of loop, it remains true before next iteration

**Termination:** When loop terminates, invariant gives us a useful property that helps to prove correctness

(Note: compare scheme of proof by induction)
Correctness

\textbf{Invariant}
\begin{align*}
\{ & \text{last1} = f_{i-1}; \text{last2} = f_{i-2} \}
\end{align*}

\textbf{Initialization}
Before first execution of the loop body, we have
\begin{itemize}
  \item $i = 2$
  \item last1 = 1 = f_1$
  \item last2 = 1 = f_0$
\end{itemize}
Correctness (2)

**Maintenance:** Proof of invariant:

Consider function body \( \{ \text{value of variables in brackets} \} \)

\[
\begin{align*}
    f & := \text{last2} + \text{last1} ; \\
    \{ & \text{last1} = f_{i-1}; \text{last2} = f_{i-2} \} \\
    \text{last2} & := \text{last1} ; \\
    \{ & \text{last1} = f_{i-1}; \text{last2} = f_{i-1} ; f = f_i \} \\
    \text{last1} & := f ; \\
    \{ & \text{last1} = f_i ; \text{last2} = f_{i-1} ; f = f_i \}
\end{align*}
\]
Correctness (2)

**Maintenance:** Proof of invariant:

Consider function body \{value of variables in brackets\}

\[
\{\text{last1} = f_{i-1};\text{last2} = f_{i-2}\}
\]

\[
f := \text{last2} + \text{last1};
\]

\[
\{\text{last1} = f_{i-1};\text{last2} = f_{i-2}; f = f_i\}
\]

\[
\text{last2} := \text{last1};
\]

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\{\text{last1} = f_{i-1};\text{last2} = f_{i-1}; f = f_i\}
\]

\[
\text{last1} := f;
\]

\[
\{\text{last1} = f_i;\text{last2} = f_{i-1}; f = f_i\}
\]

At end of (before beginning of next) loop body, we have implicitly

\[
i := i + 1;
\]

\[
\{\text{last1} = f_{i-1};\text{last2} = f_{i-2}\}
\]

thus, invariant still holds at next loop entry
Correctness (3)

Termination

- At loop termination, \( i \) exceeds \( n \); thus \( i = n + 1 \)
  (Note: think in while-loops where increment is done explicitly)
- If loop invariant holds, then last1 and last2 contain \( f_{i-1} = f_n \) and \( f_{i-2} = f_{n-1} \), respectively
- we return last1, which holds the value \( f_n \)

q.e.d.
Does Fiblt Require Fewer Operations?

We observe that:

- \( T_{\text{Fiblt}}(1) = T_{\text{Fibo}}(1) = 0 \)
  (no additions, if input parameter \( n < 2 \))

- If \( n \geq 2 \):
  - the for loop will be executed \( n - 1 \) times
  - in the loop body, there is always exactly one addition per loop iteration

Therefore:

\[
T_{\text{Fiblt}}(n) = \begin{cases} 
0 & \text{for } n \leq 1 \\
 n - 1 & \text{for } n \geq 2 
\end{cases}
\]

→ the operation count of Fiblt increases linearly with \( n \).

**Question:** will \( f_{10^9} \) be computed in 1 second?
Part IV

Asymptotic Behaviour of Functions
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Definition (Asymptotic upper bound)

\( g \) is called an asymptotic upper bound of \( f \), or \( f \in O(g) \), if

\[
\exists c > 0 \exists n_0 \forall n \geq n_0 : f(n) \leq c \cdot g(n) \quad \iff \quad 0 \leq \lim_{n \to \infty} \frac{f(n)}{g(n)} < \infty
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\]

Definition (Asymptotically tight bound)

\( g \) is called an asymptotically tight bound of \( f \), or \( f \in \Theta(g) \), if

\[
f \in O(g) \quad \text{and} \quad f \in \Omega(g)
\]
Asymptotic Behaviour of Functions (2)

Definition (Asymptotically smaller)

$f$ is called asymptotically smaller than $g$, or $f \in o(g)$, if

$$\forall c > 0 \exists n_0 \forall n \geq n_0 : f(n) \leq c \cdot g(n) \iff \lim_{n \to \infty} \frac{f(n)}{g(n)} = 0$$
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Definition (Asymptotically larger)

\( f \) is called asymptotically larger than \( g \), or \( f \in \omega(g) \), if

\[
\forall c > 0 \exists n_0 \ \forall n \geq n_0 : f(n) \geq c \cdot g(n) \iff \lim_{n \to \infty} \frac{f(n)}{g(n)} = \infty
\]
Properties of the Asymptotics Relations

$O$, $\Omega$, $\Theta$, $o$, and $\omega$ define relations:

- all of the relations are transitive, e.g.:
  
  \[ f \in O(g) \text{ and } g \in O(h) \implies f \in O(h) \]
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- $O$, $\Omega$, and $\Theta$ are **reflexive**:

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• $O$, $\Omega$, and $\Theta$ are **reflexive**:

$$f \in O(f) \quad f \in \Omega(f) \quad f \in \Theta(f)$$

• only $\Theta$ is **symmetric**:

$$f \in \Theta(g) \quad \iff \quad g \in \Theta(f)$$
Properties of the Asymptotics Relations

$O$, $\Omega$, $\Theta$, $o$, and $\omega$ define relations:

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• $O$, $\Omega$, and $\Theta$ are **reflexive**:

$$f \in O(f) \quad f \in \Omega(f) \quad f \in \Theta(f)$$

• only $\Theta$ is **symmetric**:

$$f \in \Theta(g) \quad \iff \quad g \in \Theta(f)$$

• and there is a **transpose symmetry**:

$$f \in O(g) \quad \iff \quad g \in \Omega(f)$$

$$f \in o(g) \quad \iff \quad g \in \omega(f)$$
Example: Asymptotics of the Fibonacci Numbers

“Famous” inequality

\[ 2^\left\lfloor \frac{n}{2} \right\rfloor \leq f_n \leq 2^n \]
Example: Asymptotics of the Fibonacci Numbers

“Famous” inequality
\[
2 \lfloor \frac{n}{2} \rfloor \leq f_n \leq 2^n
\]

\(f_n \in O(2^n)\) (with \(c = 1\), proof by induction):

- (Base case) for \(n = 0\): \(f_0 = 1 \leq 2^0 = 1\)
- (Base case) for \(n = 1\): \(f_1 = 1 \leq 2^1 = 2\)
- (Inductive case) from \(n - 1\) and \(n - 2\) to \(n\) (\(n \geq 2\)):

\[f_n = f_{n-1} + f_{n-2} \leq 2^{n-1} + 2^{n-2} = 3 \cdot 2^{n-2} \leq 2^n\]
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“Famous” inequality

\[ 2 \lfloor \frac{n}{2} \rfloor \leq f_n \leq 2^n \]

\[ f_n \in O(2^n) \text{ (with } c = 1\text{, proof by induction):} \]
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  - (Inductive case) from \( n - 1 \) and \( n - 2 \) to \( n \) (\( n \geq 2 \)):
    \[ f_n = f_{n-1} + f_{n-2} \leq 2^{n-1} + 2^{n-2} = 3 \cdot 2^{n-2} \leq 2^n \]

\[ f_n \in \Omega(2^{n/2}) \text{ (proof by induction over } k = n/2 \text{ – only for even } n) \]
  - (Base case) for \( k = 0 \Rightarrow n = 0 \): \( f_0 = 1 \geq 2^0 = 1 \)
  - (Ind. case) induction step: from \( n = 2k - 2 \) to \( n = 2k \) (\( n \geq 2 \)):
    \[ f_{2k} = f_{2k-1} + f_{2k-2} \geq 2f_{2k-2} = 2f_{2(k-1)} \geq 2 \cdot 2^{k-1} = 2^k \]