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Undergraduate study in
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This is an extract from a subject guide for an undergraduate course offered as part of the University of London International Programmes in Computing. Materials for these programmes are developed by academics at Goldsmiths. For more information, see: www.londoninternational.ac.uk
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preface</strong></td>
<td>v</td>
</tr>
<tr>
<td><strong>1 Algorithm analysis</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Essential reading</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Learning outcomes</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Problems and algorithms</td>
<td>1</td>
</tr>
<tr>
<td>1.3.1 Implementation</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Pseudo-code for algorithm description</td>
<td>2</td>
</tr>
<tr>
<td>1.5 Efficiency</td>
<td>3</td>
</tr>
<tr>
<td>1.6 Measures of performance</td>
<td>3</td>
</tr>
<tr>
<td>1.7 Algorithm analysis</td>
<td>4</td>
</tr>
<tr>
<td>1.8 Model of computation</td>
<td>5</td>
</tr>
<tr>
<td>1.8.1 Counting steps</td>
<td>6</td>
</tr>
<tr>
<td>1.8.2 Implementation</td>
<td>6</td>
</tr>
<tr>
<td>1.8.3 Characteristic operations</td>
<td>7</td>
</tr>
<tr>
<td>1.9 Asymptotic behaviour</td>
<td>8</td>
</tr>
<tr>
<td>1.9.1 Big $O$ notations</td>
<td>8</td>
</tr>
<tr>
<td>1.9.2 Comparing orders of two functions</td>
<td>9</td>
</tr>
<tr>
<td>1.10 The worst and average cases</td>
<td>9</td>
</tr>
<tr>
<td>1.10.1 Implementation</td>
<td>10</td>
</tr>
<tr>
<td>1.10.2 Typical growth rates</td>
<td>12</td>
</tr>
<tr>
<td>1.11 Verification of an analysis</td>
<td>12</td>
</tr>
<tr>
<td><strong>2 Abstract data types I: lists and hashing tables</strong></td>
<td>15</td>
</tr>
<tr>
<td>2.1 Essential reading</td>
<td>15</td>
</tr>
<tr>
<td>2.2 Learning outcomes</td>
<td>15</td>
</tr>
<tr>
<td>2.3 From Abstraction to Implementation</td>
<td>16</td>
</tr>
<tr>
<td>2.3.1 The string abstract data type</td>
<td>17</td>
</tr>
<tr>
<td>2.3.2 The matrix abstract data type</td>
<td>18</td>
</tr>
<tr>
<td>2.3.3 The keyed list abstract data type</td>
<td>18</td>
</tr>
<tr>
<td>2.3.4 Common operations</td>
<td>19</td>
</tr>
<tr>
<td>2.4 Data structures and software performance</td>
<td>19</td>
</tr>
<tr>
<td>2.5 Motivation of abstract data types</td>
<td>19</td>
</tr>
<tr>
<td>2.6 Arrays</td>
<td>20</td>
</tr>
<tr>
<td>2.6.1 Applications</td>
<td>21</td>
</tr>
<tr>
<td>2.6.2 Array of objects</td>
<td>23</td>
</tr>
<tr>
<td>2.6.3 Two and multi-dimensional arrays</td>
<td>24</td>
</tr>
<tr>
<td>2.7 Lists</td>
<td>24</td>
</tr>
<tr>
<td>2.7.1 References, links or pointers</td>
<td>25</td>
</tr>
<tr>
<td>2.7.2 Implementation of the links</td>
<td>26</td>
</tr>
<tr>
<td>2.7.3 Linked lists</td>
<td>27</td>
</tr>
<tr>
<td>2.7.4 Operations on lists</td>
<td>28</td>
</tr>
<tr>
<td>2.7.5 Add one node to a linked list</td>
<td>29</td>
</tr>
<tr>
<td>2.7.6 Delete one node from a linked list</td>
<td>30</td>
</tr>
<tr>
<td>2.7.7 Implementation</td>
<td>31</td>
</tr>
<tr>
<td>2.7.8 Construct a list</td>
<td>31</td>
</tr>
<tr>
<td>2.7.9 Implementation</td>
<td>32</td>
</tr>
<tr>
<td>2.7.10 Other operations</td>
<td>34</td>
</tr>
<tr>
<td>2.7.11 Comparison with arrays</td>
<td>34</td>
</tr>
<tr>
<td>2.8 Stacks</td>
<td>36</td>
</tr>
<tr>
<td>2.8.1 Operations on stacks</td>
<td>37</td>
</tr>
</tbody>
</table>
2.8.2 Implementation ........................................ 37
2.8.3 Applications ......................................... 39
2.9 Queues ..................................................... 40
2.9.1 Operations on queues ................................. 40
2.9.2 Implementation of queues ............................. 41
2.9.3 Variation of queues .................................... 43
2.10 Hashing .................................................... 44
2.10.1 Collision ............................................... 46
2.10.2 Collision resolving ................................... 46
2.10.3 Extra work for retrieval process .................... 50
2.10.4 Observation .......................................... 50

3 Algorithm design techniques 53
3.1 Essential reading ......................................... 53
3.2 Learning outcomes ....................................... 53
3.3 Recursion .................................................. 53
3.3.1 Implementation ....................................... 56
3.3.2 What happens ........................................ 57
3.3.3 Why recursion? ....................................... 58
3.3.4 Tail recursion ......................................... 63
3.3.5 Principles of recursive problem solving ............ 63
3.3.6 Common errors ....................................... 63
3.4 Divide and conquer ...................................... 65
3.4.1 Steps in the divide and conquer approach ........ 66
3.4.2 When Divide and Conquer inefficient .............. 69
3.5 Dynamic programming .................................. 70
3.5.1 Overlapped subproblems ............................. 70
3.5.2 Dynamic programming approach .................... 71
3.5.3 Efficiency of dynamic programming ................ 72
3.5.4 Similarity to the Divide and Conquer approach .. 72
3.5.5 Observation .......................................... 73

4 Abstract data types II: trees, graphs and heaps 75
4.1 Essential reading ......................................... 75
4.2 Learning outcomes ....................................... 75
4.3 Trees ....................................................... 75
4.3.1 Terms and concepts .................................. 76
4.3.2 Implementation of a binary tree ..................... 77
4.3.3 Recursive definition of Trees ........................ 79
4.3.4 Basic operations on binary trees .................... 80
4.3.5 Traversal of a binary tree ............................ 80
4.3.6 Construction of an expression tree ................. 81
4.4 Priority queues and heaps ............................. 84
4.4.1 Binary heaps ......................................... 84
4.4.2 Basic heap operations ............................... 86
4.5 Graphs .................................................... 92

5 Traversal and searching ................................ 101
5.1 Essential reading ........................................ 101
5.2 Learning outcomes ...................................... 101
5.3 Traversal .................................................. 101
5.3.1 Traversal on a linear data structure ............... 102
5.3.2 Binary tree traversal ................................ 102
5.3.3 Graph traversal ...................................... 102
5.3.4 Depth-first traversal ................................. 102
5.3.5 Breadth-first traversal ............................... 102
5.4 Searching .................................................. 104
5.5 Sequential search ....................................... 105
5.6 Binary search ............................................ 106
<table>
<thead>
<tr>
<th>6</th>
<th>Sorting</th>
<th>113</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Essential reading</td>
<td>113</td>
</tr>
<tr>
<td>6.2</td>
<td>Learning outcomes</td>
<td>113</td>
</tr>
<tr>
<td>6.3</td>
<td>Introduction</td>
<td>113</td>
</tr>
<tr>
<td>6.4</td>
<td>Motivation</td>
<td>113</td>
</tr>
<tr>
<td>6.5</td>
<td>Insertion Sort</td>
<td>114</td>
</tr>
<tr>
<td>6.5.1</td>
<td>Algorithm analysis</td>
<td>115</td>
</tr>
<tr>
<td>6.6</td>
<td>Selection sort</td>
<td>115</td>
</tr>
<tr>
<td>6.7</td>
<td>Mergesort</td>
<td>118</td>
</tr>
<tr>
<td>6.8</td>
<td>Quicksort</td>
<td>121</td>
</tr>
<tr>
<td>6.9</td>
<td>General lower bounds for sorting</td>
<td>124</td>
</tr>
<tr>
<td>6.10</td>
<td>Bucket sort</td>
<td>126</td>
</tr>
<tr>
<td>6.11</td>
<td>Sorting large records</td>
<td>127</td>
</tr>
<tr>
<td>6.12</td>
<td>Heapsort</td>
<td>128</td>
</tr>
<tr>
<td>7</td>
<td>Optimisation problems</td>
<td>137</td>
</tr>
<tr>
<td>7.1</td>
<td>Essential reading</td>
<td>137</td>
</tr>
<tr>
<td>7.2</td>
<td>Learning outcomes</td>
<td>137</td>
</tr>
<tr>
<td>7.3</td>
<td>Optimisation problems</td>
<td>137</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Multiplication of matrices</td>
<td>138</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Knapsack problem</td>
<td>139</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Coin changes</td>
<td>141</td>
</tr>
<tr>
<td>7.4</td>
<td>Greedy approach</td>
<td>145</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Huffman coding</td>
<td>145</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Huffman decompression algorithm</td>
<td>148</td>
</tr>
<tr>
<td>8</td>
<td>Limits of computing</td>
<td>151</td>
</tr>
<tr>
<td>8.1</td>
<td>Essential reading</td>
<td>151</td>
</tr>
<tr>
<td>8.2</td>
<td>Learning outcomes</td>
<td>151</td>
</tr>
<tr>
<td>8.3</td>
<td>Computability and computational complexity theory</td>
<td>151</td>
</tr>
<tr>
<td>8.4</td>
<td>Computational model</td>
<td>152</td>
</tr>
<tr>
<td>8.5</td>
<td>Decision problems</td>
<td>153</td>
</tr>
<tr>
<td>8.6</td>
<td>Measure of problem complexity</td>
<td>154</td>
</tr>
<tr>
<td>8.7</td>
<td>Problem classes</td>
<td>155</td>
</tr>
<tr>
<td>8.8</td>
<td>Class $P$</td>
<td>156</td>
</tr>
<tr>
<td>8.9</td>
<td>Class $NP$</td>
<td>156</td>
</tr>
<tr>
<td>8.10</td>
<td>$P$ and $NP$</td>
<td>157</td>
</tr>
<tr>
<td>8.11</td>
<td>NP-complete problems</td>
<td>158</td>
</tr>
<tr>
<td>8.11.1</td>
<td>What do we mean by hard?</td>
<td>158</td>
</tr>
<tr>
<td>8.11.2</td>
<td>How to prove a new problem is NP-complete</td>
<td>159</td>
</tr>
<tr>
<td>8.11.3</td>
<td>The first NP-complete problem</td>
<td>159</td>
</tr>
<tr>
<td>8.11.4</td>
<td>More NP-complete problems</td>
<td>160</td>
</tr>
<tr>
<td>9</td>
<td>Text string matching</td>
<td>161</td>
</tr>
<tr>
<td>9.1</td>
<td>Essential reading</td>
<td>161</td>
</tr>
<tr>
<td>9.2</td>
<td>Learning outcomes</td>
<td>161</td>
</tr>
<tr>
<td>9.3</td>
<td>String matching</td>
<td>161</td>
</tr>
<tr>
<td>9.4</td>
<td>The string ADT</td>
<td>162</td>
</tr>
<tr>
<td>9.5</td>
<td>String matching</td>
<td>164</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Naive string matching</td>
<td>164</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Observation</td>
<td>166</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Boyer-Moore Algorithm</td>
<td>166</td>
</tr>
<tr>
<td>9.5.4</td>
<td>Observation</td>
<td>168</td>
</tr>
<tr>
<td>9.6</td>
<td>KMP Algorithm</td>
<td>169</td>
</tr>
<tr>
<td>9.7</td>
<td>Tries</td>
<td>174</td>
</tr>
<tr>
<td>9.7.1</td>
<td>Standard tries</td>
<td>174</td>
</tr>
</tbody>
</table>
9.7.2 Compressed tries ............... 175

10 Graphics and geometry ............ 177
   10.1 Essential reading ................ 177
   10.2 Learning outcomes ............... 177
   10.3 Quadtrees ....................... 177
   10.4 Octrees .......................... 178
   10.5 Grid files ....................... 178
   10.6 Operations ...................... 178
   10.7 Simple geometric objects ....... 179
   10.8 Parameter spaces ............... 179

11 Revision for CIS226b examination 181
   11.1 Examination ..................... 181
   11.2 Revision materials ............... 181
   11.3 Questions in the examination ... 181
   11.4 Read questions carefully ....... 182
   11.5 Recommendation ................ 182
   11.6 Revision topics I ............... 183
   11.7 Revision topics II .............. 183
   11.8 Good luck! ...................... 183

A Sample examination paper .......... 185
B Sample solutions .................... 189
C Pseudocode notation ............... 195
   C.1 Values .......................... 195
   C.2 Types .......................... 195
   C.3 Operations ...................... 195
   C.4 Priority ........................ 195
   C.5 Data structures ................ 196
   C.6 Other reserved words .......... 196
   C.7 Control keywords ............... 196
   C.8 Examples of sequential structures 196
Preface

Introduction

Abstract data types or data structures provide powerful methods of organising large amounts of data. Algorithm analysis enables you to make a decision about the most suitable algorithm before programming. Techniques using abstract data types and design patterns are essential in conventional software development.

Once a good solution method is determined, a program must still be written and implementation has to be completed. In this module we therefore conduct a one hour laboratory session for every three hours of lectures at Goldsmiths College, University of London. This approach is to give you the opportunity to enhance your programming skills in Java. In addition, you will do two assignments to gain problem-solving experience.

Textbooks

Although there are many books on algorithms and data structures available on the market, it has been difficult to find a single text that suits all the needs of this module. On the other hand, you may already have some books on algorithms and data structures from previous programming modules such as CIS212 or CIS109 that you may not have finished studying.

Instead of any single text for essential and desirable reading, we therefore recommend chapters from a number of text books. All topics covered in these chapters and in this subject guide are examinable. There is also a list of books for further reading, and for supporting and historical background reading in the subject guide. Details on availability of the books can be found at www.amazon.co.uk or in your institution libraries.

The materials covered in the books may overlap and not every chapter of a book is required for the examination. Hence you are not expected to read all the books, nor all the chapters of a single book on the list. You do, however, need to get hold of at least ONE book on algorithms and data structures for frequent reference and for studying individual topics in depth. Your book does not have to be in Java but it should cover at least 80 percent of the examinable topics below:

1. Algorithms and efficiency analysis
2. Abstract data types and data structures
3. Lists, stacks, queues and sets
4. Recursions, divide and conquer
5. Trees, graphs and maps

1 Or in other similar programming languages.

2 See Chapter 11 for a list of important examinable topics.

3 Of course, you still need to have an access to the other 20 percent materials in various sources such as in the library.
6. Sorting, searching and hashing  
7. Dynamic programming  
8. Graph algorithms, greedy heuristics and approximation  
9. Complexity theory  
10. Text processing.

Note it would be inconvenient, if not impossible, for you to have to share a library's textbook with other students to study more than 20 percent of the examinable materials, because the book may be unavailable just when you need it urgently for a coursework or examination.

To best study module CIS226b, you need to follow closely the reading instruction for each chapter in the subject guide, paying a particular attention to whether the word ‘and’ is used between reading items. For example, if ‘A and B’ is found on the reading list, you are strongly recommended to consult the materials in both A and B.

Below is a collection of textbooks that are recommended at various points in the subject guide which are undated periodically. Note the books are updated frequently these days so search on the internet for the newest edition before any purchase.

**Essential reading**

The chapters of various books are specified as essential reading. These can be found at the beginning of each chapter of the subject guide. You should read carefully the specified chapter(s) in at least one of the books on the list for each chapter of this subject guide. If there is any doubt, you should consult other books on the list. A full list of these books can be found in the next section.

**Desirable reading**

The following texts are recommended because they provide the detailed background for understanding and appreciation of some topics in this module.

However, you are not required to study all the topics in these texts, for no single text can entirely meet the requirements of this course unit. The essential reading chapters are listed at the beginning of each chapter of the subject guide.

**List A**


Supporting and historical reading

These books are of interest and are recommended, but you will be fully prepared for the examination should you have studied only those essential texts above. These are provided for completeness and to allow the interested reader to pursue some topics in more depth. You will not be examined on the content of those books listed in the references other than where the material appears in the texts listed above.

List B

Additional reading


Sara Baase *Computer Algorithms: Introduction to Design and


About this subject guide

This subject guide outlines the main topics in the syllabus. It can be used as a reference which summarises, highlights and draws attention to some important points of the subject. It cannot, however, replace a textbook although it is fairly self-contained. The guide sets out a sequence which helps you to study the topics in the module within limited hours. The guide provides some additional background material including examples, lab exercises and sample examination questions. It also provides guidance for further reading. recommended textbooks.

One thing you should always bear in mind is the fact that the algorithm subject, like subjects in any other area of computer science, has kept evolving and has been updated frequently. You should therefore not be surprised if you find different approaches, explanations or results in the books you read including this guide.

About CIS226b, volume 2 of CIS226

This module provides an introduction to algorithm design and analysis techniques. Our aim is to give students an insight into various standard abstract data types and the common techniques for designing efficient algorithms.

The objectives include to:

- introduce fundamental issues in algorithm design such as efficiency, recursion, abstract data types (data structures) and complexity
- demonstrate the standard techniques in algorithm design
- study some well-known problems and algorithms
- further develop your skills in Java programming.

The learning outcomes are:

On completion of the second half of the module, students should be able to:

- demonstrate the knowledge of techniques for identifying and solving a computing problem
- choose appropriate data structures for different computation problems
- conduct a basic analysis on time-efficiency of an algorithm in the worst case
- design efficient algorithms and implement them in Java programs
explain the limit of computations and the complexity classes for
decision problems.

Prerequisites

You should be familiar with some basic discrete mathematics, such
as functions, big-O notations, sets and logarithms. These topics can
be found in CIS102 or equivalent.

You should have already had some prior experience with
programming in Java, which is covered in CIS109 or equivalent.
This module, CIS226b, focuses on algorithm design and analysis
and relies upon most of your programming skills to implement
algorithms. It would be an advantage if you are familiar with
built-in data structures in Java such as arrays and vectors, concepts
in Java such as types versus classes, inheritance, constructor
methods, method overloading, method overriding.

Most importantly, you must also have easy access to a Java platform
or have a Java platform installed on a computer at home.

Installing Java

There are lots of public domain versions of Java among which the
most popular one is called JDK (free). It is at
amount of information is provided on these sites and you can
download the software.

If you are using Linux, then the free software package normally
already includes a free Java platform.

Testing the installation

An easy way to test your installation is to type the following at a
command prompt:

    java -version

A message in response should be seen on the screen with other
system information on your platform.

For example:

    java version "1.5.0_06"
    Java(TM) 2 Runtime Environment, Standard Edition (build
    1.5.0_06-b05) Java HotSpot(TM) Client VM (build 1.5.0_06-b05,
mixed mode, sharing)

    Or, for the earlier version:

    Kaffe Virtual Machine

    Copyright (c) 1996-2004 Kaffe.org project contributors
(please see the source code for a full list of contributors).
All rights reserved. Portions Copyright (c) 1996-2002
Transvirtual Technologies, Inc.

The Kaffe virtual machine is free software, licensed under
the terms of the GNU General Public License. Kaffe.org is
an independent, free software community project, not directly
affiliated with Transvirtual Technologies, Inc. Kaffe is
a Trademark of Transvirtual Technologies, Inc. Kaffe comes
with ABSOLUTELY NO WARRANTY.

Engine: Just-in-time v3  Version: 1.1.4  Java Version: 1.1

If you see a flawed response such as a bad command or file name
or a command not found in response to your command ‘java
-version’, you know that your installation may have not been
completely successful. This sometimes may be simply because your
system cannot find the correct version of the file which runs Java
programs.

As Java has grown to so many versions and variations, we
recommend that you focus on the basic functions which can be run
in all environments.

**CmapTool**

Algorithm design, like other types of design, requires a process of
development from vague ideas to production details. CmapTools is
free software that may help designers to ease the journey of
converting their concepts to the design objects. You can find more
information about the CmapTool and download the software from
http://cmap.ihmc.us.

**Study time**

The materials covered in this module are taught internally at
Goldsmiths College, University of London in one academic term,
that is a three hour lecture and a one hour supervised lab session
per week for ten weeks. For each one hour lecture, students are
expected to spend at least two further hours on homework including
revision, attempting exercises and lab implementation.

You would, however, normally have to double the study hours if you
could not attend lectures. For example, if you self study at home,
you would expect to spend six hours on intensive study of the
materials and two hours for the lab exercises, plus a similar amount
of additional homework time, every week for ten weeks or the
equivalent.

It is, of course, impossible to tell you precisely the number of hours
required for you to study the materials in this module. It may
depend on many elements such as your academic background, the
condition of the environment, your health status, the complexity of
the subjects and your study methods. I recommend that you add an
extra couple of free hours to your plan at least in the first two weeks.
and record the time it took you to meet the requirements, and adjust your plan accordingly.

Study methods

One effective way to study algorithms is to commit yourself to various DIY (do it yourself) activities. You should not believe an algorithm until you have implemented and tested it. In theory, the performance of an algorithm can be explored by analysis or implementation. Implementation is not the main concern in this module. However, implementation is an important way forward. It is the only way, sometimes, to prove correctness (or more likely, incorrectness) in practice. Investigation of certain behaviours of an algorithm can also be an important motivation of algorithm design and analysis.

You should try to implement as many algorithms as possible in a conventional language such as Java. Attempting exercises and doing courseworks often offer good opportunities to help your understanding.

It can be useful to remember the Confucian saying about learning as you start your studies:

Tell me and I forget;
Show me and I remember;
Let me do it and I understand.

As experts have predicted that more and more people in future will write programs without being programmers, you are recommended to learn the important principles and apply them in your programming practice as much as possible. The experience could be very useful for your future career whatever you do.

More specifically:

1. For every hour of study on new material in a lecture, two hours of lab work and two hours of revision or exercises are highly recommended.
2. Use examples to help gain understanding of each problem.
3. Always ask the question: ‘Is there a better solution for the problem?’
4. Practise as much as you can.

Laboratory exercises

There is a one-hour supervised lab session every week for each student at Goldsmiths, University of London.

Lab exercise sheets are set for students to practise their programming skills using the theoretical knowledge gained from the course and are available soon after lectures each week. If you are studying at an institution, your lecturer may provide a similar resource.
Examination

Important The information and advice given in the following section are based on the examination structure used at the time this guide was written. However, the university can alter the format, style or requirements of an examination paper without notice. Because of this we strongly advise you to check the rubric/instructions on the paper you actually sit.

The content covered in CIS226b will be examined in the second half of a three-hour examination for CIS226.

Students will normally be required to answer a number of questions: each includes a few subquestions (or ‘parts’) in each half of the paper. These subquestions may be Bookwork, Similar and Unseen.

Details about the examination and revision can be found in Chapter 11.

Every year we advise the candidates to read the questions on the examination paper carefully. You should make sure that you fully understand what is required and what subquestions are involved in an examination question. You are encouraged to make notes (crossed through later as not to be marked), if necessary, while attempting the questions. Above all, you should be completely familiar with the course material. To achieve a good grade, you need to have prepared well for the examination and to be able to solve problems by applying the knowledge gained from your studies of the module.

Content and plan

The main topics that we normally cover internally at Goldsmiths College, University of London for CIS226b are as below, but you may adjust them according to your level and your own time available.

Week 1
Lecture 1-3
The aim, objectives and plan of the course
Problems and algorithms
Big-O notation
Pseudocode
Cmaptools (http://cmap.ihmc.us)
Ex 1 Time efficiency

Week 2
Lecture 4-6
Abstract Data Types
array, lists, stacks, queues, sets, (trees, graphs, hash tables, heaps)
Specialised data structures
Algorithms Design and Implementation
Ex 2 Abstract Data Types
Lab 1 Estimating time efficiency
Week 3  
Lecture 7-9  
Algorithm Design Techniques (1)  
Sorting, selection, searching and traversal.  
Ex 3 Sorting, searching, traversal and selection  
Lab 2 Implementation of ADT list, or binary tree

Week 4  
Lecture 10-12  
Algorithm Design Techniques (2)  
Divide and conquer, Recursion  
Ex 4 Divide and conquer, Recursion  
Lab 3 Implementation of searching a sorted list, or traversal of a connected graph.

Week 5  
Lecture 13-15  
Algorithm Design Techniques (3)  
Dynamic programming  
trees, graphs  
Ex 5 Dynamic programming  
Lab 4 Implementation of a Recursion programme

Week 7  
Lecture 16-18  
Algorithm Design Techniques (4)  
Greedy approach and heuristics  
hash tables, heaps  
Ex 7 Greedy approach and heuristics  
Lab 5 Implementation of dynamic programming

Week 8  
Lecture 19-21  
Limits of Computing  
Intractable problems and approximation  
Introduction to NP-completeness  
Ex 8 Intractability and approximation  
Lab 7 Greedy approach and heuristics

Week 9  
Lecture 22-24  
Some well known problems and algorithms (1)  
String matching problems  
Ex 9 String matching problems  
Lab 8 Intractability and approximation

Week 10  
Lecture 25-27  
Some well known problems and algorithms (2)  
Computational geometry problems  
Ex 10 Computational geometry problems  
Lab 9 String matching problems

Week 11  
Lecture 28-30
Revision
Ex 11 Sample examination questions
Lab 11 Computational geometry problems

Activity 0.0

WEB SITES AND SOFTWARE

1. Free Java Books
   (a) Thinking in Java
       http://www.mindview.net/Books/TIJ/
   (b) Java Gently
       http://javagently.cs.up.ac.za/jg3e/

2. What are covered in the first year Java courses in other places?
   (a) David J. Eck's Java course:
       http://math.hws.edu/eck/cs124/
   (b) Java Tutorial
       http://java.sun.com/docs/books/tutorial/

3. Installing Java system
   http://burks.bton.ac.uk
   http://java.sun.com/
   http://textpad.com

4. Download and install CmapTool
   http://cmap.ihmc.us

6 These addresses were accessible when the Guide was written. In case they have changed, you may use a search engine such as Google to search the new web address.
Chapter 1

Algorithm analysis

1.1 Essential reading


1.2 Learning outcomes

This chapter is concerned with algorithms and algorithm analysis. Having read this chapter and consulted the relevant material you should be able to:

- explain the term algorithm and the concept of the efficiency of an algorithm in terms of big-O notation
- develop a perspective on the study of computer science beyond the learning of a particular programming language such as Java
- describe commonly-used big-O categories.

1.3 Problems and algorithms

In this section, we introduce the concept of algorithms and discuss the issues of fundamental analysis of algorithms.

A problem in this course is a general question to be answered, usually possessing one or more parameters. It can be specified by describing the form of parameters taken and the questions about the parameters. An instance of a problem is an assignment of values to the parameters. An algorithm is a clearly specified set of simple instructions to be followed to solve a problem. In other words, it is a step-by-step procedure for taking any instance of a problem and producing a correct answer for that instance.

Example 1.1 Finding the minimum:

Problem Given a non-empty set of numbers, what is the minimum element of the set?
Instance:
What is the minimum element of (2,5,8,3) entered on a single line from the keyboard?

Algorithm 1.1 is a solution for solving the problem of finding the minimum of a set of data that are input from the keyboard. The algorithm should give a correct answer for any set of data.

**Algorithm 1.1 Minimum key**

<table>
<thead>
<tr>
<th>INPUT:</th>
<th>nothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT:</td>
<td>the minimum</td>
</tr>
<tr>
<td>1:</td>
<td>read min;</td>
</tr>
<tr>
<td>2:</td>
<td><strong>while</strong> not eoln <strong>do</strong></td>
</tr>
<tr>
<td>3:</td>
<td>read x</td>
</tr>
<tr>
<td>4:</td>
<td><strong>if</strong> ( x &lt; \text{min} ) <strong>then</strong></td>
</tr>
<tr>
<td>5:</td>
<td>( \text{min} \leftarrow x )</td>
</tr>
<tr>
<td>6:</td>
<td><strong>end if</strong></td>
</tr>
<tr>
<td>7:</td>
<td><strong>end while</strong></td>
</tr>
<tr>
<td>8:</td>
<td>print min;</td>
</tr>
</tbody>
</table>

1.3.1 **Implementation**

Algorithm 1.1 can be implemented to a Java method and run on a computer:

```java
import java.util.Scanner;

int min() {
    Scanner input = new Scanner(System.in);
    System.out.println("x=? (999 to end) ");
    int x = input.nextInt();
    int min = x;
    while (x!=999) {
        System.out.println("x=? (999 to end) ");
        x = input.nextInt();
        if (x < min) {
            min = x;
        }
    }
    return min;
}
```

1.4 **Pseudo-code for algorithm description**

Using a natural language such as plain English to describe an algorithm is not impossible. However, one quickly realises that any human language is too rich to be concise or precise enough for the task. A common practice is to use so-called *pseudo-code* to describe algorithms (see Appendix C for examples). The syntax of any pseudo-code is similar to that of a high-level computer language such as Java. It is therefore much more convenient for an algorithm
in pseudo-code to be translated into a computer program in some higher language than from a human language.

Thus once an algorithm for a problem is properly developed, it is a relatively easy matter to implement or translate it into a program in some computer language.

In this course, instead of giving a formal definition of the pseudo-code, we just borrow conventional syntax in Java, or the like. We encourage you to separate the algorithm design and implementation in the first and second stages respectively. During the first stage, i.e. the algorithm design stage we ignore the implementation details and focus on problem-solving techniques and algorithmic issues.

1.5 Efficiency

In this module, our goal is not only to develop a working algorithm, but also an efficient algorithm for a given problem.

The speed of hardware computation of basic operations has been improved dramatically, but efficiency matters more than ever today. This is because our ambition for computer applications has grown with computer power. Many areas demand a great increase in speed of computation. Examples include the simulation of continuous systems, high resolution graphics, and the interpretation of physical data, medical applications, and information systems.

On the other hand (and more importantly), an algorithm may be so inefficient that, even with computation speed vastly increased, it would not be possible to obtain a result within a useful period of time. The time that many algorithms take to execute is a non-linear function of the input size. This can reduce their ability to benefit from the increase in speed when the input size is large.

Example 1.2 A particular sorting algorithm takes $n^2$ comparisons to sort $n$ numbers. Suppose that computing speed increases by a factor of 100. In the time that it was required to take to execute the $n^2$ comparisons, it is now possible to do $100n^2 = (10n)^2$ comparisons. Unfortunately, with 100 times speed-up, only 10 times as many numbers can be sorted as before.

1.6 Measures of performance

Naturally, the efficiency of an algorithm is estimated by its performance. The performance of an algorithm can be measured by the *time* and *space* required in order to fulfil a task. The time and space requirement of an algorithm is called the *computational complexity* of the algorithm. The greater the amount of the time and space required, the more complex is the algorithm.

The *time complexity* of an algorithm is, loosely speaking, an imaginary *execution time* of the algorithm. The execution time can be measured by the number of some *characteristic operations* performed by the algorithm in order to transform the input data to
the results.

Note that we do not measure the time complexity by the running time of a program. This means that we do not use the common time units such as second, minute and hour. The unit of the time complexity, strictly speaking, should be the number of execution steps, although we often do not use any unit.

An algorithm consists of a set of ordered instructions and the time complexity, that is, the number of execution steps in an algorithm, is irrelevant to the real time.

Note our main interest here is in an algorithm instead of a program. A program is an implementation of an algorithm. The execution time of a program depends on the implementation including not only the operating system but also the speed of the computer itself. The same program may run faster on a computer with a faster CPU, but the same algorithm should perform the same number of algorithmic steps to accomplishment a task.

Normally we are concerned with the time complexity rather than space complexity of an algorithm. The reasons are that firstly it becomes easier and cheaper to obtain space. Secondly techniques to achieve space efficiency by spending more time are available.

In what follows, we use ‘complexity’ to mean the time complexity if not otherwise indicated.

Observation

- The complexity of an algorithm normally depends on the size of input.
- The number of operations may depend on a particular input.

Solution

- For different sets of input data, we analyse the performance of an algorithm in the worst case or in the average case.
- For different algorithms, we focus on the growth rate of the time taken by the algorithms as the input size increases.

The time complexity of an algorithm can be expressed by a function of input size: $T(n)$. We are normally interested in the behaviour of $T(n)$ as $n$ grows large.

1.7 Algorithm analysis

With the measures of performance introduced earlier, it is possible to conduct an analysis and estimate the cost of an algorithm.

Many reasons can be given to explain why we need algorithm analysis. One main reason is that there are usually several algorithmic ideas for a problem, and we would like to eliminate the inefficient algorithms early. By early, we mean that we would like to compute or estimate the computational complexity of any two algorithms before actually implementing (coding) them into programs.
Secondly, algorithms may behave differently for different input sizes, and we would like to estimate their computational complexity for large inputs. For some problems we simply have not found an efficient algorithm yet, but we may find those algorithms feasible and useful for input within some limited range.

Furthermore, the ability to do an analysis usually provides insight into designing efficient algorithms. The analysis also could pinpoint the bottlenecks which should be taken care of during coding.

In what follows, we shall introduce some fundamental methods for algorithm analysis. Before moving on, we have to first agree a model of ‘normal’ computer.

### 1.8 Model of computation

We adopt a so-called ‘random access machine’ (RAM) model. In this model, certain hardware constraints for a real computer are ignored in order to focus on algorithmic issues. Routine operations at machine level, such as fetching instructions or data from the memory are also ignored for the same reason.

We assume that our computer has the following convenient properties:

1. It has a single processor (CPU) and runs our pseudo-code algorithms in a sequential manner. A pseudo-code algorithm consists of an ordered sequence of instructions in pseudo-code (Appendix C). The instructions in each algorithm are executed one after another in the given order.
2. It takes exactly one time unit to execute a standard instruction (in pseudo code) for operations such as addition, subtraction, multiplication, division, comparison, assignment and conditional control. No complex operations, such as sorting and matrix inversion, can be done in one time unit.
3. The storage for integers is of a fixed size, for example, 32 bits.
4. It has an infinitely large memory.

The assumptions are necessary because our analysis result depends on the model. For example, assigning 100 data into an array would require 100 unit times in our model. The same task can be done in one time unit, however, in a parallel computation model such as a ‘parallel random-access machine’ (PRAM), in which the 100 memory cells can be accessed simultaneously.

The assumptions help keep analysis feasible and focused, for certain hardware details are ignorable from an algorithmic point of view. For example, standard operations such as addition, subtraction, multiplication, division, comparison, assignment and conditional control would require different amount of time to run on a real computer. The storage of real computers is limited and the memory for integers and reals may be of a different size. However, taking the difference made by these hardware details into consideration gives little impact on the result in comparison of different algorithms, because these standard operations are required for almost every algorithm. Taking too many details into consideration can, if anything, make an analysis too complicated to be carried out.
1.8.1 Counting steps

Given two algorithms $A_1$ and $A_2$, which one is more efficient? In other words, which one has lower computational complexity? To answer this question, one way is to simply count the execution steps of each algorithm and compare the numbers of the steps of the two.

Example 1.3
Problem: Compute $\sum_{k=1}^{n} k$, where $n$ is an integer.

Algorithm 1.2 Sum1(n)

```
INPUT:  n
OUTPUT: sum
1: sum ← 0
2: for k ← 1, k ≤ n, k ← k + 1 do
3:   sum ← sum + k
4: end for
5: print sum
```

From the fact $\sum_{k=1}^{n} k = \frac{n(n+1)}{2}$, we have

Algorithm 1.3 Sum2(n)

```
INPUT:  n
OUTPUT: sum
1: print n(n+1)/2
```

1.8.2 Implementation

These algorithms can be implemented to the following Java methods:

```java
int sum1( int n ) {
   int sum = 0;
   for (int k=1; k<=n; k++) {
      sum = sum + k;
   }
   return sum;
}

int sum2( int n ) {
   int sum;
   return (n*(n+1)/2);
}
```

We look at the time complexity by counting the steps taken in execution. Let any assignment, arithmetic computation $+, -, *, /$, read, print be all counted as one step. So for Algorithm 1.2, it takes $1 + n \times 1 + 1 = n + 2$ steps; and for Algorithm 1.3, it takes $1 + 1 + 1 = 3$ steps to execute. Obviously, Algorithm 1.3 is more efficient in terms of execution time.

How about the space efficiency? Let a simple variable require one unit of storage. Algorithm 1.2 needs three units since it involves three variables $sum$, $k$ and $n$, and Algorithm 1.3 only needs one unit since it involves only one variable $n$. We can therefore conclude that Algorithm 1.3 is more efficient in terms of storage, too.
In fact, Algorithm 1.3 has an important advantage, that is, it takes constant time to execute no matter how large n is. This means that it takes the same amount of time to run no matter how many such numbers need to be added up.

We have done an analysis. Had we, however, to undertake all the counting every time to analyse an algorithm, the task would be tedious and quickly become infeasible. We need some easier approach.

1.8.3 Characteristic operations

A complexity analysis gives an estimate of the resources consumed by an algorithm. The relationship between the amount of time and space allows us to focus on the time efficiency only. The time complexity is, after all, $T(n)$, a function of the input size n. The more data, the longer it takes to run the algorithm. The task of counting steps can be made easier if a reasonable measure of the input size of some major operations can be established and then only those operations relevant to the input size need to be considered.

Example 1.4 For each algorithm below, we choose a relevant characteristic operation:

1. An algorithm searching an element x in a list of names:
   Choose the comparison of x with an entry in the list;

2. An algorithm multiplying two matrices with real entries:
   Choose the multiplication of two real numbers;

3. An algorithm sorting a list of numbers:
   Choose the comparison of two list entries;

4. An algorithm to traverse a binary tree:
   Choose the visit of a tree node.

The characteristic operations could be some very expensive operations compared to others, or they might be of some theoretical interest. It allows a good sense of flexibility to choose these fundamental operations as a measure of time complexity.

To ease the analysis of algorithms, it would be useful to summarise the time complexity for common algorithmic structures below as a reference. You are encouraged to spend some time to derive the formulae by yourself and then compare yours with the ones in a textbook.

- For loops:
- Consecutive statements:
- If-then-else:

Think of an algorithm which takes a number of steps of the following order:

- Logarithmic
- Exponential.
1.9 Asymptotic behaviour

We are often interested in the rate of growth of the time required for an algorithm when the input size gets larger. So the lower order terms of the time complexity $T(n)$ could be ignored, where $n$ is a positive integer. In other words, we only need to master the asymptotic behaviour of $T(n)$. Here the term asymptotic means approximate in a specific way.

Example 1.5 Suppose that the time complexity of an algorithm is

$$T(n) = \frac{1 + n^2}{n}$$

where $n$ is the input size to the algorithm.

It is easy to see some asymptotic behaviours of $T(n)$ such as, $T(n) \sim n$ when $n \to \infty$ because

$$T(n) = \frac{1 + n^2}{n} = 1 + \frac{n}{1} \sim \frac{0 + n}{1} = n$$

Similarly, $T(n) \sim \frac{1}{n}$ when $n \to 0$.

Here $n$ and $\frac{1}{n}$ are both simpler than $T(n)$ and it is easier to handle their behaviour in an analysis.

We say that $n$ and $\frac{1}{n}$ are asymptotic behaviour of $T(n)$ when $n \to \infty$ and $n \to 0$ respectively.

1.9.1 Big $O$ notations

In general, the asymptotic behaviour of functions can be described by so-called “big-O” notations, often consisting of four members $O()$, $\Omega()$, $\Theta()$ and $o()$. They are called “big-oh”, “omega”, “theta” and “small-oh” respectively.

Let $g$ be a function of $n$. Each of $O(g(n))$, $\Omega(g(n))$, $\Theta(g(n))$ and $o(g(n))$ defines a set of functions related to $g$.

$O(g(n))$ is a set of functions that grow at most as fast as $g$ when $n \to \infty$.

$\Omega(g(n))$ is a set of functions that grow at least as fast as $g$ when $n \to \infty$.

$\Theta(g(n))$ is a set of functions that have the same growth rate as $g$ when $n \to \infty$.

$o(g(n))$ is a set of functions that grow slower than $g$ when $n \to \infty$.

Conventionally, we use $T(n) = O(g(n))$ to mean $T(n) \in O(g(n))$. We define $T(n) = O(g(n))$ if there are positive constants $c$ and $n_0$ such that $T(n) \leq cg(n)$ when $n \geq n_0$.

Similarly, $T(n) = \Omega(g(n))$ if there are positive constants $c$ and $n_0$ such that $T(n) \geq cg(n)$ when $n \geq n_0$. 

8
The worst and average cases

\[ T(n) = \Theta(g(n)) \] if and only if \( T(n) = O(g(n)) \) and \( T(n) = \Omega(g(n)) \).

\[ T(n) = o(g(n)) \] if \( T(n) = O(g(n)) \) and \( T(n) \neq \Theta(g(n)) \).

**Example 1.6** Let \( T_A(n) \) be the time complexity of an algorithm \( A \), and \( n \) is the input size of the algorithm. Suppose \( T_A = \frac{n^2}{2} \) and \( T_A = 7n \).

Illustrating definitions, we see that \( 7n \) is \( O(n^2) \) but that \( 7n \neq \Theta(\frac{n^2}{2}) \) because \( \frac{n^2}{2} \neq \Theta(7n) \).

### 1.9.2 Comparing orders of two functions

When comparing two functions in terms of order, it is often convenient to take the alternative definitions: Let \( \lim_{n \to \infty} \frac{T(n)}{g(n)} = L \).

The limit can have four possible values:

1. If \( L = 0 \) then \( T(n) = o(g(n)) \)
2. If \( L = a \neq 0 \) then \( T(n) = \Theta(g(n)) \)
3. If \( L = \infty \) then \( g(n) = o(T(n)) \)
4. If \( L \) oscillates then there is no relation (but this will not happen in our context).

**Example 1.7** Given \( T_A(n) = 1000n \) and \( T_A(n) = n^3 \), which function grows faster when \( n \to \infty \)? What is the relationship between the two functions?

**Solution** \( \lim_{n \to \infty} \frac{1000n}{n^3} = 0 \). Therefore, \( T_A(n) \) is \( o(n^3) \), which means \( T_A(n) \) grows strictly slower than \( T_A(n) \).

### 1.10 The worst and average cases

The behaviour of an algorithm usually depends not only on the size of the input, but also on the input itself. Look at Algorithm 1.4 which determines whether integer \( x \) is an element of array \( Y[0..n-1] \), where \( n \) is a non-negative integer.

**Example 1.8**

**Algorithm 1.4** boolean foundFirstX(int x, int Y[])

1: \( i \leftarrow 0 \)
2: boolean found \leftarrow false
3: while (not found) && (i < length(Y)) do
4: \( \text{found} \leftarrow (x = Y[i]) \)
5: \( i \leftarrow i + 1 \)
6: end while
7: return found

The time complexity of \( \text{foundFirstX}(x, Y) \) depends on the value of \( x \) and on the contents of the array \( Y \). For example, if \( Y[0] = x \), that is, the first element in array \( Y \) equals to \( x \), then the while loop (step 3–6 in the algorithm) will only be executed once, and the number of execution steps is only \( 1 + 1 + 1 \times (1 + 1 + 1 + 1) + 1 = 7 \),
including step 1, step 2, 1 × (step 3, 4, 5, 6), and step 7. If \( x \) equals the \( k \)th element of \( Y \), the number of execution steps becomes 
\[
1 + 1 + k \times (1 + 1 + 1 + 1) + 1 = 3 + 4k,
\]
where \( k \leq \text{length}(Y) \), including step 1, step 2, \( k \times (\text{step } 3, 4, 5, 6) \), and step 7. Each of these different situations is called a case. In each case, the algorithm gives a different performance.

We therefore need to consider the behaviour of the algorithm for two special cases, namely the worst case and the average case.\(^3\)

In terms of time complexity, the worst case is the situation where the algorithm would take the longest time. The average case is the case where the average behaviour is estimated after every instance of the problem has been taken into consideration. We define two functions of \( n \), the input size, for the two cases respectively.

In general, an algorithm may accept \( k \) different instances of size \( n \). Let \( T_i(n) \) be the time complexity of the algorithm when given the \( i \)th instance, for \( 1 \leq i \leq k \). Let \( p_i \) be the probability that this instance occurs.

Then the time complexity for

- The worst case:

\[
W(n) = \max_{1 \leq i \leq k} T_i(n)
\]

- The average case:\(^4\)

\[
A(n) = \sum_{i=1}^k p_i T_i(n)
\]

In words, \( W(n) \) is the maximum number of characteristic operations performed by the algorithm on any input of size \( n \). \( A(n) \) gives the behaviour of the algorithm on average for different instances. Clearly, \( A(n) \leq W(n) \).

The worst case analysis could help to provide an estimate for a time limit for a particular implementation of an algorithm. It is particularly useful in real time applications. The average case analysis is more meaningful in providing an overall picture because it computes the number of steps performed for each possible input instance of size \( n \) and then takes the (probability-weighted) average.

In this course, we shall consider only the worst case analysis if not specified otherwise.

The result of an algorithm analysis can sometimes turn out to be unsatisfactory or extremely difficult to achieve. In these cases, an empirical\(^5\) approach should be considered.

1.10.1 Implementation

Algorithm 1.4 can be realised in the following Java method:

```java
boolean foundFirstX(int x, int Y[]) {
    boolean found = false;
    int i=0;
    while ((!found) && (i < Y.length)) {

10
```
The worst and average cases

```java
    boolean foundFirstX( int x, int Y[]) {
        int count = 1;
        boolean found = false;
        count ++;
        int i=0;
        System.out.println("Step 1--2: "+count);
        count ++;
        while ( ( !found ) && ( i< Y.length ) ) {
            count ++;
            found = ( x==Y[i] );
            count ++;
            i++;
            count ++; // for while
        }
        System.out.println("Step 1--6: "+count);
        count ++;
        System.out.println("All steps: "+count);
        return found;
    }
```

It is easy to modify the program slightly in order to compute the actual number of Java statements executed. In the example below, we define a variable count before (or after) each statement, and display the value of count at a few places of the program.

You can conduct an experiment in which different integer arrays Y[] are input and the different number of execution steps are displayed on your screen. For example, if call the methods with “int A[] = 9, 4, 5, 7, 1, 2;”, you would see

```
... Step 1 and 2: 2
Step 1--6: 21
All steps: 22
...

If with “int A[] = 2, 4, 5, 7, 1, 2;”, you would get

... Step 1--2: 2
Step 1--6: 6
All steps: 7
...
```

This can be implemented in two classes as in Example 1.9:

1. Place the method foundFirstX in Section 1.10.1 in a class experimentCount;
2. Write the main class test which inputs a x and an array, say, A, and print out the foundFirstX(x, A).

**Example 1.9** class experimentCount {
    boolean foundFirstX( int x, int Y[]) {

... // copy the method here
}
}

class test {

    public static void main(String args[]) {
        experimentCount account = new experimentCount();

        int A[] = {9, 4, 5, 7, 1, 2};
        int B[] = {2, 4, 5, 7, 1, 2};

        account.printArray(A);
        System.out.println(account.foundFirstX(2, A));
        System.out.println();
        account.printArray(B);
        System.out.println(account.foundFirstX(2, B));
    }
}

1.10.2 Typical growth rates

Some functions are commonly seen with typical growth rates in the algorithm analysis. We list some common ones here.

Note All logarithms in this subject guide are of base 2 if not stated otherwise.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>constant</td>
</tr>
<tr>
<td>log n</td>
<td>logarithmic</td>
</tr>
<tr>
<td>log² n</td>
<td>log-squared</td>
</tr>
<tr>
<td>n</td>
<td>linear</td>
</tr>
<tr>
<td>n log n</td>
<td>n-log-n</td>
</tr>
<tr>
<td>n²</td>
<td>quadratic</td>
</tr>
<tr>
<td>n³</td>
<td>cubic</td>
</tr>
<tr>
<td>2ⁿ</td>
<td>exponential</td>
</tr>
</tbody>
</table>

1.11 Verification of an analysis

It is important to conduct an algorithm analysis, before any implementation, to avoid any unnecessary expensive labour. It is even more important to make sure that the analysis result is correct. Hence verification of an analysis is necessary and highly recommended, although it sometimes turns out to be difficult.

For example, we can always:

- check if the empirical running time matches the running time predicted by the analysis
- for a range of n, compute the value T(n)/f(n) where f(n) is the analysis result and T(n) is the empirically observed running time. This should be ideally a constant as n varies.
Activity 1.11

**TIME COMPLEXITY**

1. Discuss briefly the time complexity in the worst case for the algorithm below. Indicate the input, output of the algorithm and the main comparison you have counted.

**Algorithm 1.5** insertionsort(int array[0..n-1])

```java
1: for i ← 1, i ≤ n – 1, i + + do
2:    current ← array[i]
3:    position ← i – 1
4:    while position ≥ 1 and current < array[position] do
5:       array[position + 1] ← array[position]
6:       position ← position – 1
7:    end while
8:    array[position + 1] ← current
9: end for
```

2. Consider the big O behaviour of the code below in terms of $N$. Discuss briefly its time complexity.

```java
1: k ← 1
2: repeat
3:    k ← 2 × k
4: until k ≥ N
```

3. A certain algorithm always requires 1000 operations, regardless of the amount of data input. Provide a big-O classification of the algorithm that reflects the efficiency of the algorithm as accurately as possible.

4. Modify the main class `test` in Example 1.9 (Section 1.10.1) so that the program can take a $x$ and an array $A$ of integers from the keyboard, and print out the number of execution steps of program `foundFirstX(x, A)`.

**Hint** You only need to re-write some lines of the main method below (see the comments):

```java
class test {

    public static void main(String args[]) {
        experimentCount account = new experimentCount();

        // ... to be modified from here to the end.
        int A[] = {9, 4, 5, 7, 1, 2};
        int B[] = {2, 4, 5, 7, 1, 2};
        account.printArray(A);
        System.out.println(account.foundFirstX(2, A));
        System.out.println();
        account.printArray(B);
        System.out.println(account.foundFirstX(2, B));
    }
}
```