Basics of
COMPUTER ORGANIZATION & ARCHITECTURE
Problems and Solutions

S.S.S.P. Rao

Alpha Science

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To my Sister and Brother-in-law
Indira Mahalakshmi and Sri krishna

Foreword

Computer Science is a dynamic subject in which change is the norm. Every eighteen months the power of processors double. The capacity of secondary storage doubles almost every 15 months. In addition the speed of communications systems and their bandwidth are rapidly increasing. Whereas the capacity and power of computers are increasing the cost has remained constant. The revolution in hardware has enabled very powerful software to be supported. Writing a text-book on computer organization and architecture is a challenge in this dynamic environment as it can become obsolete even while writing it! To guard against this, authors have to emphasize fundamental, invariant aspects of the subject by selecting appropriate topics to discuss and by choosing a method of presentation which enhances students' ability to understand, analyze and synthesize.

A famous educational psychologist Benjamin Bloom created a taxonomy of learning domains in 1956 in order to promote higher forms of cognition. His taxonomy has six classes. At the lowest level of cognition is remembering or recalling what is learnt. Next one is understanding, namely, comprehending the meaning and interpreting the acquired knowledge. Analyzing is at a higher level which requires students to separate concepts into component parts to enable them to understand the organization and structure of the subject. Creating or synthesizing a new system from component parts is at next higher level of cognition. At the top is evaluation which requires students to judge the relative merits of alternative solutions or designs.

The education and evaluation system in many institutions emphasize only recall. As pointed out by Prof. S.S.S.P. Rao in his Preface to this book, he found that his students had difficulty in examinations which test higher cognitive abilities. To alleviate this problem students face, Prof. Rao has taken a different approach in writing this book. He has given a short introduction to each chapter emphasizing fundamentals of the topic. It is followed by questions and answers which to some extent, follow Bloom's taxonomy, starting with recall and ending with design. The topics cover a normal undergraduate curriculum of this subject. It is a valuable addition to

the vast literature on this popular subject. I commend this effort by a very experienced teacher and I am sure that if students diligently work out by themselves the answers to the problems in the book and compare their answers with that provided by Prof. Rao, they will learn Digital Computer Organization and Architecture very effectively.

V. Rajaraman
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Preface

Digital Computer Organization and Architecture is a very interesting topic and this book gives the reader a very good understanding of the functioning of the digital computer and its tremendous capabilities. This course was taught by me for the undergraduate students of Electrical and Computer Science and Engineering at IIT-Bombay for several years. There are very many good books on this topic by many authors. At one time I had also planned to write a book on this topic. But, then I noticed one thing. Even though this topic is simple and not very complicated, in my 40 years of teaching experience at IIT-Bombay, students could not do well in the examinations and very few students used to get good grades. Then I felt that even though there are very good books, they are not able to solve the problems. Then a thought crossed my mind that why not I take all the questions I asked in the examinations I conducted on this topic and write a book on *Basics of Computer Organization and Architecture: Problems and Solutions*. This book may help the student to understand the subject in a better way and make him confident enough to solve a variety of problems on this topic. Even though this book deals with problems and solutions, if one looks at the book in its totality it also serves as another text book on this topic. The problems are in graded form staring from simple to a reasonably complex level.

This book starts from a brief history of electronic computers and covers all units of digital computer including number systems and codes, fixed point arithmetic, floating point arithmetic, decimal arithmetic, ALU Design, control unit, hardwired and micro-programmed control unit configurations and design, memories, memory interfacing, buses, examples of standard serial and parallel buses, input and output devices and I/O modes, introduction to microprocessors, microcontrollers, introduction to embedded systems with an example. I conclude with the hope that this book will help the student to understand the subject better and give him enough practice to solve problems confidently and efficiently.

S.S.S.P. Rao

Acknowledgements

This level one course on Computer Organization and Architecture was taught by me for several years for the undergraduate students of Indian Institute of Technology, Bombay and further, upon my retirement to the students of IIT-Hyderabad for two years as a visiting professor. Even though the course is not very difficult and a number of excellent text books are available on this subject, all through my professional career, I wondered why many students failed to get good grades in this course. I came to the conclusion that even though the students understand the subject, they are not able to solve the problems due to lack of better understanding of the basic concepts. During my tenure as a Professor of IIT-Bombay, I set many quizzes, mid-semester and end-semester examination papers. Then a thought came to my mind as to why not I take those question papers and write answers and publish a book on *Basics of Computer Organization and Architecture: Problems and Solutions*. Then immediately I conveyed this idea to many publishers. First response I got immediately from Sri N.K. Mehra of Narosa Publishing House informing that they are very much interested in publishing this book. Then we signed the agreement. First I would like to place on record my sincere thanks and appreciation to Sri N.K. Mehra for his interest, excellent support and encouragement. Then I started writing the solutions to the questions chapter wise. During this exercise, many of my colleagues helped me to a great extent. It is definitely not out of place to thank profusely my IIT-Bombay post graduate students N.B. Sonawalla, S.S. Marathe (1979), A.S. Mankar, A.C. Shelat (1980), and A.P. Tillu (1984) who were involved in the design of IBM 360 compatible computer using the AMD bit-slice processor 2901/2903 as their final year project. This project received financial funding from the Department of Electronics, Government of India. ORG Systems, Baroda provided support for fabricating the printed circuit boards, backplane wiring etc. I am extremely thankful to all the students, Government of India and ORG Systems. When the project was complete, IBM 360 Software test routines, and Micro-diagnostics ran successfully on this machine designed by my students. This exercise gave me a thorough insight into Computer Organisation and Architecture which made me to tune my lecture materials. I have put all that experience in writing this book. I would like to thank very sincerely Dr. Vamsi Srikantam who took great pains to go through my drafts and gave me very good suggestions for improvement of the content. I am highly grateful to him for his valuable help. Then my sincere thanks to my past secretary, Ms. Nasima Kazi, at IIT-Bombay. She had drawn many figures very meticulously with a fine touch. I am sure the reader will appreciate the diagrams when he/she looks at them. I am extremely grateful to my

colleague Mr. Parthasaraty at CMC-Hyderabad for the help he rendered in suggesting some corrections, modifying some diagrams and text format for better readability. Further, Ms Usha Priyadharshini helped me in giving some valuable suggestions for the material on compact disk and also getting me some figures for the chapter on Input/Output Devices. Her contribution is commendable. My sincere thanks to her. Last but not the least, I want to express my sense of appreciation and gratitude to my wife, Rajeswari, who gave me immense encouragement and support while I was busy with my writing at home.

S.S.S.P. Rao

Contents

CHAPTER 1

Electronic Computers: Brief History

1.1 INTRODUCTION

Computing is intimately connected to the representation of numbers. Advances in the numeral system and mathematical notations eventually led to the discovery of mathematical operations such as addition, subtraction, multiplication, division, squaring, square root etc. The earliest known tool for use in computation was the abacus, constructed as a bamboo frame with beads sliding on wires. This abacus is still in use till today in some parts of the world.

With advances in electronics, engineers could build amplifiers with a gain of the order of 10^5 or more. This amplifier is called Operational amplifier. With this operational amplifier, units that can perform integration, differentiation, addition, subtraction etc., were built. Using these components, a computing system that works with continuous variables and solves differential equations was built which is called the Analog computer. Analog computer works in parallel and handles continuous variables, and hence it works faster. Differential equations play a prominent role in engineering, physics and other disciplines. Analog computer was heavily used then.

The concept of programmable computers was developed by an English mechanical engineer Charles Babbage around 1820. Further developments of his work resulted in an electrical computer in 1942 that used vacuum tubes for digital computation including binary arithmetic and Boolean logic. This is the beginning of the digital computer era.

Since earlier digital computer were not very fast and analog computer works in parallel, engineers thought of taking best of both worlds by combining analog computer and digital computer through a suitable interface so that the overall system works faster. This configuration of both analog and digital computer system is called a Hybrid computer.

Due to the tremendous advances in electronics and digital computer architecture, digital computers started operating at higher speeds with high reliability. Parallel and Super computers started appearing which not only do number crunching but could be used in various applications

that include Natural Language Processing, Machine Learning, Machine Translation and Web Knowledge Processing etc.

Since analog computers have severe problems of drift and also used for limited operations, analog computers have become obsolete along with the hybrid computers. This chapter discusses analog, digital and hybrid computers and the reason for analog and hybrid computer becoming obsolete and presents a brief history of electronic computers of yesterday and today.

1.2 PROBLEMS AND SOLUTIONS

1.1. *What are the Electronic computers that were avialable in 1960s?*

Solution:

(*a*) Analog computer (*b*) Digital computer

(*c*) Hybrid computer

1.2 *What is an Analog computer?*

Solution: Analog computer works in parallel and handles continuous variables. And hence it works faster. There are mechanical and electronic analog computers. The oldest mechanical analog computer that existed in 100BC was a Greek machine Antikythera. Electronic analog computers use units such as Integrators, Summers, Function generators etc.

The main element in these units is the Operational amplifier, an amplifier with very high gain of the order of 10^5 or more. Analog computer mainly solves differential equations using the above units. Since the voltages and frequency have limitations, one needs to do Amplitude and Time scaling of the differential equations before they are solved by the analog computer. Once amplitude scaling and time scaling are done, based on the differential equations the Integrators, Summers and Functions generators need to be connected using cords (wires). There will be also a control unit to start the analog computer. The results can be either seen on CROs or printed on printers.

Some commercial Analog computers are Heathkit H1, EC-1, GTE EA 22, EPT-5 (Russian)

1.3 *What are the essential units of an Analog computer?*

Solution:

Essential components of Analog computer