THE x86 MICROPROCESSORS

Second Edition

Courage is what it takes to stand up
and speak; courage is also what it takes
to sit down and listen.

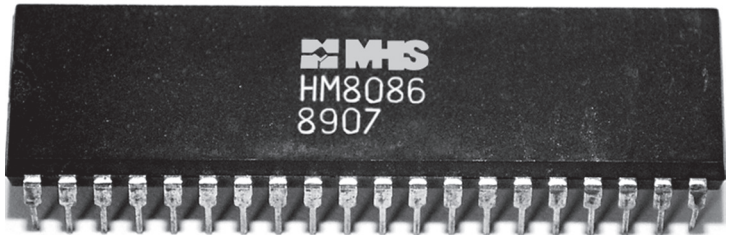
—— Winston Churchill

THE x86 MICROPROCESSORS

Second Edition

8086 to Pentium, Multicores, Atom and the 8051 Microcontroller

Architecture, Programming and Interfacing



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The pin diagrams, timing diagrams and internal architecture of x86 processors are reproduced in this book from the manuals of Intel with the permission of Intel Corporation, California.

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First Impression

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This book is dedicated
to all the members of my family,
and to my students
of the past, present and future.

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ONLINE CHAPTERS

PREFACE

Preamble

I have been teaching Electronics Engineering since 1985. In these years, I have taught subjects as varied as basic electronics, electronic circuits, digital signal processing, communications, information theory, digital image processing, computer architecture, computer programming and microprocessors, to name just a few. However, microprocessors, microcontrollers, assembly language programming and hardware interfacing caught my fancy and interest, at some point in time. This book is a result of my continued interest in these topics. The first edition was published in 2010, and this is the second edition in which the latest technology trends are covered.

Although I have used a number of text books for teaching microprocessors, I have felt that something is missing in most of them – either they do not touch upon programming concepts well or their approach to the x86 series of microprocessors creates an impression that it is tough to understand and manage, and that assembly language programming is unfriendly and difficult to master. In this book, I have tried to eliminate these shortcomings by describing the concepts in a step-by-step approach, aiming to keep simplicity of ideas, lucidity of explanations and clarity in presentation as my guiding principles.

The first set of the x86 family comprised the 8086, 80186, 80286, 80386, 80486 and Pentium processors. Later, Pentium Pro, Pentium IV and the Core microarchitectures appeared on the scene. At present, the Core i3, i5 and i7 processors hold sway among most cutting edge appliances. This second edition of my book on the x86 microprocessors continues to extend a detailed study of the x86 family of microprocessors covering all these processors.

This book explores the x86 family architecture based on the architecture of the elementary processor, that is, the 8086. The higher-order processors are delineated with focus on the enhancements, improvements and differences in these processors vis-à-vis the features of the basic 8086 processor. This is the best approach to learn the family architecture and it is followed by students worldwide. Most PCs across the world use the x86 architecture. Hence, it is an important subject that is taught and learnt at the academic and at the professional level. With the ongoing shift in computing scenario towards tablets and smart phones, knowing about the contribution of x86 microprocessors to this field gains added significance. We, thus, take a close look at Intel's Atom processor.

Prerequisite

Microprocessors form a key subject of study at the bachelor's level degree program of engineering, where it is taught as a core subject for all circuit-related branches, that is, electronics, electrical, computer science and information technology. A prerequisite for mastering this subject is a course on logic design, implying that students need to know the basic building blocks of a digital system. A course on computer organization and architecture would be helpful to the student, but it is not mandatory for understanding the subject. However, not all institutions deal with computer architecture in their study modules before teaching microprocessors. Hence, this book is aimed at being the first introduction to microprocessors.

Approach

The theme of the book is centered on the architecture of the x86 microprocessor and a detailed study of assembly language programming and interfacing to external chips. Throughout the book, the emphasis is on ensuring that the reader can grasp concepts and ideas easily. To this end, solved examples, worked-out problems, tested programs and explanatory diagrams have been included.

New to This Edition

- An exclusive chapter on advanced computer architecture dealing with the micro architecture of the very recent processors
- A comprehensive analysis of multicore concepts and multicore processors
- A chapter that reviews all the processors of Intel that were launched after Pentium
- An extensive discussion on Atom, Intel's high-end embedded processor
- Three chapters devoted to the 8051, the basic 8-bit microcontroller, with focus on its architecture as well as assembly language programming and interfacing to internal and external peripherals
- A complete discussion on the ACPI-based power management used in all modern computing devices
- Chapters on the 80186 microprocessor and the x86-based personal computer from the first edition have been shifted online to the book's URL, so as to make way for a comprehensive discussion of upgraded and contemporary processors in the book's printed version.

Organization of the book

Students who start learning microprocessors would have already learnt binary and other number systems. However, years of teaching have convinced me that a fresh look at these concepts would be in order, to understand assembly language programming. That is why an elaborate treatment has been meted out to these concepts in Chapter 0. It is important to be clear about topics like sign extension, signed arithmetic and BCD arithmetic. Readers would do well to be conversant with the concepts presented in Chapter 0. The discussion on the elements of computer architecture in this chapter is meant for those who have not studied this topic earlier. Similarly, the chapter also gives an overview of the 8085 processor for the benefit of those who have to learn about 8085 as part of their curriculum requirements. A study of the 8085 processor is not necessary to understand the x86 family of processors.

Chapter 1 explains the basic architecture of the 8086 processor. This chapter, fundamental to understanding the topics covered in the book, is profuse with numerical problems that explain important concepts.

Chapters 2 to 5 are devoted, for the most part, to assembly programming. Chapter 2 introduces the MASM assembler. We discuss Version 6.14, which is useful for effective assembly language programming. The steps for using the assembler to run programs are discussed in this chapter. The DOS and debugging commands of Appendix B may also be useful for getting a good grasp of programming skills. Chapter 5 includes an

introduction to C programming with embedded assembly modules. These four chapters cover most of the instructions of the 8086 processor the use of which has been highlighted in solved examples. Adequate end-of-chapter questions have been provided to ensure proficiency in programming. Advanced concepts like modular programming and high-level language constructs of MASM have also been described.

Chapters 6 and 7 are devoted to hardware. Chapter 6 talks about the pins of the 8086 processor and how these pins are used in the minimum and maximum mode configurations. Timing diagrams are introduced here. Chapter 7 elaborates on the techniques of address decoding and is important for understanding the hardware interfacing chapters that follow.

Chapter 8 is an interesting chapter because it introduces the concept of 'interrupts', which is an important theme in the study of computers. How hardware can be manipulated using software interrupts is explained here. Text mode video and TSR programming are introduced with practical worked-out examples. These help one to use the knowledge of assembly language to understand the PC.

Chapters 9 to 11 deal with the interfacing of the 8086 processor to various peripherals. A number of interfacing chips are introduced here. A detailed study of a few of these chips would stand the student in good stead. For example, understanding the 8255 chip would help us to learn about other peripheral chips with ease. These chapters have been designed to meet the needs of undergraduate students who use these chips for their laboratory work.

Chapter 12 discusses memory from the user's point of view. State-of-the-art memory trends like synchronous dynamic random access memory (SDRAM) and terms like double data rate (DDR) have been explained. Chapter 13 is devoted to the basic principles of multiprocessing and bus arbitration techniques. In addition, it discusses floating point arithmetic and the use of the arithmetic co-processor, including the programming aspects.

Chapter 14 is quite long. It takes a close look at the processors that came after the 80186 (which was an embedded processor never used in a PC), dealing at length with the 80386 processor, which is Intel's first 32-bit processor. Difficult topics such as address translation, protection and multitasking are elucidated for the student's benefit. Repeated reading of this topic will sort out many of the initial difficulties faced by the reader. The discussion in the chapter then moves on to the advanced features incorporated in the 80486 and Pentium processors.

Chapter 15 is a unique chapter in that it is devoted to no processor in particular. Instead, it traces the evolution of techniques used for performance enhancement from the first generation processors to the present time. Understanding this chapter makes the topic of 'advanced computer architecture' very exciting and interesting. It can make one appreciate the hard work put into the making of high-end microprocessors.

Chapter 16 goes one step beyond the contents of Chapter 15. The principle behind the idea of 'multicore' technology is explained here. As most of the present-day processors come with multicore components, unravelling the intricacies of such processors is an interesting exercise.

In Chapter 17, processors that came after Pentium are discussed. To understand this chapter, the contents of the previous two chapters must be studied well. With this chapter, we conclude our study of microprocessors – from the first x86 processor to the latest one, which uses the Haswell microarchitecture.

Chapter 18 is important because of two reasons: first, it elaborates upon the Atom, which marked Intel's entry into the high-end embedded field; and second, it presents the concept of advanced configuration and power interface (ACPI), which is the power management standard for all systems. ACPI is relevant for all systems, but the topic is included in this chapter because power management becomes imperative for embedded systems in particular.

Chapters 19, 20 and 21 reveal details about the 8051 microcontroller. This topic is taken up because almost all universities in India teach microprocessors and microcontrollers as a single course. The 8051 is a popular microcontroller that is easy for students to understand. It can be considered as the first building block for learning embedded systems. The 8051's architecture, programming and interfacing with internal and external peripherals are covered in these three chapters with the aid of elaborate programming examples using assembly language.

The book comes with seven appendices that relate, in order, to the Intel manual of the 8086 processor, the use of DOS and debug commands, the instruction set and instruction timing of the 8086 processor, the DOS and BIOS interrupt list, the instruction set of the 8087 processor, the instruction set of the 8051 and finally, a step-by-step guidance for using the Keil IDE for programming the 8051.

In addition, there is an appendix on the installation of MASM 32 made available on the book's Website. Other online appendices include information on the assembler MASM 6.14 and a step-by-step guide to using MASM in DOSBox. In addition, a tutorial on using NASM on Linux is also available for students. These appendices add value to the book by disseminating additional information on selected topics to the discerning learner.

I hope I have effectively addressed all topics pertaining to a compelling study of the x86 family of microprocessors. I suggest that all teachers who handle this subject should emphasize on the use of assemblers and ascertain that programs are tested practically to make the topics more interesting.

Contact

Your feedback and suggestions for the improvement of this book are welcome. While every attempt has been made to eliminate errors in this book, a few may still have managed to creep in. Kindly point them out to me – my email id is lbd@nitc.ac.in.

ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS TO THE SECOND EDITION

In this second edition, I have added a few more chapters to the book. I would like to acknowledge the support and help received for this endeavour from many quarters. I profusely thank Sajana Ranjit (Learning Links, Bangalore) and Sumeet Verma (Intel, India) for getting me acquainted with the Intel University Alliance program. The program gave me an opportunity to know more about Intel's x86 processors, especially the Atom processor, which I have written about, in Chapter 18. I am deeply indebted to Mr Shrikant Shah, Principal Design Engineer at Intel, Arizona, USA, for reviewing the material on the Atom processor and giving many helpful suggestions.

My students in NIT, Calicut, have always been my inspiration. The doubts and queries they asked, when I taught the course 'Advanced Processor Architecture', encouraged me to write Chapter 15, in which I have delved into the microarchitecture of the most recent processors. In addition, Muhammed Yazar (Amazon, India), when he was a final year Computer Science student, reviewed the chapter and offered many useful suggestions and revisions. I am extremely thankful to him. I also thank Arvind E. Vijayan, final year Electronics Engineering student, who helped me with the online resources for the use of MASM in the latest versions of Windows.

I am also obliged to my colleague Dhanraj K. J., who helped in clarifying the theoretical concepts of multicore processors. This has definitely made Chapter 16 more attractive. I appreciate the efforts of the team at Pearson, especially Sojan Jose, Vijay Pritha and Ramesh M. R, with whom I interacted continuously in the process of this work.

ACKNOWLEDGEMENTS TO THE FIRST EDITION

As I complete writing this book, I realize, with a sense of deep humility that I have a lot of people to thank. I first thank Sojan Jose, editor at Pearson Education, who discovered the author in me. It was only his enthusiasm, encouragement and support that gave me the courage to embark upon this venture. Ramesh, Thomas and other team members of this project at Pearson Education have impressed me with their professionalism and I thank them wholeheartedly for all the work they have put in to complete this book.

After I finished writing the first few chapters, I used the material to teach a course to the fourth-semester students (B070EC batch). I remember that many students participated actively in the teaching–learning process, which, in effect, gave me tips and suggestions on how this book should be. I thank them all and place on record my appreciation of their curiosity and determination to delve into the subject beyond mere superficiality.

Many of my colleagues were instrumental in helping me in this venture. The discussions I had with Jagandand, EED, and Saidalvi, CSED, were fruitful and helped to evolve some of the topics discussed in this book. I am grateful to Anand, senior mechanic at the Embedded Systems laboratory, who assisted me in carrying out the hardware work associated with interfacing, and his expertise has indeed made the work easier for me. I thank Dr Lillykutty Jacob, former head of the department of electronics and communications engineering, who reduced the quantum of topics that I had to teach

for one semester and enabled me to speed up the writing of this book. I am indebted to Kishore, who shared my duties at the microprocessor lab so that I could find time to complete the last few chapters as scheduled. I am obliged to my M.Tech students, Shiny and Shaeen, for their help in reading through some of the chapters, and to Sneha, Nitin, Venkat and Divya for their assistance in a few hardware experiments that were conducted in the course of writing this book.

It was Dr Mohamed Rafiquzzaman (Professor, California State Polytechnic University, Pomona, USA) who introduced me to the MASM32 assembler and the Olly debugger that have been discussed in Chapter 15. I am indebted to him. I also thank Dr Krishna Vedula who was the chief organizer of the IUCEE workshop, where I got the opportunity to meet Prof. Rafi.

This book contains a lot of diagrams, and I was lucky to find a few people who could draw really well. I thank Shelitha, Beljith and Ranjusha for their help with the illustrations.

The last chapter of this book contains information on how the modern PC works. I thank Sajth, of Dot Computers, Calicut, for clarifying my doubts and queries on this topic and also for lending me the motherboard and components, which I have used for generating the images presented in that chapter. I appreciate the contribution of Rajesh of Raja Studio, Kattangal, who photographed the chips, boards and other components that feature in the opening pages of each chapter.

I acknowledge the support of my friends Dr Elizabeth Elias, Dr Sally George, Dr Jeevamma Jacob, Dr Sathidevi, Dr E. Gopinathan, Dr Suresh Babu, Dr Sreelekha and Dr Deepthi whose companionship has always been a source of great encouragement to me.

My department colleagues have always been helpful and I think I am lucky to be a part of this group of motivated individuals. I am deeply indebted to my institution for nurturing me for the past twenty-five years (almost) and giving me the freedom to grow.

I am happy that my family has always been a source of solace for me.

Last, but not the least, I thank my students. All these years, I have been inspired by them. I have wanted to learn and know more, only on account of their ‘demand’. I hope I will continue to have such students in the future as well.

Lyla B. Das

ABOUT THE AUTHOR

Lyla B. Das is Associate Professor, Department of Electronics Engineering, National Institute of Technology Calicut (NITC), Kerala. She has a diverse mix of industrial, teaching and research experience spanning more than 30 years. As a young graduate specializing in Electronics and Communications from the College of Engineering, Trivandrum, she joined Keltron Controls as Deputy Engineer in 1981. She joined NITC (then Regional Engineering College, Calicut) as a lecturer in 1985 and proceeded to complete her master's degree in digital communications from the same college. Over the years, she was successively elevated as Assistant Professor and then Associate Professor, a position which she currently holds.

Keen to actively seek and impart knowledge, Lyla B. Das currently teaches courses on microprocessors, microcontrollers, digital system design using VHDL and system design using embedded processors at the undergraduate as well as postgraduate level. She has presented research papers in conferences of national and international stature and has worked on numerous projects based on microprocessors and microcontrollers. An avid reader of contemporary research material, she keeps herself abreast of the current trends in her chosen field and guides students in their M.Tech. research theses.

The first edition of this book, *The x86 Microprocessors,* was her maiden venture as author and it was published to wide acclaim in 2010. Her second book, *The Embedded Systems – An Integrated Approach*, was published in 2012.

Lyla B. Das has worked on various projects funded by the Ministry of Human Resource Development (MHRD) in thrust areas of growth including the setting up of an embedded systems laboratory in 2005–2008. She has delivered expert lectures on image compression using wavelets, advanced microprocessors and microcontrollers, FPGA-based systems and embedded systems at several engineering colleges across India. As a dedicated academician, she continues to be very active in the work involving processors, embedded systems and computer architecture.