

Werner Hilf
Anton Nausch

the M68000 family

Volume 1

Architecture,
Addressing Modes,
and Instruction Set



MOTOROLA

Series in Solid-State Electronics

The M68000 Family

Volume 1

The M68000 Family

Volume 1

**Architecture,
Addressing Modes
and
Instruction Set**



PRENTICE HALL, Englewood Cliffs, New Jersey 07632

© 1989, 1988 by Markt & Technik Verlag Aktiengesellschaft
8013 Haar bei München (Germany)

Cover design: Tom Turley

Translated by: Jack L. Davies, Munich, West-Germany

Limits of Liability and Disclaimer of Warranty

The Authors and Publisher of this book have used their best efforts in preparing the book and the programs contained in it. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The Authors and Publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The Authors and Publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

UNIX is a registered trademark of AT&T Bell Laboratories.

EXORmacs, VERSAdos, RMS68K are trademarks of Motorola, Inc.

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-541525-X

Prentice-Hall International (UK) Limited, *London*

Prentice-Hall of Australia Pty. Limited, *Sydney*

Prentice-Hall Canada Inc., *Toronto*

Prentice-Hall Hispanoamericana, S.A., *Mexico*

Prentice-Hall of India Private Limited, *New Delhi*

Prentice-Hall of Japan, Inc., *Tokyo*

Simon & Schuster Asia Pte. Ltd., *Singapore*

Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Table of Contents

Preface to the English Edition	9
Preface to the Second German Edition	11
1 General Background Information	13
1.1 Introduction	13
1.1.1 Definition of the "M68000 Family"	13
1.1.2 Who the Book is Designed for	14
1.2 History of the M68000 Family	15
1.2.1 General History of Computers	16
1.2.2 The History of 8-bit Microprocessors and Microcomputers	20
1.2.3 The History of 16/32-bit Microprocessors	24
1.2.4 The History of 32-bit Microprocessors	25
1.2.5 The Controversy Between RISC and CISC Philosophies	27
1.2.6 The Design Philosophy of the M68000 Family	29
1.3 The M68000 Family and its Producer	31
1.4 The New Programming Techniques	32
1.5 Foundations of Operating Systems	34
2 Organization of the M68000 Microprocessors	39
2.1 Technology and Architecture of Processors in the M68000 Family	39
2.1.1 Microcode Versus Combinatorial Logic	39
2.1.2 Internal Versus External Storage of Microcode	42
2.1.3 Horizontal Versus Vertical Microcode	43
2.1.4 Custom Microprocessors in the M68000 Family	45
2.1.5 Architecture of the Control Unit	45
2.1.6 Parallel Processing, Pipelining and Prefetch	47
2.2 Architectures of Systems	49
2.2.1 Block Diagram for a Typical System	49
2.2.2 Definition of the Pins on a 68000 Microprocessor	50
2.2.3 Definition of a Minimal System	55
2.3 Data Formats and Registers	57
2.3.1 Data Formats	57
2.3.2 Registers	61

2.4	The User Mode and the Supervisor Mode	65
2.5	Handling of Exceptions and Exception Vectors	67
2.5.1	Descriptions of the Exceptions	72
2.5.2	Handling of Exceptions	80
2.5.3	Exception Priorities	80
2.5.4	Saving Important Information on the Stack	81
2.5.5	Execution Times for Exceptions	83
2.6	The Asynchronous Bus-Signals and Timing Diagrams	84
2.6.1	The Read Bus Cycle	88
2.6.2	The DTACK Signal and Memory-Access Times of a Processor	90
2.6.3	The Write Bus Cycle	91
2.6.4	The Read-Modify-Write Bus Cycle	93
2.7	Function-Code Outputs FC0-FC2	95
2.8	The Synchronous Bus-Signals and Timing Diagrams	98
2.9	Handling of Interrupts	101
2.9.1	Identification of Interrupts	103
2.9.2	Sequence of Steps for Handling an Interrupt	103
2.9.3	Autovector Interrupts	106
2.9.4	Non-autovector Interrupts	107
2.9.5	Polling and Daisy Chaining of Interrupts	110
2.9.6	Interrupt Synchronization for Older Processor Types	111
2.10	RESET, HALT and Bus Error (BERR)	111
2.10.1	RESET	112
2.10.2	HALT	113
2.10.3	Bus Error (BERR)	115
2.10.4	Double Bus Error	118
2.10.5	Summary	118
2.11	Direct Memory Access (DMA)	118
3	Addressing Modes	123
3.1	General Principles of Addressing Modes	123
3.1.1	General Types of Addressing Modes	123
3.1.2	Definition of an "Effective Address"	124
3.1.3	Syntax for Instructions	126
3.1.4	A Model for Representing Addressing Modes	128
3.1.5	Addressing Modes and Addressing Categories	128
3.2	Register Direct-Addressing Modes	131
3.2.1	Data-Register Direct-Addressing Mode	131
3.2.2	Address-Register Direct-Addressing Mode	135
3.2.3	Status-Register (and Condition-Code-Register Direct-Addressing Mode	137
3.3	Absolute-Addressing Modes	139
3.3.1	Short-Address Absolute-Addressing Mode	140
3.3.2	Long-Address Absolute-Addressing Mode	147
3.4	Immediate-Addressing Modes	150
3.4.1	Immediate-Addressing Mode for Bytes (and Quick)	150
3.4.2	Immediate-Addressing Mode for Words	153
3.4.3	Immediate-Addressing Mode for Long Words	156

3.5	Address-Register Indirect-Addressing Modes	158
3.5.1	Address-Register Indirect-Addressing Mode	158
3.5.2	Address-Register Indirect-Addressing Mode, with Postincrement	160
3.5.3	Address-Register Indirect-Addressing Mode, with Predecrement	162
3.5.4	Address-Register Indirect-Addressing Mode, with an Offset	164
3.5.5	Address-Register Indirect-Addressing Mode, with an Index and with or Without an Offset	167
3.6	Relative-Addressing Modes	172
3.6.1	Program-Counter Relative-Addressing Mode, with or Without an Offset	174
3.6.2	Program-Counter Relative-Addressing Mode, with an Index with or Without an Offset	176
3.6.3	Branch Instructions (Conditional and Unconditional Jumps)	178
3.6.3.1	Branch Instructions with an 8-bit Jump Distance	179
3.6.3.2	Branch Instructions with a 16-bit Jump Distance	182
3.7	Addressing Modes that Sign Extend	182
3.8	Extra Addressing Modes of the 68020 and 68030 Microprocessors	183
4	Instructions of the M68000 Microprocessors	191
4.1	Summary of the Instruction Sets for 68000/08/10/12 Microprocessors	191
4.2	Detailed Description of the Instruction Set of the 68000/08/10/12 Microprocessors	196
4.3	Summary of Differences Among All M68000 Microprocessors	442
5	Masks of the 68000 Microprocessor	447
5.1	Introduction to Masks	447
5.2	The Prototype "XC68000" Microprocessor	448
5.3	The Main Mask Versions	449
Bibliography		451

Preface to the English Edition

The original German edition of this book that first appeared in 1984 has been a major success on the German market, primarily

- as an official training manual in many courses on microcomputers by many professional and public schools,
- as a reference work for designers and developers of both hardware and software for the M68000 family, and
- as an introduction to microprocessors in general and the M68000 family in particular for many enthusiasts.

In particular, it consolidates a large amount of relevant information from a variety of both English and German sources into one book that is convenient for the reader to use. This success led to the decision to publish an English edition of the book.

Several additions and changes have been incorporated into this new English edition. Due to the later release, all information has been updated to include new support devices and microprocessors (such as the 68030 microprocessor). The literature on the M68000 family comes from a variety of sources and points-of-view, with the result that there are many apparent logical inconsistencies in the information. We have therefore made a major effort to resolve these apparent inconsistencies in one single consistent treatment of the subject. Examples include such simple problems as how to count the number of instructions and addressing modes for each microprocessor in the family.

Realizing that many readers of this new edition will be beginners in the field of computers, we have included a more complete history of computers that tries to show why the M68000 family was designed the way it was—in its historical context. The emphasis of Chapter 2 was changed, from a presentation on the architecture of the 68000 microprocessor to a presentation on the architecture of all M68000 microprocessors with emphasis upon the 68000 microprocessor as an example. Therefore, specific differences between the 68000, 68008, 68010, 68012, 68020, and 68030 microprocessors are at least mentioned as the general architecture is described in Chapter 2. These differences are explained in more detail in Chapter 8 where the later processors are presented separately. The description of the additional addressing modes for the 68020 and 68030 microprocessors has been expanded and brought forward from Chapter 8 to the last section of Chapter 3 on addressing modes in general. Likewise, the additional instructions and changed instructions for the 68010 and 68012 microprocessors have been brought forward from Chapter 8 and integrated in alphabetical order in Chapter 4. However, the additional instructions for the 68020 and 68030 microprocessors have only been presented separately in summary form as the last section of Chapter 4. They are presented in more detail in Chapter 8.

Our special thanks to Jack L. Davies for his excellent translation and supportive ideas in issuing this book.

Preface to the Second German Edition

This book is intended for use both as an introduction to the M68000 family and as a reference work. The authors have attempted to present complex information explicitly in detail. This is one of the main reasons why this book had to be divided into two volumes shortly before it was first published in 1984. Fortunately, a separation was possible that is convenient for the reader.

In Volume I, the fundamentals are presented and the architecture for both hardware and software is presented more or less theoretically. You will find a brief historical background and second sources in Chapter 1. Fundamentals for a microcoded CPU and the pin layouts for the 68000 microprocessors are given in detail in Chapter 2. Important concepts and definitions that you will encounter in both volumes are also presented in Chapter 2. The addressing modes are presented in detail in Chapter 3 and the individual instructions are presented in detail with numerous small examples in Chapter 4. The last chapter in this volume presents the different versions of the 68000 microprocessor at the mask level.

Volume II is particularly suitable for those readers who have already acquired some experience with the M68000 family. It has the subtitle of "Applications and the M68000 Devices". You will find supplementary information and practical hints for working with the 68000 microprocessor in it. The software aspects are covered in Chapter 6, with many examples of short programs in assembler with M68000 instructions. Chapter 7 covers the most important support devices in both the 8-bit M6800 and 16-bit M68000 families. Chapter 8 covers the new and future microprocessors in the M68000 family. A complete single-board computer system, including software monitor, is described in Chapter 9 and a more complete illustrative example. Since the VME bus should not be overlooked in any discussion of the M68000 family, it is described in Chapter 10.

Both volumes present additional information concerning the 68000 microprocessor, e.g. laying the foundations for new programming techniques, new operating systems, and support devices for the next generation within the M68000 family.

The authors are in the fortunate position to have been intimately involved with the M68000 family, as employees of the prime source, from the day when this family was first introduced to the market. In creating and presenting numerous training courses internationally, the authors were able to develop their own understanding of this information, as well as to experiment with techniques for explaining this information to typical users. This experience played an important role in developing the format for this book. The reader should realize that the information in this book assumes some prior knowledge about microprocessors. As an example, the basic functions of a microprocessor are not explained in detail in this book. However, the reader will find a variety of other good books available for this type of introduction.

The authors wish to thank Motorola Inc. for the information and illustrations that they have made available to us for this purpose. We also wish to thank the companies Hitachi Europe, Rockwell International GmbH, and Valvo (Hamburg) for the information that they gave to us, particularly for Chapter 7 in Volume II.

In the second edition, a number of typographical errors were corrected and some of the formulations were improved. In particular, an extra subchapter, 2.4.4, was added to Chapter 2 in order to explain the differences between user and supervisor modes in more detail. The treatment of interrupts was expanded to include summaries. The "MC68000 16-bit Microprocessor Programming Reference Card" from Motorola, that is included separately with this book should be a welcome supplement for most readers. We thank Motorola Inc. for having provided the master copy for printing this card. The addition of an index in this edition emphasizes the role of this book as a training and reference work.

Munich, West Germany

W. Hilf, A. Nausch

1

General Background Information

1.1 Introduction

1.1.1 Definition of the "M68000 Family"

When Motorola introduced its 8-bit "M6800 family" in 1974, the 6800 was approximately the 20th 8-bit microprocessor released to the market—but it was the first microprocessor that was released as a family, together with various support devices. Since then, other manufacturers have adopted the same procedure of developing and releasing families rather than individual processors. In this context, it is not surprising that in 1979 Motorola also introduced its first 16-bit microprocessor, the 68000 microprocessor, as a member of a new family, called "the M68000 family".

The "M68000 family" has two dimensions or subfamilies:

- a subfamily of different microprocessors and
- a subfamily of different support devices.

In addition, the microprocessors of the M68000 family can also use the support devices from the related 8-bit M6800 family.

The subfamily of microprocessors is illustrated in Figure 1-1 below:

The subfamily of support devices contains the following categories of devices:

- peripheral-interface devices, including
- serial-interface devices
- parallel-interface devices
- data-communications devices
- floppy-disk controllers
- graphics controllers
- multi-function devices
- DMA devices
- memory-management units
- clocks and timers

As you can see from this listing, the availability of single devices for these complex functions can greatly simplify the task of an engineer in designing a new computer system around a new microprocessor. Otherwise, the engineer would have to design all of these circuits in detail himself, rather than to connect standard building blocks with predefined interfaces to the new microprocessor.

Since different terminology is used to describe the microprocessors and support devices of the M68000 family by

- Motorola (all device names begin with the prefix "MC", but the family is called the "M68000 family"),
- the second sources (all device names have the same number but different prefixes and suffixes), and
- the neutral literature (uses no prefixes),

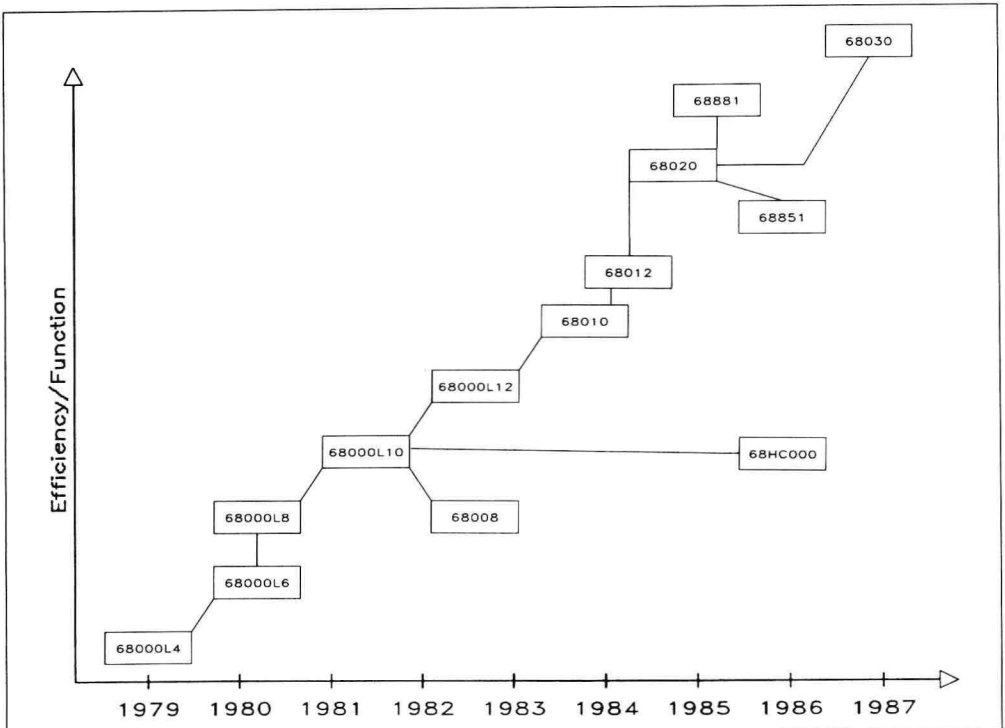


Figure 1-1: Microprocessors in the M68000 Family

we have established the following conventions for this book:

- “the M68000 family” refers to all microprocessors and support devices in the family,
- “an M68000 microprocessor” refers to any one of the several microprocessors in the M68000 family,
- “a 68000 microprocessor” refers to the single microprocessor with the Motorola designation of “MC68000”,
- the names of individual support devices also have no prefix, and
- a “C” is sometimes used in a number or as a suffix for a device that is implemented in CMOS technology.

In addition, references to the literature that is listed in the bibliography are enclosed in square brackets, []’s.

1.1.2 Who the Book is Designed for

This book is designed for both

- hardware engineers, who want to design the hardware for a simple or complex computer system that is based upon the M68000 family of microprocessors and support devices, and
- software engineers, who want to develop system software or specialized application software for use on computer systems that are based upon the M68000 family (at the level of an assembler language), as well as
- owners or users of computer systems that are based upon the M68000 family, who have an interest in understanding more clearly how their computer systems and software work, and

- computer enthusiasts who are curious and want to know more about how microprocessors work and how the microprocessors in the M68000 family work as specific examples.

Therefore, the potential reader can be

- a beginner, with some basic knowledge of the binary number system and access to a computer system that is based upon the M68000 family (with an assembler for some simple experimentation) or
- an experienced professional who wants to study the details of how the M68000 family works or to use the book as a reference work (from one single consistent source).

This book, or subsets thereof, can be used as a part of a neutral course on microcomputers in general, hardware design with microprocessors, or software design with microprocessors. In this case, this book presents the M68000 family as one example and other books can be used to present other families in order to maintain neutrality.

The reader does not have to read this book from A to Z, but rather can select most any order for reading the individual chapters. Cross references are included in each chapter to sections of the same or other chapters that may be relevant for understanding a particular point. This enables a casual reader to read the book in most any order, to browse through the main points, and then to study particular points of interest in more detail. An expert with prior experience with the M68000 family can use the book as a reference work for more detailed information on most aspects from one single source.

Volume I presents a more general background, including:

- a general history of microprocessors, that shows the relationships between the M68000 microprocessors within this historical framework,
- an explanation of the architecture of the M68000 microprocessors, with particular emphasis upon the 68000 microprocessor as the first in this family,
- an explanation of the basic concepts that are necessary to understand how M68000 microprocessors work, such as registers, data formats, exceptions, interrupts, buses and timing for the 68000 microprocessor,
- an explanation of the addressing modes that are available within the M68000 family (extended for the 68020 and 68030 microprocessors), and
- a complete description of each instruction in the instruction sets for the 68000, 68008, 68010, and 68012 microprocessors (some additions for the 68010 and 68012) and a summary description of the instructions added for the 68020 and 68030 microprocessors.

Volume II presents more specific information, including:

- how to program M68000 microprocessors, with practical examples (based upon the instruction set of the 68000 and 68008 microprocessors – that is a subset of the instruction sets of the other microprocessors),
- a detailed description of all major support devices in the M68000 family,
- a detailed description of the differences of the 68008, 68010, 68010, 68020, and 68030 microprocessors to the first 68000 microprocessor (the emphasis is on the differences in this volume, whereas it was on the similarities in the first volume), and
- a detailed description of a single-board computer system, as a practical example, including a monitor program as system software.

1.2 History of the M68000 Family

Where does the history of the M68000 family begin? To be complete, we would have to start with the discovery of the number systems and ancient tools to aid in computations with numbers. Then, we would have to trace the development of mathematics and computers, as well as related technologies. However,

we must limit the presentation here to the more recent developments that have a more direct bearing upon explaining why the M68000 family has become what it is today.

1.2.1 General History of Computers

One way of classifying computers into different groups is by the criterion of the technology that they use for performing computational tasks. With this approach, there are four generations, as follows:

Generation 0: Mechanical and Electromechanical

Examples of mechanical computers include:

- the abacus
- the slide rule
- the Jacquard loom
- the analytical engine of Charles Babbage

Examples of electromechanical computers include:

- the Bush differential analyzer
- the Mark I computer (with relays)

Generation 1: Electronic Tubes

The ENIAC was the first of the "first-generation computers". It was developed by the US Army in order to meet the computational requirements for calculating ballistic trajectories during the second world war. It was followed by the EDVAC and EDSAC computers, with improved architectures. The first commercial computers were based upon the EDVAC and EDSAC computers.

Generation 2: Transistors

Seymour Cray pioneered in designing the first computer that used only transistors without any electronic tubes in 1960 at the Control Data Corporation (he later formed his own company). However, the basic architecture and design remained essentially the same. (It was difficult to combine transistors and electronic tubes in the same computers, since both the signal levels and the required power voltages are quite different.)

Generation 3: Integrated Circuits

Since integrated circuits are essentially several transistors on one crystal "chip", the transition from using transistors to integrated circuits was more gradual, whereby many computers were made using both transistors and integrated circuits during this transition.

It is semantically incorrect to speak of 4th and 5th generation computers in this sequence, since the so-called 4th and 5th generation computers are really only third-generation computers that differ from one another in other ways than their basic technology. Therefore, we are still in the middle of the third generation in this sequence defined by basic technology as the criterion. The true 4th and 5th generations, in this sequence, will use other technologies, such as optics, 3-dimensional integrated circuits or biological molecules.

IBM came close to developing the first 4th-generation computer in this sequence, based upon Josephson junctions as the basic technology. However, both IBM and its competitors encountered technical dif-