B. A. BOWEN AND W. R. BROWN

VLSI SYSTEMS DESIGN FOR DIGITAL SIGNAL PROCESSING

VOLUME 1

SIGNAL PROCESSING AND SIGNAL PROCESSORS

VLSI SYSTEMS DESIGN FOR DIGITAL SIGNAL PROCESSING

Volume I: Signal Processing and Signal Processors

B. A. Bowen

Department of Systems and Computer Engineering
Carleton University
Ottawa

and

W. R. Brown

Department of National Defense
Ottawa

PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*

Library of Congress Cataloging in Publication Data

Bowen, B. A.
VLSI systems design for digital signal processing.

Bibliography: v. 1
Includes index.
Contents: v. 1. Signal processing and signal processors.
1. Signal processing—Digital techniques. 2. Integrated circuits—Very large scale integration. I. Brown, W. R. (William Roy) II. Title. III. Title: V.L.S.I. systems design for digital signal processing.
TK7868.D5B68 621.3819'592 81-13854
ISBN 0-13-942706-6 (v. 1) AACR2

Editorial/production supervision and interior design: Nancy Milnamow
Cover design: Dawn Stanley
Manufacturing buyer: Gordon Osbourne

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-942706-6

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall of Canada, Ltd., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

Global Preface

PREAMBLE

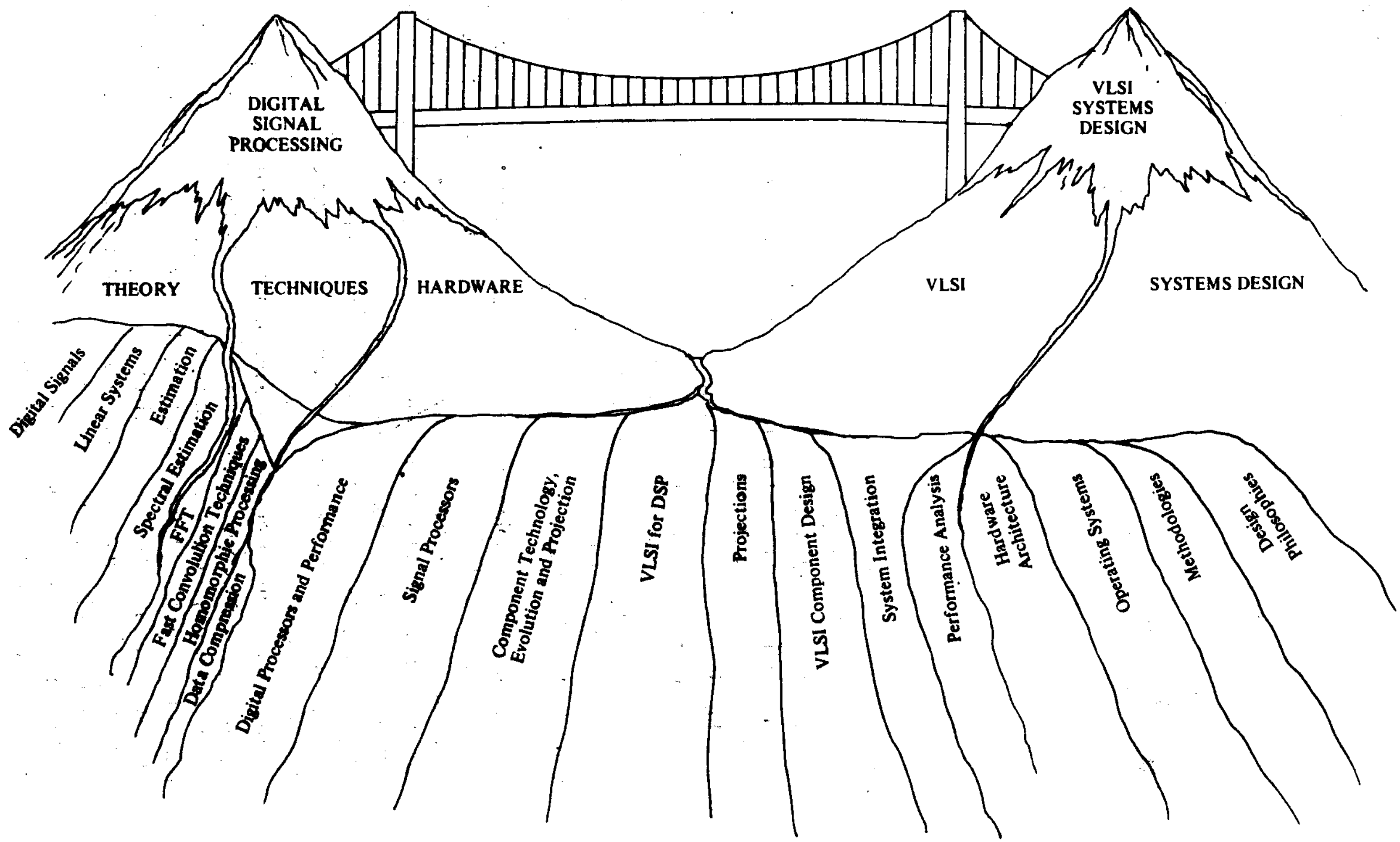
The rapid advances being made in the field of digital component technology are having profound effects on all aspects of digital systems design. Nowhere are these effects being felt more strongly than in the design of high performance systems for such applications as digital signal processing.

The classical architectural alternatives for realizing the high performance requirements of signal processing systems must be re-examined in the light of the exponential increases occurring in component capabilities. This two volume set brings together a wide variety of logical concepts that impact the design of such systems which acknowledge and take advantage of modern component technology.

Classically, the implementation of digital signal processing techniques has been constrained by the limitations of component technology. System realizations have tended toward one of two general approaches depending on performance requirements. Where high performance real time processing requirements were stringent, the trend was toward inflexible dedicated hardware systems. Where a lower performance was tolerable, the more flexible approach of a software implementation on a general purpose computer was often taken.

Initial attempts to provide both flexibility and high performance resulted in the evolution of supercomputers. These systems tended to be expensive and difficult to program and often achieved their full processing potential for only a limited class of problems. Over the past decade, the use of specialized high-speed array processors attached to a conventional general-purpose host computer has become the standard approach to the implementation of general purpose digital signal processors.

Modern component technology has recently opened a floodgate of high performance components that have dramatically altered the cost/performance


DIGITAL SIGNAL PROCESSING
VLSI SYSTEMS DESIGN
THEORY
TECHNIQUES
HARDWARE
VLSI
SYSTEMS DESIGN
Digital Signals
Linear Systems
Estimation
Spectral Estimation
FFT
Fast Convolution Techniques
Homomorphic Processing
Data Compression
Digital Processors and Performance
Signal Processors
Component Technology, Evolution and Projection
VLSI for DSP
Projections
VLSI Component Design
System Integration
Performance Analysis
Hardware Architecture
Operating Systems
Methodologies
Design Philosophies

criteria for all digital systems. In particular, the feasibility of systems consisting of programmable and configurable chips is exerting its influence on a wide range of new application areas.

In order to exploit the capabilities of these new components for the solution of signal processing problems, it is necessary for those involved in signal processing and for digital systems architects to find a bridge between their respective fields. It is the overall purpose of these three volumes to explore both worlds and establish such a bridge in the form of a systems design philosophy and methodology. For this bridge to support traffic it was found necessary to establish firm foundations on both sides and to create examples of safe passage.

A fundamental concept of the philosophy presented in Volume II is that design should be driven by systems requirements while accommodating implementation constraints. To present a design methodology and illustrate its application to digital signal processor design, it was found necessary to establish firmly the computational requirements and implementation constraints of signal processors. It is to this end that Volume I is dedicated. From a pedagogical point of view, Volume I is designed to be a senior course in digital signal processing with a strong engineering emphasis on the architecture of real processors. The content of the three volumes reflects the two major topics indicated in the title: systems design and signal processing. The material on signal processing is presented first since the first step in any design process must be the identification of the item to be designed. We wish to emphasize, however, that the goal is to unite these two major areas under the influence of VLSI (Very Large Scale Integration) component technology as a single coherent topic. To discuss "VLSI Systems Design for Digital Signal Processing" as a single topic, we must define that topic and what it encompasses.

There appear to be two possible interpretations of the title:

1. the design of VLSI components (themselves complex systems) intended for use in digital signal processing applications,
2. the design of digital signal processing systems that utilize VLSI components.

It is the second interpretation that we address in these volumes.

The subject matter encompassed tends to become almost cosmological in nature, seeming to immerse the reader (and at times, the authors) in an endless interlocked array of concepts which appear to expand without limit. Indeed, during the course of structuring the material there were times when it appeared that organizing a course of instruction to teach a centipede to walk would be an easier task. However, a concerted effort has been made to weave the required concepts together to form a coherent pattern.

In general, Volume I concerns digital signal processing and the basic concepts of digital signal processor architectures, while Volume II addresses the concepts of systems design and presents the bridge between the two fields in light of VLSI technology. It is in the areas of processor architectures and component technology that the underlying concepts of both signal processing and systems design merge.

It is recommended that the reader examine the introductions to Volumes I and II in sequence. In this way, an overall picture of the scope of the material to be presented, its organization and interrelation should emerge. This overall picture will be enhanced by a further reading of the introductions and summaries to each chapter prior to attempting the main body of the text. The bibliographies have been organized to suggest two levels of additional reading: first, tutorial expositions, usually in text books; second, more advanced or, perhaps, specialized reading, most often in papers. By these means, a complete personal road map can be constructed.

All this material is intended for use by electrical engineers at the senior undergraduate or introductory graduate level. While the material in Volume I is concerned specifically with digital signal processing, the design philosophies and methodology of Volume II are applicable to the design of digital systems in general. Indeed, the central theme of Volume II may be considered as systems design with digital signal processing representing a generalized case study framework within which the concepts of systems design are illustrated.

The choice of digital signal processing as the subject of the case study seems justifiable (aside from being of interest to the authors). Current trends and projections regarding digital component technology indicate that the capability to fabricate high performance digital signal processors at a reasonable cost is increasing dramatically. With increased performance and reduced cost the demand for signal processing systems can also be expected to increase. Thus, engineers entering the field of digital systems design need a broad familiarity with the basic concepts of signal processor design.

ACKNOWLEDGEMENTS

It is not unusual for professors to be supported by their students. This is never more true than in the preparation of books. Many students received early courses of instruction from incomplete manuscripts (and perhaps thought). Their reactions and comments formed powerful stimulus for modification and enhanced clarity. We hope we learned enough. John Bird read an early version of Chapters 1-4 of Volume I and his detailed knowledge of the mathematics proved invaluable.

Several of our colleagues read earlier versions of Volumes I and II. Their comments are particularly appreciated. Professors George and Coll made a host of suggestions which strongly influenced our choice of order and presentation. Professor Coll also provided valuable insight into the pragmatics of adaptive processing from his long experience in this field.

Grateful acknowledgement must also go to Karl Karlstrom of Prentice-Hall. As other P-H authors will agree, Karl provides that hearty laugh and subtle encouragement to press over the rough parts of a project. And of course, a phone call always meant a chance to talk to Rhoda Haas, and that added a further sparkle.

Finally, we are grateful to Elaine Carlyle who, with her innumerable skills and infinite patience, forms a super system in her own right, and without whom the pragmatics of preparing a manuscript could easily have become a serious matter.

Introduction to Volume I

In order to design digital signal processors that take advantage of advanced component technology, we must first understand the computational requirements and, as well, have an appreciation for the constraints imposed by technology. It is the purpose of this volume to present an overview of the important elements of background theory, processing techniques, and hardware evolution in a manner that will:

provide for the reader who is unfamiliar with digital signal processing a concise presentation of the major concepts;

lead to the identification of the basic computational requirements associated with digital signal processing theory and techniques;

set the stage for the systems design discussions of Volume II by establishing an appropriate perspective on how the dynamic nature of component technology effects the implementation of signal processors.

The material of this volume is organized basically in two parts. The first five chapters form Part A which reviews the underlying theory and basic techniques of digital signal processing. Chapter 5 provides the bridge from processing to processors. Chapters 6 and 7 make up Part B and concern the architecture and performance limitations of processors and hardware evolution.

It is not our intention to present a comprehensive treatment of the theoretical aspects of digital signal processing in Part A. The aim here is to place in perspective the wide range of theoretical material that forms the foundation of digital signal processing.

While a great deal of mathematical terminology and symbolism is presented in Part A (often in a somewhat encyclopaedic terseness), the major goal is to give the reader an overall grasp of signal processing theory, the link between this theory and some common processing techniques and, most importantly, the implied computational requirements for the implementation of these techniques in terms of digital hardware and/or software systems.

Chapter 5 provides a focal point for the material of Part A and establishes the context for moving from processing theory to processors. Since the move from theory to implementation must always take place within some context, Chapter 5 examines the general characteristics of a range of digital signal processing application areas with a focus on their influences on processing systems. The fundamental computational operations are summarized within an overall perspective of the interaction of theory, applications, and implementation issues.

Having established our foundations in digital signal processing theory, we proceed in Part B to establish the initial foundations of digital systems architecture. As in Part A, our approach here is to review the underlying concepts and to identify those major issues which influence the design of signal processors. We begin with an examination of the basic von Neumann machine architecture which embodies most of the fundamental concepts of digital computing architecture. The performance limitations and principal approaches to performance enhancement are explained through an examination of two early super computers. We then examine a selection of digital signal processors which illustrates the evolution of architectural concepts. The goal here is to expose answers to such questions as:

What implementation problems and performance limitations were faced?
How were these problems overcome or circumvented?
What problems have not been overcome?
Has anything changed that might allow unsolved problems of the past to be overcome now?
How does the specific system application affect the implementation, or vice versa?

In considering such questions, we note that the evolution of component technology has had a profound impact on signal processor performance (perhaps even more so than the implementation of classic architectural concepts for performance enhancement). Thus, Part B (and Volume I) concludes with an overview of integrated circuit technology evolution, some projections for future advances in VLSI components, and their impact on signal processors.

B. A. Bowen
W. R. Brown

Contents

THE BRIDGE

Part B: SIGNAL PROCESSORS

PART **A**

SIGNAL PROCESSING

INTRODUCTION

The topic of digital signal processing (DSP) may be approached in one of two ways. The first follows the historical development of the theory. This approach considers signals and signal processing in the analog domain and then maps the results to the digital domain for implementation. The second approach is to consider signal processing in terms of operations on the numbers which characterize a signal. In this approach the first concern is with the numerical representation of digital signals. The concepts of processing can then be developed in a purely digital context. This second approach leads to a broader range of issues and exposes implementation mechanisms which are more global than those available in the analog world. Indeed, there seems to be a major conceptual disadvantage to basing our concepts in the analog world; digital processing deals with numbers and operations on them, so practitioners must build a familiarity with such representations. It is therefore the second approach that we have chosen for our overview of digital signal processing theory.

Several excellent texts are currently available on the general theory of digital signal processing, the majority of which were published since the mid-1970s (see annotated bibliography). The general structure of the presentation in virtually all of these texts follows the same basic pattern.

- A discussion of deterministic discrete-time signals, and discrete-time linear systems based on $\mathcal{Z}$-transform techniques;
- A discussion of finite impulse response (FIR) and infinite impulse response (IIR) digital filters focusing on design techniques and quantization effects;
- A discussion of Hilbert transforms;

- A discussion of discrete Fourier transform (DFT) coefficient computation focused on the fast Fourier transform (FFT) algorithms followed by applications in the computation of correlation, convolutions and power spectra and the chirp-*z* transform algorithm;
- A discussion of generalized linear filtering (homomorphic processing);
- A discussion on digital hardware and processor implementation examples, either special purpose, general purpose or both;
- A discussion of one or two application areas.

This presentation pattern is not exact for any of the texts but represents a composite view. Gold and Rader [3], who published the first comprehensive treatment of digital signal processing theory, seem to have set this presentation pattern with the exception of the last two points. The texts by Oppenheim and Schaffer [6] and by Rabiner and Gold [10], both published in 1975, are probably the most well known general treatments of digital signal processing theory. These texts both follow the same general structure with Rabiner and Gold including chapters on two-dimensional processing, speech, and radar applications but omitting generalized linearity. Oppenheim and Schaffer treat generalized linearity in detail and also include chapters on random signal modeling and introduce some of the problems of estimation theory associated with power spectrum estimation. Peled and Liu [9] give a brief introduction to the basic concepts of the theory, and concentrate on practical implementations and example processors. Tretter [16], on the other hand, tends toward the theoretical approach, specifically excluding the last three points of the general pattern. Tretter, however, emphasizes the time domain approach to linear systems through state space representations and the importance of estimation theory in signal processing, including chapters on linear parameter estimation and recursive estimation techniques.

These books form a cornerstone of DSP which have provided the basis for the wide dissemination of both the theory and the practice of the discipline. It is difficult to imagine anyone in the field who has not devoted many hours of study to these books (including the present authors).

No single book can carry every aspect of this field to its ultimate conclusion. It would be naive to think of or propose such a proposition. Further reading is necessary and a guided tour is presented in the bibliography. Rabiner and Gold suggested in their introduction that their book should follow Oppenhiem and Schaffer. Perhaps this book fits before both. It is an attempt to bring this important field to the undergraduate classroom.

Our presentation differs from the standard format chiefly in terms of emphasis. It is an overview that is aimed at identifying the computational requirements of digital signal processing so that we can get on with the task of systems design. Several areas—such as filter design techniques—are mentioned only briefly. While these topics are certainly of importance, a more detailed discussion contributes little to determining computational require-