The Student's Guide to VHDL Second Edition

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Second Edition

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To my son Alexander

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Preface

VHDL is a language for describing digital electronic systems. It arose out of the United States government's Very High Speed Integrated Circuits (VHSIC) program. In the course of this program, it became clear that there was a need for a standard language for describing the structure and function of integrated circuits (ICs). Hence the VHSIC Hardware Description Language (VHDL) was developed. It was subsequently developed further under the auspices of the Institute of Electrical and Electronic Engineers (IEEE) and adopted in the form of the IEEE Standard 1076, Standard VHDL Language Reference Manual, in 1987. This first standard version of the language is often referred to as VHDL-87.

Like all IEEE standards, the VHDL standard is subject to review from time to time. Comments and suggestions from users of the 1987 standard were analyzed by the IEEE working group responsible for VHDL, and in 1992 a revised version of the standard was proposed. This was eventually adopted in 1993, giving us VHDL-93. A second round of revision of the standard was started in 1998. That process was completed in 2001, giving us VHDL-2002. After that, further development took place in the IEEE working group and in a technical committee of an organization, Accellera, whose charter is to promote standards for electronics design. These efforts led to the current version of the language, VHDL-2008, described in this book.

VHDL is designed to fill a number of needs in the design process. First, it allows description of the structure of a system, that is, how it is decomposed into subsystems and how those subsystems are interconnected. Second, it allows the specification of the function of a system using familiar programming language forms. Third, as a result, it allows the design of a system to be simulated before being manufactured, so that designers can quickly compare alternatives and test for correctness without the delay and expense of hardware prototyping. Fourth, it allows the detailed structure of a design to be synthesized from a more abstract specification, allowing designers to concentrate on more strategic design decisions and reducing time to market.

This book presents a structured guide to the modeling facilities offered by the VHDL language, showing how they can be used for the design of digital systems. The book does not purport to teach digital design, since that topic is large enough by itself to warrant several textbooks covering its various aspects. Instead, the book assumes that the reader has at least a basic grasp of digital design concepts, such as might be gained from a first course in digital design in an engineering degree program. Some exposure to computer programming and to concepts of computer organization will also be beneficial. *The Student's Guide to VHDL* is a condensed edition of *The Designer's Guide to VHDL*, which is a complete reference describing all of the features in the language. In *The Student's Guide*, we have selected those features that are most commonly used in the educational context, making the book suitable for use in an introductory or intermediate-level course in digital or computer design. Those who need a complete language reference for use in advanced courses or professional practice may prefer to use *The Designer's Guide*.

One pervasive theme running through the presentation in this book is that modeling a system using a hardware description language is essentially a software design exercise. This implies that good software engineering practice should be applied. Hence the treatment in this book draws directly from experience in software engineering. There are numerous hints and techniques from small-scale and large-scale software engineering presented throughout the book, with the sincere intention that they might be of use to readers.

Structure of the Book

The Student's Guide to VHDL is organized so that it can be read linearly from front to back. This path offers a graduated development, with each chapter building on ideas introduced in the preceding chapters. Each chapter introduces a number of related concepts or language facilities and illustrates each one with examples.

Chapter 1 introduces the idea of a hardware description language and outlines the reasons for its use and the benefits that ensue. It then proceeds to introduce the basic concepts underlying VHDL, so that they can serve as a basis for examples in subsequent chapters. The next three chapters cover the aspects of VHDL that are most like conventional programming languages. These may be used to describe the behavior of a system in algorithmic terms. Chapter 2 explains the basic type system of the language and introduces the scalar data types. Chapter 3 describes the sequential control structures, and Chapter 4 covers composite data structures used to represent collections of data elements. In Chapter 5, the main facilities of VHDL used for modeling hardware are covered in detail. These include facilities for modeling the basic behavioral elements in a design, the signals that interconnect them and the hierarchical structure of the design.

The next group of chapters extends this basic set of facilities with language features that make modeling of large systems more tractable. Chapter 6 introduces procedures and functions, which can be used to encapsulate behavioral aspects of a design. Chapter 7 introduces the package as a means of collecting together related parts of a design or of creating modules that can be reused in a number of designs. Chapter 8 deals with the important topic of resolved signals, and Chapter 9 describes a number of predefined and standard packages for use in VHDL designs.

The third group of chapters covers advanced modeling features in VHDL. Chapter 10 covers aliases as a way of managing the large number of names that arise in a large model. Chapter 11 describes generic constants as a means of parameterizing the behavior and structure of a design. Chapter 12 deals with the topics of component instantiation and configuration. These features are important in large real-world models, but they can be difficult to understand. Hence this book introduces structural modeling through the mechanism of direct instantiation in earlier chapters and leaves the more general case of component instantiation and configuration until this later chapter. In Chapter 13, generated regular structures are covered.

In the last two chapters, we focus on synthesis. Chapter 14 covers guidelines for writing synthesizable models. Then Chapter 15 is a case study, showing development of a synthesizable processor core and its use in a small embedded system, a digital alarm clock.

Each chapter in the book is followed by a set of exercises designed to help the reader develop understanding of the material. Where an exercise relates to a particular topic de-

scribed in the chapter, the section number is included in square brackets. An approximate "difficulty" rating is also provided, expressed using the following symbols:

❶ quiz-style exercise, testing basic understanding

❷ basic modeling exercise—10 minutes to half an hour effort

❸ advanced modeling exercise—one half to two hours effort

❹ modeling project—half a day or more effort

Answers for the first category of exercises are provided in Appendix C. The remaining categories involve developing VHDL models. Readers are encouraged to test correctness of their models by running them on a VHDL simulator. This is a much more effective learning exercise than comparing paper models with paper solutions.

Changes in the Second Edition

The first edition of this book was published in 1998, not long after VHDL-93 had gained acceptance. The latest revision of the language, VHDL-2008, adds a number of significant new language features, making this edition of *The Student's Guide to VHDL* significantly bigger than its predecessor. VHDL-2008 also specifies numerous minor new features and changes to existing features to enhance the usability of the language. This edition integrates descriptions of several of the new and revised features into the text. The differences between the various versions are highlighted in call-outs within the text, headed with "VHDL-2002," "VHDL-93," or "VHDL-87," as appropriate. In addition, some of the material has been removed or rearranged. There is a greater emphasis on synthesis in this edition. What was an appendix on the topic in previous editions of *The Designer's Guide to VHDL* has been substantially revised and promoted to full chapter status in this book. Finally, this edition includes a listing of the main VHDL standard packages as an appendix for reference.

Resources for Help and Information

Although this book covers many of the features of VHDL, there will no doubt be questions that it does not answer. For these, the reader will need to seek other resources.

Accellera is one of a number of organizations that sponsors the EDA Industry Working Groups Web server (www.eda.org). The server has links to Web pages and repositories of several VHDL standards groups and user groups.

Readers who have access to the Usenet electronic news network will find the news group comp.lang.vhdl a valuable resource. This discussion group is a source of announcements, sample models, questions and answers and useful software. Participants include VHDL users and people actively involved in the language standard working group and in VHDL tool development. The "frequently asked questions" (FAQ) file for this group is a mine of useful pointers to books, products and other information. It is archived at www.eda.org.

This book contains numerous examples of VHDL models that may also serve as a resource for resolving questions. The VHDL source code for these examples and the case

studies, as well as other related information, is available on the companion website for the book at *books.elsevier.com/companions/9781558608658*.

Although I have been careful to avoid errors in the example code, there are no doubt some that I have missed. I would be pleased to hear about them, so that I can correct them in the on-line code and in future printings of this book. Errata and general comments can be e-mailed to me at *vhdl-book@ashenden.com.au*.

Acknowledgments

The seeds for this book go back to 1990 when I developed a brief set of notes, *The VHDL Cookbook*, for my computer architecture class at the University of Adelaide. At the time, there were few books on VHDL available, so I made my booklet available for on-line access. News of its availability spread quickly around the world, and within days, my e-mail in-box was bursting. At the time of writing this, nearly 20 years later, I still regularly receive messages about the *Cookbook*. Many of the respondents urged me to write a full textbook version. With that encouragement, I embarked upon the exercise that led to the first edition of *The Designer's Guide to VHDL*. Two years after publication of *The Designer's Guide*, the need for a book specifically for students became evident. That led to publication of the first edition of *The Student's Guide to VHDL*. I am grateful to the many engineers, students and teachers around the world who gave me the impetus to write these books and who made them such a success. I hope this new edition will continue to meet the need for a VHDL reference for student use.

In the previous editions of *The Designer's Guide* and *The Student's Guide*, I had the opportunity to extend thanks to the many people who assisted in development of the books. They included my colleagues at the University of Adelaide; my research collaborators, Phil Wilsey at the University of Cincinnati and Perry Alexander at the University of Kansas; the staff at Morgan Kaufmann Publishers, including, in particular, Denise Penrose; the reviewers of the manuscript for the first edition, namely, Poras Balsara of the University of Texas, Paul Menchini of Menchini & Associates, David Pitts of GTE Labs and the University of Lowell and Philip Wilsey of the University of Cincinnati; David Bishop for his contribution to the material on synthesis in the first edition of *The Designer's Guide*; and Mentor Graphics Corporation, for use of their ModelSim simulator to check the example models. I remain grateful to all of these people and organizations for their valuable contributions to the earlier editions and to this edition.

For the current edition, I would also like to thank Jim Lewis, who collaborated on a recent book, *VHDL-2008: Just the New Stuff*. Much of the material from that book has found its way into this book in one form or another. Thanks also to Mentor Graphics Corporation for continued use of the ModelSim simulator to check the example code. I continue to enjoy an excellent working relationship with the staff at Morgan Kaufmann Publishers and their parent company, Elsevier. Thanks to Chuck Glaser, Senior Acquisitions Editor, for his support in the continued development of these VHDL books; to Dawnmarie Simpson, Senior Project Manager in the Production Department, for her meticulous attention to detail; and to Denise Penrose, Publisher, for her longstanding support of my writing endeavors.

I have dedicated *The Designer's Guide to VHDL* to my wife Katrina, in appreciation of her undestanding, encouragement, and support during the writing and revising of that

book. The first edition of *The Student's Guide to VHDL* I dedicated to our son, Alexander, who was very young at that time. Since then, he has maintained his keen interest in learning and intellectual inquiry, as well as a great sense of humor. It is fitting that I dedicate this second edition to my young scholar also.