Xilinx is disclosing this Document and Intellectual Property (hereinafter “the Design”) to you for use in the development of designs to operate on, or interface with Xilinx FPGAs. Except as stated herein, none of the Design may be copied, reproduced, distributed, republished, downloaded, displayed, posted, or transmitted in any form or by any means including, but not limited to, electronic, mechanical, photocopying, recording, or otherwise, without the prior written consent of Xilinx. Any unauthorized use of the Design may violate copyright laws, trademark laws, the laws of privacy and publicity, and communications regulations and statutes.

Xilinx does not assume any liability arising out of the application or use of the Design; nor does Xilinx convey any license under its patents, copyrights, or any rights of others. You are responsible for obtaining any rights you may require for your use or implementation of the Design. Xilinx reserves the right to make changes, at any time, to the Design as deemed desirable in the sole discretion of Xilinx. Xilinx assumes no obligation to correct any errors contained herein or to advise you of any correction if such be made. Xilinx will not assume any liability for the accuracy or correctness of any engineering or technical support or assistance provided to you in connection with the Design.

THE DESIGN IS PROVIDED “AS IS” WITH ALL FAULTS, AND THE ENTIRE RISK AS TO ITS FUNCTION AND IMPLEMENTATION IS WITH YOU. YOU ACKNOWLEDGE AND AGREE THAT YOU HAVE NOT RELIED ON ANY ORAL OR WRITTEN INFORMATION OR ADVICE, WHETHER GIVEN BY XILINX, OR ITS AGENTS OR EMPLOYEES. XILINX MAKES NO OTHER WARRANTIES, WHETHER EXPRESS, IMPLIED, OR STATUTORY, REGARDING THE DESIGN, INCLUDING ANY WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, TITLE, AND NONINFRINGEMENT OF THIRD-PARTY RIGHTS.

IN NO EVENT WILL XILINX BE LIABLE FOR ANY CONSEQUENTIAL, INDIRECT, EXEMPLARY, SPECIAL, OR INCIDENTAL DAMAGES, INCLUDING ANY LOST DATA AND LOST PROFITS, ARISING FROM OR RELATING TO YOUR USE OF THE DESIGN, EVEN IF YOU HAVE BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THE TOTAL CUMULATIVE LIABILITY OF XILINX IN CONNECTION WITH YOUR USE OF THE DESIGN, WHETHER IN CONTRACT OR TORT OR OTHERWISE, WILL IN NO EVENT EXCEED THE AMOUNT OF FEES PAID BY YOU TO XILINX HERETOUNDER FOR USE OF THE DESIGN. YOU ACKNOWLEDGE THAT THE FEES, IF ANY, REFLECT THE ALLOCATION OF RISK SET FORTH IN THIS AGREEMENT AND THAT XILINX WOULD NOT MAKE AVAILABLE THE DESIGN TO YOU WITHOUT THESE LIMITATIONS OF LIABILITY.

The Design is not designed or intended for use in the development of on-line control equipment in hazardous environments requiring fail-safe controls, such as in the operation of nuclear facilities, aircraft navigation or communications systems, air traffic control, life support, or weapons systems (“High-Risk Applications”). Xilinx specifically disclaims any express or implied warranties of fitness for such High-Risk Applications. You represent that use of the Design in such High-Risk Applications is fully at your risk.

© 2004-2008 Xilinx, Inc. All rights reserved. XILINX, the Xilinx logo, and other designated brands included herein are trademarks of Xilinx, Inc. PowerPC is a trademark of IBM Corp. and used under license. PCI, PCI-X, and PCI EXPRESS are registered trademarks of PCI-SIG. All other trademarks are the property of their respective owners.

Revision History

The following table shows the revision history for this document...

<table>
<thead>
<tr>
<th>Version</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/20/04</td>
<td>1.0</td>
</tr>
<tr>
<td>06/10/04</td>
<td>1.1</td>
</tr>
<tr>
<td>11/21/05</td>
<td>1.1.1</td>
</tr>
<tr>
<td>06/24/08</td>
<td>1.1.2</td>
</tr>
</tbody>
</table>
Preface

Limitations

Limited Warranty and Disclaimer

These designs are provided to you “as-is”. Xilinx and its licensors make and you receive no warranties or conditions, express, implied, statutory or otherwise, and Xilinx specifically disclaims any implied warranties of merchantability, non-infringement, or fitness for a particular purpose. Xilinx does not warrant that the functions contained in these designs will meet your requirements, or that the operation of these designs will be uninterrupted or error free, or that defects in the Designs will be corrected. Furthermore, Xilinx does not warrant or make any representations regarding use or the results of the use of the designs in terms of correctness, accuracy, reliability, or otherwise.

Limitation of Liability

In no event will Xilinx or its licensors be liable for any loss of data, lost profits, cost or procurement of substitute goods or services, or for any special, incidental, consequential, or indirect damages arising from the use or operation of the designs or accompanying documentation, however caused and on any theory of liability. This limitation will apply even if Xilinx has been advised of the possibility of such damage. This limitation shall apply notwithstanding the failure of the essential purpose of any limited remedies herein.

Technical Support Limitations

This module is not supported by general Xilinx Technical support as an official Xilinx product. Please refer any issues initially to the provider of the module. The author will gratefully receive any issues or potential continued improvements of the PicoBlaze™ microcontroller.

Ken Chapman
Senior Staff Engineer
E-mail: picoblaze@xilinx.com

The author will also be pleased to hear from anyone using the PicoBlaze™ microcontroller with information about your application and how these macros have been useful.
Acknowledgments

Xilinx thanks the following individuals for their contribution to the PicoBlaze microcontroller cause:

- **Henk van Kampen, Mediatronix**  
  Developer of the pBlazIDE graphical, integrated development environment.

- **Prof. Dr.-Ing. Bernhard Lang, University of Applied Sciences, Osnabrueck, Germany**  
  Concept of using VHDL simulation variables to display disassembled op-code instructions.

- **Kris Chaplin, Xilinx Ltd.**  
  JTAG-based program loader, update function.
The PicoBlaze™ embedded microcontroller is an efficient, cost-effective embedded processor core for Spartan®-3, Virtex®-II, and Virtex-II Pro FPGAs. This user guide describes the capabilities, features, and benefits of PicoBlaze hardware design and how to effectively use the PicoBlaze instruction set and tools to create software applications.

Guide Contents

This manual contains the following chapters:

- **Chapter 1, “Introduction,”** describes the features and functional blocks of the PicoBlaze microcontroller.
- **Chapter 2, “PicoBlaze Interface Signals,”** defines the PicoBlaze signals.
- **Chapter 3, “PicoBlaze Instruction Set,”** summarizes the instruction set of the PicoBlaze microcontrollers.
- **Chapter 4, “Interrupts,”** describes how the PicoBlaze microcontroller uses interrupts.
- **Chapter 5, “Scratchpad RAM,”** describes the 64-byte scratchpad RAM.
- **Chapter 6, “Input and Output Ports,”** describes the input and output ports supported by the PicoBlaze microcontroller.
- **Chapter 7, “Instruction Storage Configurations,”** provides several examples of instruction storage with the PicoBlaze microcontroller.
- **Chapter 8, “Performance,”** provides performance values for the PicoBlaze microcontroller.
- **Chapter 10, “Using the PicoBlaze Microcontroller in an FPGA Design,”** describes the design flow process with the PicoBlaze microcontroller.
- **Chapter 9, “PicoBlaze Development Tools,”** describes the available development tools.
- **Chapter 11, “Assembler Directives,”** describes the assembler directives that provide advanced control.
- **Chapter 12, “Simulating PicoBlaze Code,”** describes the tools that simulate PicoBlaze code.
- **Appendix A, “Related Materials and References,”** provides additional resources useful for the PicoBlaze microcontroller design.
- **Appendix B, “Example Program Templates,”** provides example KCPSM3 and pBlazIDE code templates for use in application programs.
- **Appendix C, “PicoBlaze Instruction Set and Event Reference,”** summarizes the PicoBlaze instructions and events in alphabetical order.
- **Appendix D, “Instruction Codes,”** provides the 18-bit instruction codes for all PicoBlaze instructions.
- **Appendix E, “Register and Scratchpad RAM Planning Worksheets,”** provides worksheets to use for the PicoBlaze microcontroller design.
Table of Contents

Preface: Limitations
  Limited Warranty and Disclaimer ........................................... 3
  Limitation of Liability ...................................................... 3
  Technical Support Limitations ............................................. 3

Preface: Acknowledgments

About This Guide
  Guide Contents .............................................................. 5

Chapter 1: Introduction
  PicoBlaze Microcontroller Features ..................................... 13
  PicoBlaze Microcontroller Functional Blocks ......................... 14
    General-Purpose Registers ............................................. 14
    1,024-Instruction Program Store .................................... 14
    Arithmetic Logic Unit (ALU) .......................................... 15
    Flags ........................................................................... 15
    64-Byte Scratchpad RAM ................................................. 15
    Input/Output ............................................................... 15
    Program Counter (PC) .................................................... 16
    Program Flow Control .................................................... 16
    CALL/RETURN Stack ..................................................... 16
    Interrupts ...................................................................... 16
    Reset ........................................................................... 16
  Why the PicoBlaze Microcontroller? .................................... 17
  Why Use a Microcontroller within an FPGA? ......................... 17

Chapter 2: PicoBlaze Interface Signals

Chapter 3: PicoBlaze Instruction Set
  Address Spaces ................................................................... 24
  Processing Data ................................................................... 26
    Logic Instructions .......................................................... 26
      Bitwise AND, OR, XOR .................................................. 26
      Complement/Invert Register .......................................... 27
      Invert or Toggle Bit ...................................................... 27
      Clear Register ............................................................ 27
      Set Bit ......................................................................... 27
      Clear Bit ...................................................................... 28
    Arithmetic Instructions ................................................... 28
      ADD and ADDCY Add Instructions ................................... 28
      SUB and SUBCY Subtract Instructions ............................. 29
Increment/Decrement ............................................. 29
Negate .................................................................... 30
Multiplication .......................................................... 30
Division .................................................................. 32
No Operation (NOP) .................................................. 33
Setting and Clearing CARRY Flag .............................. 34
  Clear CARRY Flag .................................................. 34
  Set CARRY Flag ..................................................... 34
Test and Compare ..................................................... 34
  Test ....................................................................... 34
  Compare ............................................................... 36
Shift and Rotate Instructions ..................................... 36
  Shift ..................................................................... 36
  Rotate ................................................................. 37
Moving Data ............................................................. 38
Program Flow Control ............................................. 38
  JUMP .................................................................. 39
  CALL/RETURN ...................................................... 40

Chapter 4: Interrupts
Example Interrupt Flow ............................................ 44

Chapter 5: Scratchpad RAM
Address Modes ....................................................... 47
  Direct Addressing ................................................... 47
  Indirect Addressing ................................................. 47
Implementing a Look-Up Table .................................. 48
Stack Operations ...................................................... 49
FIFO Operations ...................................................... 49

Chapter 6: Input and Output Ports
PORT_ID Port .......................................................... 51
INPUT Operations ..................................................... 52
  Applications with Few Input Sources ......................... 54
  READ_STROBE Interaction with FIFOs .................... 54
OUTPUT Operations ................................................ 55
  Simple Output Structure for Few Output Destinations ... 56
Pipelining for Maximum Performance ....................... 58
Repartitioning the Design for Maximum Performance ...... 60

Chapter 7: Instruction Storage Configurations
Standard Configuration – Single 1Kx18 Block RAM .......... 61
Standard Configuration with UART or JTAG Programming Interface ......................................................... 62
Two PicoBlaze Microcontrollers Share a 1Kx18 Code Image ......................................................... 62
Two PicoBlaze Microcontrollers with Separate Code Images in a Block RAM ........................................ 63
Distributed ROM Instead of Block RAM ....................... 63
Chapter 8: Performance
Input Clock Frequency .................................................. 65
Predicting Executing Performance ................................. 65

Chapter 9: PicoBlaze Development Tools
KCPSM3 ................................................................. 67
Assembler ............................................................... 67
Assembly Errors ......................................................... 68
Input and Output Files .................................................. 68
Mediatronix pBlazIDE .................................................. 69
Configuring pBlazIDE for the PicoBlaze Microcontroller ..... 69
Importing KCPSM3 Code into pBlazIDE ......................... 70
Differences Between the KCPSM3 Assembler and pBlazIDE 71
Directives ....................................................................... 71

Chapter 10: Using the PicoBlaze Microcontroller in an FPGA Design
VHDL Design Flow ....................................................... 73
KCPSM3 Module .......................................................... 73
Connecting the Program ROM ....................................... 74
Black Box Instantiation of KCPSM3 using KCPSM3.ngc ..... 75
Generating the Program ROM using prog_rom.coe ............ 75
Generating an ESC Schematic Symbol ............................... 75
Verilog Design Flow ..................................................... 75

Chapter 11: Assembler Directives
Locating Code at a Specific Address ............................... 77
Naming or Aliasing Registers ........................................... 77
Defining Constants ....................................................... 78
Naming the Program ROM Output File ............................. 78
KCPSM3 ................................................................. 78
pBlazIDE ............................................................... 78
Defining I/O Ports (pBlazIDE) ........................................ 78
Input Ports ............................................................... 79
Output Ports .............................................................. 79
Input/Output Ports ....................................................... 80
Custom Instruction Op-Codes ......................................... 81

Chapter 12: Simulating PicoBlaze Code
Instruction Set Simulation with pBlazIDE ......................... 84
Simulator Control Buttons ............................................. 85
Using the pBlazIDE Instruction Set Simulator with KCPSM3 Programs .......................... 86
Simulating FPGA Interaction with the pBlazIDE Instruction Set Simulator .................. 86
Turbocharging Simulation using FPGAs! .......................... 87
Appendix A: Related Materials and References

Appendix B: Example Program Templates

KCPSM3 Syntax .................................................................................................................. 91
pBlazIDE Syntax .................................................................................................................. 92

Appendix C: PicoBlaze Instruction Set and Event Reference

ADD sX, Operand — Add Operand to Register sX ............................................................. 93
ADDCY sX, Operand — Add Operand to Register sX with Carry ................................. 94
AND sX, Operand — Logical Bitwise AND Register sX with Operand ................. 95
CALL [Condition,] Address — Call Subroutine at Specified Address .................. 96
COMPARE sX, Operand — Compare Operand with Register sX .............................. 98
DISABLE INTERRUPT — Disable External Interrupt Input ...................................... 99
ENABLE INTERRUPT — Enable External Interrupt Input ........................................ 99
FETCH sX, Operand — Read Scratchpad RAM Location to Register sX ............... 100
INPUT sX, Operand — Set PORT_ID to Operand, Read value on IN_PORT ............. 101
INTERRUPT Event, When Enabled ............................................................................... 102
JUMP [Condition,] Address — Jump to Specified Address ..................................... 103
LOAD sX, Operand — Load Register sX with Operand ............................................. 104
OR sX, Operand — Logical Bitwise OR Register sX with Operand ...................... 105
OUTPUT sX, Operand — Write Register sX Value to OUT_PORT ......................... 106
RESET Event .................................................................................................................. 107
RETURN [Condition] — Return from Subroutine Call ............................................ 108
RETURNI [ENABLE/DISABLE] — Return from Interrupt Service Routine ............ 109
RL sX — Rotate Left Register sX ............................................................................... 110
RR sX — Rotate Right Register sX ........................................................................... 110
SL[0 | 1 | X | A] sX — Shift Left Register sX ............................................................... 111
SR[0 | 1 | X | A] sX — Shift Right Register sX ............................................................. 112
STORE sX, Operand — Write Register sX Value to Scratchpad RAM ................. 114
SUB sX, Operand — Subtract Operand from Register sX ..................................... 115
SUBCY sX, Operand — Subtract Operand from Register sX with Borrow .......... 116
TEST sX, Operand — Test Bit Location in Register sX, Generate Odd Parity ...... 118
XOR sX, Operand — Logical Bitwise XOR Register sX with Operand .................. 120

Appendix D: Instruction Codes

Appendix E: Register and Scratchpad RAM Planning Worksheets

Registers ....................................................................................................................... 125
Scratchpad RAM ........................................................................................................ 126
Chapter 1

Introduction

The PicoBlaze™ microcontroller is a compact, capable, and cost-effective fully embedded 8-bit RISC microcontroller core optimized for the Spartan®-3, Virtex®-II, and Virtex-II Pro FPGA families. The PicoBlaze microcontroller provides cost-efficient microcontroller-based control and simple data processing.

The PicoBlaze microcontroller is optimized for efficiency and low deployment cost. It occupies just 96 FPGA slices, or only 12.5% of an XC3S50 FPGA and a miniscule 0.3% of an XC3S5000 FPGA. In typical implementations, a single FPGA block RAM stores up to 1024 program instructions, which are automatically loaded during FPGA configuration. Even with such resource efficiency, the PicoBlaze microcontroller performs a respectable 44 to 100 million instructions per second (MIPS) depending on the target FPGA family and speed grade.

The PicoBlaze microcontroller core is totally embedded within the target FPGA and requires no external resources. The PicoBlaze microcontroller is extremely flexible. The basic functionality is easily extended and enhanced by connecting additional FPGA logic to the microcontroller’s input and output ports.

The PicoBlaze microcontroller provides abundant, flexible I/O at much lower cost than off-the-shelf controllers. Similarly, the PicoBlaze peripheral set can be customized to meet the specific features, function, and cost requirements of the target application. Because the PicoBlaze microcontroller is delivered as synthesizable VHDL source code, the core is future-proof and can be migrated to future FPGA architectures, effectively eliminating product obsolescence fears. Being integrated within the FPGA, the PicoBlaze microcontroller reduces board space, design cost, and inventory.

The PicoBlaze FPC is supported by a suite of development tools including an assembler, a graphical integrated development environment (IDE), a graphical instruction set simulator, and VHDL source code and simulation models. Similarly, the PicoBlaze microcontroller is also supported in the Xilinx System Generator development environment.

The various PicoBlaze code examples throughout this application note are written for the Xilinx KCPSM3 assembler. The Mediatronix pBlazIDE assembler has a code import function that reads the KCPSM3 syntax.

PicoBlaze Microcontroller Features

As shown in the block diagram in Figure 1-1, the PicoBlaze microcontroller supports the following features:

- 16 byte-wide general-purpose data registers
- 1K instructions of programmable on-chip program store, automatically loaded during FPGA configuration
PicoBlaze 8-bit Embedded Microcontroller

Chapter 1: Introduction

- Byte-wide Arithmetic Logic Unit (ALU) with CARRY and ZERO indicator flags
- 64-byte internal scratchpad RAM
- 256 input and 256 output ports for easy expansion and enhancement
- Automatic 31-location CALL/RETURN stack
- Predictable performance, always two clock cycles per instruction, up to 200 MHz or 100 MIPS in a Virtex-II Pro FPGA
- Fast interrupt response; worst-case 5 clock cycles
- Optimized for Xilinx Spartan-3, Virtex-II, and Virtex-II Pro FPGA architectures—just 96 slices and 0.5 to 1 block RAM
- Assembler, instruction-set simulator support

**Figure 1-1: PicoBlaze Embedded Microcontroller Block Diagram**

### PicoBlaze Microcontroller Functional Blocks

#### General-Purpose Registers

The PicoBlaze microcontroller includes 16 byte-wide general-purpose registers, designated as registers s0 through sF. For better program clarity, registers can be renamed using an assembler directive. All register operations are completely interchangeable; no registers are reserved for special tasks or have priority over any other register. There is no dedicated accumulator; each result is computed in a specified register.

#### 1,024-Instruction Program Store

The PicoBlaze microcontroller executes up to 1,024 instructions from memory within the FPGA, typically from a single block RAM. Each PicoBlaze instruction is 18 bits wide. The instructions are compiled within the FPGA design and automatically loaded during the FPGA configuration process.
Other memory organizations are possible to accommodate more PicoBlaze controllers within a single FPGA or to enable interactive code updates without recompiling the FPGA design. See Chapter 7, “Instruction Storage Configurations,” for more information.

Arithmetic Logic Unit (ALU)

The byte-wide Arithmetic Logic Unit (ALU) performs all microcontroller calculations, including:

- basic arithmetic operations such as addition and subtraction
- bitwise logic operations such as AND, OR, and XOR
- arithmetic compare and bitwise test operations
- comprehensive shift and rotate operations

All operations are performed using an operand provided by any specified register (sX). The result is returned to the same specified register (sX). If an instruction requires a second operand, then the second operand is either a second register (sY) or an 8-bit immediate constant (kk).

Flags

ALU operations affect the ZERO and CARRY flags. The ZERO flag indicates when the result of the last operation resulted in zero. The CARRY flag indicates various conditions, depending on the last instruction executed.

The INTERRUPT_ENABLE flag enables the INTERRUPT input.

64-Byte Scratchpad RAM

The PicoBlaze microcontroller provides an internal general-purpose 64-byte scratchpad RAM, directly or indirectly addressable from the register file using the STORE and FETCH instructions.

The STORE instruction writes the contents of any of the 16 registers to any of the 64 RAM locations. The complementary FETCH instruction reads any of the 64 memory locations into any of the 16 registers. This allows a much greater number of variables to be held within the boundary of the processor and tends to reserve all of the I/O space for real inputs and output signals.

The six-bit scratchpad RAM address is specified either directly (ss) with an immediate constant, or indirectly using the contents of any of the 16 registers (sY). Only the lower six bits of the address are used; the address should not exceed the 00 - 3F range of the available memory.

Input/Output

The Input/Output ports extend the PicoBlaze microcontroller’s capabilities and allow the microcontroller to connect to a custom peripheral set or to other FPGA logic. The PicoBlaze microcontroller supports up to 256 input ports and 256 output ports or a combination of input/output ports. The PORT_ID output provides the port address. During an INPUT operation, the PicoBlaze microcontroller reads data from the IN_PORT port to a specified register, sX. During an OUTPUT operation, the PicoBlaze microcontroller writes the contents of a specified register, sX, to the OUT_PORT port.

See Chapter 6, “Input and Output Ports,” for more information.
Program Counter (PC)

The Program Counter (PC) points to the next instruction to be executed. By default, the PC automatically increments to the next instruction location when executing an instruction. Only the JUMP, CALL, RETURN, and RETURNI instructions and the Interrupt and Reset Events modify the default behavior. The PC cannot be directly modified by the application code; computed jump instructions are not supported.

The 10-bit PC supports a maximum code space of 1,024 instructions (000 to 3FF hex). If the PC reaches the top of the memory at 3FF hex, it rolls over to location 000.

Program Flow Control

The default execution sequence of the program can be modified using conditional and non-conditional program flow control instructions.

The JUMP instructions specify an absolute address anywhere in the 1,024-instruction program space.

CALL and RETURN instructions provide subroutine facilities for commonly used sections of code. A CALL instruction specifies the absolute start address of a subroutine, while the return address is automatically preserved on the CALL/RETURN stack.

If the interrupt input is enabled, an Interrupt Event also preserves the address of the preempted instruction on the CALL/RETURN stack while the PC is loaded with the interrupt vector, 3FF hex. Use the RETURNI instruction instead of the RETURN instruction to return from the interrupt service routine (ISR).

CALL/RETURN Stack

The CALL/RETURN hardware stack stores up to 31 instruction addresses, enabling nested CALL sequences up to 31 levels deep. Since the stack is also used during an interrupt operation, at least one of these levels should be reserved when interrupts are enabled.

The stack is implemented as a separate cyclic buffer. When the stack is full, it overwrites the oldest value. Consequently, there are no instructions to control the stack or the stack pointer. No program memory is required for the stack.

Interrupts

The PicoBlaze microcontroller has an optional INTERRUPT input, allowing the PicoBlaze microcontroller to handle asynchronous external events. In this context, “asynchronous” relates to interrupts occurring at any time during an instruction cycle. However, recommended design practice is to synchronize all inputs to the PicoBlaze controller using the clock input.

The PicoBlaze microcontroller responds to interrupts quickly in just five clock cycles. See Chapter 4, “Interrupts,” for more information.

Reset

The PicoBlaze microcontroller is automatically reset immediately after the FPGA configuration process completes. After configuration, the RESET input forces the processor into the initial state. The PC is reset to address 0, the flags are cleared, interrupts are disabled, and the CALL/RETURN stack is reset.
Why the PicoBlaze Microcontroller?

There are literally dozens of 8-bit microcontroller architectures and instruction sets. Modern FPGAs can efficiently implement practically any 8-bit microcontroller, and available FPGA soft cores support popular instruction sets such as the PIC, 8051, AVR, 6502, 8080, and Z80 microcontrollers. Why use the PicoBlaze microcontroller instead of a more popular instruction set?

The PicoBlaze microcontroller is specifically designed and optimized for the Spartan-3, Virtex-II, and Virtex-II Pro FPGA architectures. Its compact yet capable architecture consumes considerably less FPGA resources than comparable 8-bit microcontroller architectures within an FPGA. Furthermore, the PicoBlaze microcontroller is provided as a free, source-level VHDL file with royalty-free re-use within Xilinx FPGAs.

Some standalone microcontroller variants have a notorious reputation for becoming obsolete. Because it is delivered as VHDL source, the PicoBlaze microcontroller is immune to product obsolescence as the microcontroller can be retargeted to future generations of Xilinx FPGAs, exploiting future cost reductions and feature enhancements. Furthermore, the PicoBlaze microcontroller is expandable and extendable.

Before the advent of the PicoBlaze and MicroBlaze™ embedded processors, the microcontroller resided externally to the FPGA, limiting the connectivity to other FPGA functions and restricting overall interface performance. By contrast, the PicoBlaze microcontroller is fully embedded in the FPGA with flexible, extensive on-chip connectivity to other FPGA resources. Signals remain within the FPGA, improving overall performance. The PicoBlaze microcontroller reduces system cost because it is a single-chip solution, integrated within the FPGA and sometimes only occupying leftover FPGA resources.

The PicoBlaze microcontroller is resource efficient. Consequently, complex applications are sometimes best portioned across multiple PicoBlaze microcontrollers with each controller implementing a particular function, for example, keyboard and display control, or system management.

Why Use a Microcontroller within an FPGA?

Microcontrollers and FPGAs both successfully implement practically any digital logic function. However, each has unique advantages in cost, performance, and ease of use. Microcontrollers are well suited to control applications, especially with widely changing requirements. The FPGA resources required to implement the microcontroller are relatively constant. The same FPGA logic is re-used by the various microcontroller instructions, conserving resources. The program memory requirements grow with increasing complexity.

Programming control sequences or state machines in assembly code is often easier than creating similar structures in FPGA logic.

Microcontrollers are typically limited by performance. Each instruction executes sequentially. As an application increases in complexity, the number of instructions required to implement the application grows and system performance decreases accordingly. By contrast, performance in an FPGA is more flexible. For example, an algorithm can be implemented sequentially or completely in parallel, depending on the
performance requirements. A completely parallel implementation is faster but consumes more FPGA resources.

A microcontroller embedded within the FPGA provides the best of both worlds. The microcontroller implements non-timing crucial complex control functions while timing-critical or data path functions are best implemented using FPGA logic. For example, a microcontroller cannot respond to events much faster than a few microseconds. The FPGA logic can respond to multiple, simultaneous events in just a few to tens of nanoseconds. Conversely, a microcontroller is cost-effective and simple for performing format or protocol conversions.

<table>
<thead>
<tr>
<th>Table 1-1: PicoBlaze Microcontroller Embedded within an FPGA Provides the Optimal Balance between Microcontroller and FPGA Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
</tr>
<tr>
<td>• Easy to program, excellent for control and state machine applications</td>
</tr>
<tr>
<td>• Resource requirements remain constant with increasing complexity</td>
</tr>
<tr>
<td>• Re-uses logic resources, excellent for lower-performance functions</td>
</tr>
<tr>
<td>• Significantly higher performance</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• Executes sequentially</td>
</tr>
<tr>
<td>• Performance degrades with increasing complexity</td>
</tr>
<tr>
<td>• Program memory requirements increase with increasing complexity</td>
</tr>
</tbody>
</table>
Chapter 2

PicoBlaze Interface Signals

The top-level interface signals to the PicoBlaze™ microcontroller appear in Figure 2-1 and are described in Table 2-1. Figure 7-1 provides additional detail on the internal structure of the PicoBlaze controller.

Table 2-1: PicoBlaze Interface Signal Descriptions

<table>
<thead>
<tr>
<th>Signal</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN_PORT[7:0]</td>
<td>Input</td>
<td><strong>Input Data Port:</strong> Present valid input data on this port during an INPUT instruction. The data is captured on the rising edge of CLK.</td>
</tr>
<tr>
<td>INTERRUPT</td>
<td>Input</td>
<td><strong>Interrupt Input:</strong> If the INTERRUPT_ENABLE flag is set by the application code, generate an INTERRUPT Event by asserting this input High for at least two CLK cycles. If the INTERRUPT_ENABLE flag is cleared, this input is ignored.</td>
</tr>
<tr>
<td>RESET</td>
<td>Input</td>
<td><strong>Reset Input:</strong> To reset the PicoBlaze microcontroller and to generate a RESET Event, assert this input High for at least one CLK cycle. A Reset Event is automatically generated immediately following FPGA configuration.</td>
</tr>
<tr>
<td>CLK</td>
<td>Input</td>
<td><strong>Clock Input:</strong> The frequency may range from DC to the maximum operating frequency reported by the Xilinx ISE® development software. All PicoBlaze synchronous elements are clocked from the rising clock edge. There are no clock duty-cycle requirements beyond the minimum pulse width requirements of the FPGA.</td>
</tr>
<tr>
<td>OUT_PORT[7:0]</td>
<td>Output</td>
<td><strong>Output Data Port:</strong> Output data appears on this port for two CLK cycles during an OUTPUT instruction. Capture output data within the FPGA at the rising CLK edge when WRITE_STROBE is High.</td>
</tr>
</tbody>
</table>
### Table 2-1: PicoBlaze Interface Signal Descriptions (Continued)

<table>
<thead>
<tr>
<th>Signal</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PORT_ID[7:0]</td>
<td>Output</td>
<td><strong>Port Address:</strong> The I/O port address appears on this port for two CLK cycles during an INPUT or OUTPUT instruction.</td>
</tr>
<tr>
<td>READ_STROBE</td>
<td>Output</td>
<td><strong>Read Strobe:</strong> When asserted High, this signal indicates that input data on the IN_PORT[7:0] port was captured to the specified data register during an INPUT instruction. This signal is asserted on the second CLK cycle of the two-cycle INPUT instruction. This signal is typically used to acknowledge read operations from FIFOs.</td>
</tr>
<tr>
<td>WRITE_STROBE</td>
<td>Output</td>
<td><strong>Write Strobe:</strong> When asserted High, this signal validates the output data on the OUT_PORT[7:0] port during an OUTPUT instruction. This signal is asserted on the second CLK cycle of the two-cycle OUTPUT instruction. Capture output data within the FPGA on the rising CLK edge when WRITE_STROBE is High.</td>
</tr>
<tr>
<td>INTERRUPT_ACK</td>
<td>Output</td>
<td><strong>Interrupt Acknowledge:</strong> When asserted High, this signal acknowledges that an INTERRUPT Event occurred. This signal is asserted during the second CLK cycle of the two-cycle INTERRUPT Event. This signal is optionally used to clear the source of the INTERRUPT input.</td>
</tr>
</tbody>
</table>
Table 3-1 summarizes the entire PicoBlaze™ processor instruction set, which appears alphabetically. Instructions are listed using the KCPSM3 syntax. If different, the pBlazIDE syntax appears in parentheses. Each instruction includes an overview description, a functional description, and how the ZERO and CARRY flags are affected. For more details on each instruction, see Appendix C, “PicoBlaze Instruction Set and Event Reference.”

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Function</th>
<th>ZERO</th>
<th>CARRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD sX, kk</td>
<td>Add register sX with literal kk</td>
<td>sX ← sX + kk</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>ADD sX, sY</td>
<td>Add register sX with register sY</td>
<td>sX ← sX + sY</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>ADDCY sX, kk (ADDC)</td>
<td>Add register sX with literal kk with CARRY bit</td>
<td>sX ← sX + kk + CARRY</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>ADDCY sX, sY (ADDC)</td>
<td>Add register sX with register sY with CARRY bit</td>
<td>sX ← sX + sY + CARRY</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>AND sX, kk</td>
<td>Bitwise AND register sX with literal kk</td>
<td>sX ← sX AND kk</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>AND sX, sY</td>
<td>Bitwise AND register sX with register sY</td>
<td>sX ← sX AND sY</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>CALL aaa</td>
<td>Unconditionally call subroutine at aaa</td>
<td>TOS ← PC, PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CALL C, aaa</td>
<td>If CARRY flag set, call subroutine at aaa</td>
<td>If CARRY=1, {TOS ← PC, PC ← aaa}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CALL NC, aaa</td>
<td>If CARRY flag not set, call subroutine at aaa</td>
<td>If CARRY=0, {TOS ← PC, PC ← aaa}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CALL NZ, aaa</td>
<td>If ZERO flag not set, call subroutine at aaa</td>
<td>If ZERO=0, {TOS ← PC, PC ← aaa}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CALL Z, aaa</td>
<td>If ZERO flag set, call subroutine at aaa</td>
<td>If ZERO=1, {TOS ← PC, PC ← aaa}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>COMPARE sX, kk (COMP)</td>
<td>Compare register sX with literal kk. Set CARRY and ZERO flags as appropriate. Registers are unaffected.</td>
<td>If sX=kk, ZERO ← 1&lt;br&gt;If sX&lt;k, CARRY ← 1</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>COMPARE sX, sY (COMP)</td>
<td>Compare register sX with register sY. Set CARRY and ZERO flags as appropriate. Registers are unaffected.</td>
<td>If sX=sY, ZERO ← 1&lt;br&gt;If sX&lt;sY, CARRY ← 1</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>DISABLE INTERRUPT (DINT)</td>
<td>Disable interrupt input</td>
<td>INTERRUPT_ENABLE ← 0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 3-1: PicoBlaze Instruction Set (alphabetical listing)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Function</th>
<th>ZERO</th>
<th>CARRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENABLE INTERRUPT (EINT)</td>
<td>Enable interrupt input</td>
<td>INTERRUPT_ENABLE ← 1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Interrupt Event</td>
<td>Asynchronous interrupt input. Preserve flags and PC. Clear INTERRUPT_ENABLE flag. Jump to interrupt vector at address 3FF.</td>
<td>Preserved ZERO ← ZERO Preserved CARRY ← CARRY INTERRUPT_ENABLE ← 0 TOS ← PC PC ← 3FF</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FETCH sX, (sY) (FETCH sX, sY)</td>
<td>Read scratchpad RAM location pointed to by register sY into register sX</td>
<td>sX ← RAM[(sY)]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FETCH sX, ss</td>
<td>Read scratchpad RAM location ss into register sX</td>
<td>sX ← RAM[ss]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>INPUT sX, (sY) (IN sX, sY)</td>
<td>Read value on input port location pointed to by register sY into register sX</td>
<td>PORT_ID ← sY sX ← IN_PORT</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>INPUT sX, pp (IN)</td>
<td>Read value on input port location pp into register sX</td>
<td>PORT_ID ← pp sX ← IN_PORT</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JUMP aaa</td>
<td>Unconditionally jump to aaa</td>
<td>PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JUMP C, aaa</td>
<td>If CARRY flag set, jump to aaa</td>
<td>If CARRY=1, PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JUMP NC, aaa</td>
<td>If CARRY flag not set, jump to aaa</td>
<td>If CARRY=0, PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JUMP NZ, aaa</td>
<td>If ZERO flag not set, jump to aaa</td>
<td>If ZERO=0, PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JUMP Z, aaa</td>
<td>If ZERO flag set, jump to aaa</td>
<td>If ZERO=1, PC ← aaa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LOAD sX, kk</td>
<td>Load register sX with literal kk</td>
<td>sX ← kk</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LOAD sX, sY</td>
<td>Load register sX with register sY</td>
<td>sX ← sY</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OR sX, kk</td>
<td>Bitwise OR register sX with literal kk</td>
<td>sX ← sX OR kk</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>OR sX, sY</td>
<td>Bitwise OR register sX with register sY</td>
<td>sX ← sX OR sY</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>OUTPUT sX, (sY) (OUT sX, sY)</td>
<td>Write register sX to output port location pointed to by register sY</td>
<td>PORT_ID ← sY OUT_PORT ← sX</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OUTPUT sX, pp (OUT sX, pp)</td>
<td>Write register sX to output port location pp</td>
<td>PORT_ID ← pp OUT_PORT ← sX</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RETURN (RET)</td>
<td>Unconditionally return from subroutine</td>
<td>PC ← TOS+1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RETURN C (RET C)</td>
<td>If CARRY flag set, return from subroutine</td>
<td>If CARRY=1, PC ← TOS+1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RETURN NC (RET NC)</td>
<td>If CARRY flag not set, return from subroutine</td>
<td>If CARRY=0, PC ← TOS+1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RETURN NZ (RET NZ)</td>
<td>If ZERO flag not set, return from subroutine</td>
<td>If ZERO=0, PC ← TOS+1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RETURN Z (RET Z)</td>
<td>If ZERO flag set, return from subroutine</td>
<td>If ZERO=1, PC ← TOS+1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3-1: **PicoBlaze Instruction Set (alphabetical listing)**

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Function</th>
<th>ZERO</th>
<th>CARRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>RETURNI DISABLE</td>
<td>Return from interrupt service routine. Interrupt remains disabled.</td>
<td>PC ← TOS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(RETI DISABLE)</td>
<td></td>
<td>ZERO ← Preserved ZERO</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← Preserved CARRY</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>INTERRUPT_ENABLE ← 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RETURNI ENABLE</td>
<td>Return from interrupt service routine. Re-enable interrupt.</td>
<td>PC ← TOS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(RETI ENABLE)</td>
<td></td>
<td>ZERO ← Preserved ZERO</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← Preserved CARRY</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>INTERRUPT_ENABLE ← 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL sX</td>
<td>Rotate register sX left</td>
<td>sX ← [sX[6:0],sX[7]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR sX</td>
<td>Rotate register sX right</td>
<td>sX ← [sX[0],sX[7:1]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL0 sX</td>
<td>Shift register sX left, zero fill</td>
<td>sX ← [sX[6:0],0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL1 sX</td>
<td>Shift register sX left, one fill</td>
<td>sX ← [sX[6:0],1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLA sX</td>
<td>Shift register sX left through all bits, including CARRY</td>
<td>sX ← [sX[6:0],CARRY]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLX sX</td>
<td>Shift register sX left. Bit sX[0] is unaffected.</td>
<td>sX ← [sX[6:0],sX[0]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[7]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR0 sX</td>
<td>Shift register sX right, zero fill</td>
<td>sX ← [0,sX[7:1]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR1 sX</td>
<td>Shift register sX right, one fill</td>
<td>sX ← [1,sX[7:1]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRA sX</td>
<td>Shift register sX right through all bits, including CARRY</td>
<td>sX ← [CARRY,sX[7:1]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRX sX</td>
<td>Arithmetic shift register sX right. Sign extend sX. Bit sX[7] is unaffected.</td>
<td>sX ← [sX[7],sX[7:1]]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARRY ← sX[0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STORE sX, (sY)</td>
<td>Write register sX to scratchpad RAM location pointed to by register sY</td>
<td>RAM[(sY)] ← sX</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(STORE sX, sY)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STORE sX, ss</td>
<td>Write register sX to scratchpad RAM location ss</td>
<td>RAM[ss] ← sX</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SUB sX, kk</td>
<td>Subtract literal kk from register sX</td>
<td>sX ← sX – kk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB sX, sY</td>
<td>Subtract register sY from register sX</td>
<td>sX ← sX – sY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUBCY sX, kk</td>
<td>Subtract literal kk from register sX with CARRY (borrow)</td>
<td>sX ← sX – kk - CARRY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SUBC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUBCY sX, sY</td>
<td>Subtract register sY from register sX with CARRY (borrow)</td>
<td>sX ← sX – sY - CARRY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SUBC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3-1: PicoBlaze Instruction Set (alphabetical listing)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Function</th>
<th>ZERO</th>
<th>CARRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST sX, kk</td>
<td>Test bits in register sX against literal kk. Update CARRY and ZERO flags. Registers are unaffected.</td>
<td>If (sX AND kk) = 0, ZERO ← 1, CARRY ← odd parity of (sX AND kk)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>TEST sX, sY</td>
<td>Test bits in register sX against register sY. Update CARRY and ZERO flags. Registers are unaffected.</td>
<td>If (sX AND sY) = 0, ZERO ← 1, CARRY ← odd parity of (sX AND kk)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>XOR sX, kk</td>
<td>Bitwise XOR register sX with literal kk</td>
<td>sX ← sX XOR kk</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>XOR sX, sY</td>
<td>Bitwise XOR register sX with register sY</td>
<td>sX ← sX XOR sY</td>
<td>?</td>
<td>0</td>
</tr>
</tbody>
</table>

sX = One of 16 possible register locations ranging from s0 through sF or specified as a literal
sY = One of 16 possible register locations ranging from s0 through sF or specified as a literal
aaa = 10-bit address, specified either as a literal or a three-digit hexadecimal value ranging from 000 to 3FF or a labeled location
kk = 8-bit immediate constant, specified either as a literal or a two-digit hexadecimal value ranging from 00 to FF or specified as a literal
pp = 8-bit port address, specified either as a literal or a two-digit hexadecimal value ranging from 00 to FF or specified as a literal
ss = 6-bit scratchpad RAM address, specified either as a literal or a two-digit hexadecimal value ranging from 00 to 3F or specified as a literal
RAM[n] = Contents of scratchpad RAM at location n
TOS = Value stored at Top Of Stack

### Address Spaces

As shown in Table 3-2, the PicoBlaze microcontroller has five distinct address spaces. Specific instructions operate on each of the address spaces.
### Table 3-2: PicoBlaze Address Spaces and Related Instructions

<table>
<thead>
<tr>
<th>Address Space</th>
<th>Size (Depth x Width)</th>
<th>Addressing Modes</th>
<th>Instructions that Operate on Address Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruction</td>
<td>1Kx18</td>
<td>Direct</td>
<td>• JUMP&lt;br&gt;• CALL&lt;br&gt;• RETURN&lt;br&gt;• RETURNI&lt;br&gt;• INTERRUPT event&lt;br&gt;• RESET event&lt;br&gt;All others increment the PC to the next location</td>
</tr>
<tr>
<td>Register File</td>
<td>16x8</td>
<td>Direct</td>
<td>• LOAD&lt;br&gt;• AND&lt;br&gt;• OR&lt;br&gt;• XOR&lt;br&gt;• TEST (read only)&lt;br&gt;• ADD&lt;br&gt;• ADDCY&lt;br&gt;• SUB&lt;br&gt;• SUBCY&lt;br&gt;• COMPARE (read only)&lt;br&gt;• SR0&lt;br&gt;• SR1&lt;br&gt;• SRX&lt;br&gt;• SRA&lt;br&gt;• RR&lt;br&gt;• SL0&lt;br&gt;• SL1&lt;br&gt;• SLX&lt;br&gt;• SLA&lt;br&gt;• RL&lt;br&gt;• INPUT&lt;br&gt;• OUTPUT (read only)&lt;br&gt;• STORE (read only)&lt;br&gt;• FETCH</td>
</tr>
<tr>
<td>Scratchpad RAM</td>
<td>64x8</td>
<td>Direct&lt;br&gt;Indirect</td>
<td>• STORE&lt;br&gt;• FETCH</td>
</tr>
<tr>
<td>I/O</td>
<td>256x8</td>
<td>Direct&lt;br&gt;Indirect</td>
<td>• INPUT&lt;br&gt;• OUTPUT</td>
</tr>
<tr>
<td>CALL/RETURN Stack</td>
<td>31x10</td>
<td>N/A</td>
<td>• CALL&lt;br&gt;• Enabled INTERRUPT event&lt;br&gt;• RETURN&lt;br&gt;• RETURNI&lt;br&gt;• RESET event</td>
</tr>
</tbody>
</table>
Processing Data

All data processing instructions operate on any of the 16 general-purpose registers. Only the data processing instructions modify the ZERO or CARRY flags as appropriate for the instruction. The data processing instructions consists of the following types:

- Logic instructions
- Arithmetic instructions
- Test and Compare instructions
- Shift and Rotate instructions

Logic Instructions

The logic instructions perform a bitwise logical AND, OR, or XOR between two operands. The first operand is a register location. The second operand is either a register location or a literal constant. Besides performing pure AND, OR, and XOR operations, the logic instructions provide a means to:

- complement or invert a register
- clear a register
- set or clear specific bits within a register

Bitwise AND, OR, XOR

All logic instructions are bitwise operations. The AND operation, illustrated in Figure 3-1, shows that corresponding bit locations in both operands are logically ANDed together and the result is placed back into register $sX$. If the resulting value in register $sX$ is zero, then the ZERO flag is set. The CARRY flag is always cleared by a logic instruction.

![Figure 3-1: Bitwise AND Instruction](image)

The OR and XOR instructions are similar to the AND instruction illustrated in Figure 3-1 except that they perform an OR or XOR logical operation, respectively.

See also:

- “AND $sX$, Operand — Logical Bitwise AND Register $sX$ with Operand,” page 93
- “OR $sX$, Operand — Logical Bitwise OR Register $sX$ with Operand,” page 103
- “XOR $sX$, Operand — Logical Bitwise XOR Register $sX$ with Operand,” page 118
Complement/Invert Register

The PicoBlaze microcontroller does not have a specific instruction to invert individual bits within register \( sX \). However, the XOR \( sX, FF \) instruction performs the equivalent operation, as shown in Figure 3-2.

```
complement:
; XOR sX, FF  invert all bits in register sX, same as one's complement

LOAD s0, AA ; load register   s0 = 10101010
XOR s0, FF ; invert contents  s0 = 01010101
```

*Figure 3-2: Complementing a Register Value*

Invert or Toggle Bit

The PicoBlaze microcontroller does not have a specific instruction to invert or toggle an individual bit or bits within a specific register. However, the XOR instruction performs the equivalent operation. XORing register \( sX \) with a bit mask inverts or toggles specific bits, as shown in Figure 3-3. A ‘1’ in the bit mask inverts or toggles the corresponding bit in register \( sX \). A ‘0’ in the bit mask leaves the corresponding bit unchanged.

```
toggle_bit:
; XOR sX, <bit_mask>

XOR s0, 01 ; toggle the least-significant bit in register sX
```

*Figure 3-3: Inverting an Individual Bit Location*

Clear Register

The PicoBlaze microcontroller does not have a specific instruction to clear a specific register. However, the XOR \( sX, sX \) instruction performs the equivalent operation. XORing register \( sX \) with itself clears registers \( sX \) and sets the ZERO flag, as shown in Figure 3-4.

```
XOR sX, sX ; clear register sX, set ZERO flag
```

*Figure 3-4: Clearing a Register and Setting the ZERO Flag*

The LOAD \( sX, 00 \) instruction also clears register \( sX \), but it does not affect the ZERO flag, as shown in Figure 3-5.

```
LOAD sX,00 ; clear register sX, ZERO flag unaffected
```

*Figure 3-5: Clearing a Register without Modifying the ZERO Flag*

Set Bit

The PicoBlaze microcontroller does not have a specific instruction to set an individual bit or bits within a specific register. However, the OR instruction performs the equivalent
operation. ORing register \( sX \) with a bit mask sets specific bits, as shown in Figure 3-6. A ‘1’ in the bit mask sets the corresponding bit in register \( sX \). A ‘0’ in the bit mask leaves the corresponding bit unchanged.

```
set_bit:
    ; OR sX, <bit_mask>
    OR s0, 01 ; set bit 0 of register s0
```

Figure 3-6: 16-Setting a Bit Location

Clear Bit

The PicoBlaze microcontroller does not have a specific instruction to clear an individual bit or bits within a specific register. However, the AND instruction performs the equivalent operation. ANDing register \( sX \) with a bit mask clears specific bits, as shown in Figure 3-7. A ‘0’ in the bit mask clears the corresponding bit in register \( sX \). A ‘1’ in the bit mask leaves the corresponding bit unchanged.

```
clear_bit:
    ; AND sX, <bit_mask>
    AND s0, FE ; clear bit 0 of register s0
```

Figure 3-7: Clearing a Bit Location

Arithmetic Instructions

The PicoBlaze microcontroller provides basic byte-wide addition and subtraction instructions. Combinations of instructions perform multi-byte arithmetic plus multiplication and division operations. If the end application requires significant arithmetic performance, consider using the 32-bit MicroBlaze RISC processor core for Xilinx FPGAs (see Reference 4).

ADD and ADDCY Add Instructions

The PicoBlaze microcontroller provides two add instructions, ADD and ADDCY, that compute the sum of two 8-bit operands, either without or with CARRY, respectively. The first operand is a register location. The second operand is either a register location or a literal constant. The resulting operation affects both the CARRY and ZERO flags. If the resulting sum is greater than 255, then the CARRY flag is set. If the resulting sum is either 0 or 256 (register \( sX \) is zero with CARRY set), then the ZERO flag is set.

The ADDCY instruction is an add operation with carry. If the CARRY flag is set, then ADDCY adds an additional one to the resulting sum.

The ADDCY instruction is commonly used in multi-byte addition. Figure 3-8 demonstrates a subroutine that adds two 16-bit integers and produces a 16-bit result. The upper byte of each 16-bit value is labeled as MSB for most-significant byte; the lower byte of each 16-bit value is labeled LSB for least-significant byte.
The PicoBlaze microcontroller provides two subtract instructions, \texttt{SUB} and \texttt{SUBCY}, that compute the difference of two 8-bit operands, either without or with CARRY (borrow), respectively. The CARRY flag indicates if the subtract operation generates a borrow condition. The first operand is a register location. The second operand is either a register location or a literal constant. The resulting operation affects both the CARRY and ZERO flags. If the resulting difference is less than 0, then the CARRY flag is set. If the resulting difference is 0 or -256, then the ZERO flag is set.

The \texttt{SUBCY} instruction is a subtract operation with borrow. If the CARRY flag is set, then \texttt{SUBCY} subtracts an additional one from the resulting difference.

The \texttt{SUBCY} instruction is commonly used in multi-byte subtraction. Figure 3-9 demonstrates a subroutine that subtracts two 16-bit integers and produces a 16-bit difference. The upper byte of each 16-bit value is labeled as MSB for most-significant byte; the lower byte of each 16-bit value is labeled LSB for least-significant byte.

See also:
- “ADD sX, Operand —Add Operand to Register sX,” page 91
- “ADDCY sX, Operand —Add Operand to Register sX with Carry,” page 92

\textbf{SUB and SUBCY Subtract Instructions}

```
ADD16:
    NAMEREG s0, a_lsb ; rename register s0 as “a_lsb"
    NAMEREG s1, a_msb ; rename register s1 as “a_msb"
    NAMEREG s2, b_lsb ; rename register s2 as “b_lsb"
    NAMEREG s3, b_msb ; rename register s3 as “b_lsb"
    ADD a_lsb, b_lsb ; add LSBs, keep result in a_lsb
    ADDCY a_msb, b_msb ; add MSBs, keep result in a_msb
    RETURN
```

Figure 3-8: 16-Bit Addition Using ADD and ADDCY Instructions

```
SUB16:
    NAMEREG s0, a_lsb ; rename register s0 as “a_lsb"
    NAMEREG s1, a_msb ; rename register s1 as “a_msb"
    NAMEREG s2, b_lsb ; rename register s2 as “b_lsb"
    NAMEREG s3, b_msb ; rename register s3 as “b_lsb"
    SUB a_lsb, b_lsb ; subtract LSBs, keep result in a_lsb
    SUBCY a_msb, b_msb ; subtract MSBs, keep result in a_msb
    RETURN
```

Figure 3-9: 16-Bit Subtraction Using SUB and SUBCY Instructions

See also:
- “SUB sX, Operand —Subtract Operand from Register sX,” page 113
- “SUBCY sX, Operand —Subtract Operand from Register sX with Borrow,” page 114

\textbf{Increment/Decrement}

The PicoBlaze microcontroller does not have a dedicated increment or decrement instruction. However, adding or subtracting one using the \texttt{ADD} or \texttt{SUB} instructions provides the equivalent operation, as shown in Figure 3-10.
R

If incrementing or decrementing a multi-register value—i.e., a 16-bit value—perform the operation using multiple instructions. Incrementing or decrementing a multi-byte value requires using the add or subtract instructions with carry, as shown in Figure 3-11.

Negate

The PicoBlaze microcontroller does not have a dedicated instruction to negate a register value, taking the two’s complement. However, the instructions in Figure 3-12 provide the equivalent operation.

Multiplication

The PicoBlaze microcontroller core does not have a dedicated hardware multiplier. However, the PicoBlaze microcontroller performs multiplication using the available arithmetic and shift instructions. Figure 3-14 demonstrates an 8-bit by 8-bit multiply routine that produces a 16-bit multiplier product in 50 to 57 instruction cycles, or 100 to 114 clock cycles. By contrast, the 8051 microcontroller performs the same multiplication in eight instruction cycles or 96 clock cycles on a the standard 12-cycle 8051.
If multiplication performance is important to the application, connect one of the FPGA’s 18x18 hardware multipliers the PicoBlaze I/O ports, as shown in Figure 3-15. The hardware multiplier computes the 16-bit result in less than one instruction cycle. Figure 3-16 shows the routine required to multiply two 8-bit values using the hardware multiplier. This same technique can be expanded to multiply two 16-bit values to produce a 32-bit result. This example also illustrates how to use FPGA logic attached to the PicoBlaze microcontroller to accelerate algorithms.
Division

The PicoBlaze microcontroller core does not have a dedicated hardware divider. However, the PicoBlaze microcontroller performs division using the available arithmetic and shift instructions. Figure 3-17 demonstrates a subroutine that divides an unsigned 8-bit number by another unsigned 8-bit number to produce an 8-bit quotient and an 8-bit remainder in 60 to 74 instruction cycles, or 120 to 144 clock cycles.
No Operation (NOP)

The PicoBlaze instruction set does not have a specific NOP instruction. Typically, a NOP instruction is completely benign, does not affect register contents or flags, and performs no operation other than requiring an instruction cycle to execute. A NOP instruction is therefore sometimes useful to balance code trees for more predictable execution timing.

There are a few possible implementations of an equivalent NOP operation, as shown in Figure 3-18 and Figure 3-19. Loading a register with itself does not affect the register value or the status flags.

```
; Divide Routine (8-bit / 8-bit = 8-bit result, remainder)
; ==============================================================
; Shift and subtract algorithm
;
div_8by8:
   NAMEREG s0, dividend ; preserved
   NAMEREG s1, divisor  ; preserved
   NAMEREG s2, quotient ; preserved
   NAMEREG s3, remainder ; modified
   NAMEREG s4, bit_mask ; used to test bits in dividend,
                         ;   one-hot encoded, modified
   ;
   LOAD remainder, 00 ; clear remainder
   LOAD bit_mask, 80 ; start with most-significant bit (msb)

div_loop:
   TEST dividend, bit_mask ; test bit, set CARRY if bit is '1'
   SLA remainder ; shift CARRY into lsb of remainder
   SL0 quotient ; shift quotient left (multiply by 2)
   ;
   COMPARE remainder, divisor ; is remainder > divisor?
   JUMP C, no_sub ; if divisor is greater, continue to next bit
   SUB remainder, divisor ; if remainder > divisor, then subtract
   ADD quotient, 01 ; add one to quotient

no_sub:
   SR0 bit_mask ; shift to examine next bit position
   JUMP NZ, div_loop ; if bit_mask=0, then all bits examined
                        ; otherwise, examine next bit

RETURN
```

Figure 3-18: 8-bit Divided by 8-bit Routine

If reading this document in Adobe Acrobat, use the Select Text tool to select code snippets, then copy and paste the text into your text editor.

```
nop:
   LOAD sX, sX
```

Figure 3-18: Loading a Register with Itself Acts as a NOP Instruction
A similar NOP technique is to simply jump to the next instruction, which is equivalent to the default program flow. The JUMP instruction consumes an instruction cycle (two clock cycles) without affecting register contents.

```c
JUMP next
next: <next instruction>
```

*Figure 3-19: Alternative NOP Method Using JUMP Instructions*

**Setting and Clearing CARRY Flag**

Sometimes, application programs need to specifically set or clear the CARRY flag, as shown in the following examples.

**Clear CARRY Flag**

ANDing a register with itself clears the CARRY flag without affecting the register contents, as shown in Figure 3-20.

```c
clear_carry_bit:
    AND sX, sX ; register sX unaffected, CARRY flag cleared
```

*Figure 3-20: ANDing a Register with Itself Clears the CARRY Flag*

**Set CARRY Flag**

There are various methods for setting the CARRY flag, one of which appears in Figure 3-21. Generally, these methods affect a register location.

```c
set_carry:
    LOAD sX, 00
    COMPARE sX, 01 ; set CARRY flag and reset ZERO flag
```

*Figure 3-21: Example Operation that Sets the CARRY Flag*

**Test and Compare**

The PicoBlaze microcontroller introduces two new instructions not available on previous PicoBlaze variants. The PicoBlaze microcontroller provides the ability to test individual bits within a register and the ability to compare a register value against another register or an immediate constant. The TEST or COMPARE instructions only affect the ZERO and CARRY flags; neither instruction affects register contents.

**Test**

The TEST instruction performs bit testing via a bitwise logical AND operation between two operands. Unlike the AND instruction, only the ZERO and CARRY flags are affected; no registers are modified. The ZERO flag is set if all the bitwise AND results are Low, as shown in Figure 3-22.
Each bit of register \( s_X \) is logically ANDed with either the contents of register \( s_Y \) or a literal constant, \( kK \). The operation sets the ZERO flag if the result of all bitwise AND operations is zero.

If the second operand contains a single ‘1’ bit, then the CARRY flag tests if the corresponding bit in register \( s_X \) is ‘1’ as shown in the example in Figure 3-23.

Figure 3-22: The TEST Instruction Affects the ZERO Flag

In a broader application, the CARRY bit generates the odd parity for the included bits in register \( s_X \), as shown in Figure 3-24. The second operand acts as a mask. If a bit in the second operand is ‘0’, then the corresponding bit in register \( s_X \) is not included in the generated parity value. If a bit in the second operand is ‘1’, then the corresponding bit in register \( s_X \) is included in the final parity value.

Figure 3-23: Generate Parity for a Register Using the TEST Instruction

Figure 3-24: The TEST Instruction Affects the CARRY Flag
The example in Figure 3-25 demonstrates how to generate parity for all eight bits in a register.

```
generate_parity:
  TEST sx, FF ; include all bits in parity generation
```

Figure 3-25: Generate Parity for a Register Using the TEST Instruction

See also “TEST sx, Operand — Test Bit Location in Register sx, Generate Odd Parity,” page 116.

**Compare**

The COMPARE instruction performs an 8-bit subtraction of two operands but only affects the ZERO and CARRY flags, as shown in Table 3-3. No registers are modified.

The ZERO flag is set when both input operands are identical. When set, the CARRY flag indicates that the second operand is greater than the first operand.

<table>
<thead>
<tr>
<th>Flag</th>
<th>When Flag=0</th>
<th>When Flag=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZERO</td>
<td>Operand_1 ≠ Operand_2</td>
<td>Operand_1 = Operand_2</td>
</tr>
<tr>
<td>CARRY</td>
<td>Operand_1 &gt; Operand_2</td>
<td>Operand_1 &lt; Operand_2</td>
</tr>
</tbody>
</table>

See also “COMPARE sx, Operand — Compare Operand with Register sx,” page 96.

**Shift and Rotate Instructions**

**Shift**

The PicoBlaze microcontroller supports a rich set of shift instructions, summarized in Table 3-4, that modify the contents of a single register. All shift instructions affect the CARRY and ZERO flags.

The SL0 sx instruction shift the contents of register sx left by one bit position. The most-significant bit, bit 7, shifts into the CARRY flag, The least-significant bit position is filled with a ‘0’. The SR0 instruction is similar except the least-significant bit, bit 0, shifts into the CARRY flag and the most-significant bit is filled with a ‘0’.

The SL1 and SR1 shift instructions are similar to SL0 and SR0 except that the empty bit location is filled with a ‘1’. The ZERO flag is always ‘0’ when using SL1 and SR1 because there is always a ‘1’ shifted into the affected register, making the register non-zero.

The SRX sx instruction performs an arithmetic shift right operation and sign extends register sx, preserving the sign bit. The most-significant bit, bit 7, is unaffected during the shift operation and is copied back into bit 7. The SLX sx instruction is similar but shifts the register sx contents to the left, replicating bit 0 and filling the register with the bit 0 value.

The SLA sx instruction left shifts the contents of register sx through the CARRY bit, the CARRY bit feeding back into the least-significant bit, bit 0, of register sx. The SRA sx instruction is similar to SLA but with a right shift.
Processing Data

Table 3-4: PicoBlaze Shift Instructions

<table>
<thead>
<tr>
<th></th>
<th>Shift Left</th>
<th>Shift Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL0</td>
<td>Shift Left with ‘0’ fill.</td>
<td>Shift Right with ‘0’ fill.</td>
</tr>
<tr>
<td></td>
<td>CARRY</td>
<td>Register sX</td>
</tr>
<tr>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td>‘0’</td>
</tr>
<tr>
<td>SL1</td>
<td>Shift Left with ‘1’ fill.</td>
<td>Shift Right with ‘1’ fill.</td>
</tr>
<tr>
<td></td>
<td>CARRY</td>
<td>Register sX</td>
</tr>
<tr>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td>‘1’</td>
</tr>
<tr>
<td>SLX</td>
<td>Shift Left, eXtend bit 0.</td>
<td>Shift Right, sign eXtend.</td>
</tr>
<tr>
<td></td>
<td>CARRY</td>
<td>Register sX</td>
</tr>
<tr>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
<tr>
<td>SLA</td>
<td>Shift Left through All bits, including CARRY.</td>
<td>Shift Right through All bits, including CARRY.</td>
</tr>
<tr>
<td></td>
<td>CARRY</td>
<td>Register sX</td>
</tr>
<tr>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
</tbody>
</table>

See also:

- “SL[ 0 | 1 | X | A ] sX — Shift Left Register sX,” page 109
- “SR[ 0 | 1 | X | A ] sX — Shift Right Register sX,” page 110

Rotate

The rotate instructions, shown in Table 3-5, rotate the contents of the specified register left or right. The RL sX instruction shifts the contents of register sX left with the most-significant bit, bit 7, feeding the least-significant bit, bit 0. The most-significant bit, bit 7, also shifts into the CARRY flag. The RR sX instruction is similar but shifts the contents of register sX to the right and copies the least-significant bit, bit 0, into the CARRY flag.

Table 3-5: PicoBlaze Rotate Instructions

<table>
<thead>
<tr>
<th></th>
<th>Rotate Left</th>
<th>Rotate Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td>Rotate Left</td>
<td>Rotate Right</td>
</tr>
<tr>
<td></td>
<td>CARRY</td>
<td>Register sX</td>
</tr>
<tr>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
</tbody>
</table>

See also:

- “RL sX — Rotate Left Register sX,” page 108
- “RR sX — Rotate Right Register sX,” page 108
Moving Data

Data movement between various resources is an essential microcontroller function. Figure 3-26 shows the various PicoBlaze instructions to move data.

The LOAD $sX, sY$ instruction moves data between two PicoBlaze registers; Register $sX$ receives the data. The LOAD $sX, kk$ instruction loads an immediate byte-wide constant into the specified register. See also “LOAD $sX, Operand — Load Register $sX$ with Operand,” page 102. The LOAD instructions do not affect the CARRY or ZERO flags.

The STORE and FETCH instructions move data between the register file and the scratchpad RAM. See “Chapter 5, "Scratchpad RAM,” for more information.

During an INPUT operation, data from the IN_PORT input port is always read to one of the registers. Likewise, during an OUTPUT instruction, data written to the OUT_PORT output port always originates from one of the registers. The input/output address, provided on the PORT_ID output, originates either from one of the registers or as a literal constant from the instruction store. See Chapter 6, “Input and Output Ports,” for more information.

Program Flow Control

The Program Counter (PC) points to the next instruction to be executed and directly controls the PicoBlaze program flow. By default, the PicoBlaze microcontroller proceeds to the next instruction in the instruction store (PC=PC+1). The PC cannot be directly accessed. However, three different PicoBlaze instructions, JUMP and the CALL/RETURN pair potentially modify the default program flow by loading the PC with a different value. An enabled interrupt event also modifies program flow but this case is described in Chapter 4, “Interrupts.” Likewise, a Reset Event resets the PC to zero, restarting program execution.
The JUMP, CALL, and RETURN instructions are all conditionally executed, depending if a condition is specified and specifically whether the CARRY or ZERO flags are set or cleared. Table 3-6 summarizes the possible conditions. The condition is specified as an instruction operand. The instruction is unconditionally executed if no condition is specified.

**Table 3-6: Instruction Conditional Execution**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;none&gt;</td>
<td>Always true. Execute instruction unconditionally.</td>
</tr>
<tr>
<td>C</td>
<td>CARRY = 1. Execute instruction if CARRY flag is set.</td>
</tr>
<tr>
<td>NC</td>
<td>CARRY = 0. Execute instruction if CARRY flag is cleared.</td>
</tr>
<tr>
<td>Z</td>
<td>ZERO = 1. Execute instruction if ZERO flag is set.</td>
</tr>
<tr>
<td>NZ</td>
<td>ZERO = 0. Execute instruction if ZERO flag is cleared.</td>
</tr>
</tbody>
</table>

**JUMP**

The JUMP instruction is conditional and executes only if the specified condition, listed in Table 3-6, is met. If the condition is false, then the conditional JUMP instruction has no effect other than requiring two clock cycles to execute. No registers or flags are affected.

If the conditional JUMP instruction is executed, then the PC is loaded with the address of the specified label, which is computed and assigned by the assembler. The PicoBlaze processor then executes the instruction at the specified label.

The JUMP instruction does not interact with the CALL/RETURN stack.

Arrow ‘A’ in Figure 3-27 illustrates the program flow during a JUMP instruction. When the PicoBlaze microcontroller executes the JUMP C, skip_over instruction, it first checks if the CARRY bit is set. If the CARRY bit is set, then the address of the skip_over label is loaded into the PC. The PicoBlaze microcontroller then jumps to and executes the instruction located at that address. Program flow continues normally from that point.
The **JUMP** instruction does not affect the ZERO and CARRY flags. All jumps are absolute; there are no relative jumps. Likewise, computed jumps are not supported. See also “**JUMP [Condition,] Address — Jump to Specified Address, Possibly with Conditions,**” page 101.

The **CALL** instruction differs from the **JUMP** instruction in that program flow temporarily jumps to a subroutine function and then returns to the instruction following the **CALL** instruction, as shown in Figure 3-27. The **CALL** instruction is conditional and executes only if the specified condition, listed in Table 3-6, is met. If the condition is false, then the conditional **CALL** instruction has no effect other than requiring two clock cycles to execute. No registers or flags are affected.

If the conditional **CALL** instruction is executed, then the current PC value is pushed on top of the **CALL/RETURN** stack. The address of the specified label, which is computed and assigned by the assembler, is loaded into the PC. The **PicoBlaze** microcontroller then executes the instruction at the specified label. See arrow ‘1’ in Figure 3-27.

The **PicoBlaze** microcontroller continues executing instructions in the subroutine call until it encounters a **RETURN** instruction. See arrow ‘2’ in Figure 3-27.

Every **CALL** instruction should have a corresponding **RETURN** instruction. The **RETURN** instruction is also conditional and executes only if the specified condition, listed in Table 3-6, is met. The **RETURN** instruction terminates the subroutine call, pops the top of the **CALL/RETURN** stack, increments the value, and loads the value into the PC, which returns the program flow to the instruction immediately following the original **CALL** instruction. See arrow ‘3’ in Figure 3-27.

If the conditional **CALL** instruction is executed, the ZERO and CARRY flags are potentially modified by the instructions within the called subroutine, but not directly by the **CALL** or

---

**Figure 3-27: Example JUMP and CALL/RETURN Procedures**

If CARRY is set, load the PC with the address of the label `skip_over`.

Call `my_subroutine`. Save the current PC to top of CALL/RETURN stack. Load the PC with the address of `my_subroutine`.

Return from `my_subroutine`. Load the PC with the top of the CALL/RETURN stack plus 1. Execute the instruction immediately following the associated **CALL** instruction.

```
ADDRESS 000

main:                   
                        ...
JUMP C 
                        skip_over
                        
CALL my_subroutine

ADD s0, s1

skip_over: 1

JUMP main

my_subroutine: 2

RETURN

```

If CARRY is set, load the PC with the address of the label `skip_over`.

Call `my_subroutine`. Save the current PC to top of CALL/RETURN stack. Load the PC with the address of `my_subroutine`.

Return from `my_subroutine`. Load the PC with the top of the CALL/RETURN stack plus 1. Execute the instruction immediately following the associated **CALL** instruction.

```
ADDRESS 000

main:                   
                        ...
JUMP C 
                        skip_over
                        
CALL my_subroutine

ADD s0, s1

skip_over: 1

JUMP main

my_subroutine: 2

RETURN

```

---

If the conditional **CALL** instruction is executed, the ZERO and CARRY flags are potentially modified by the instructions within the called subroutine, but not directly by the **CALL** or
RETURN instructions themselves. If the CALL instruction is not executed, then the flags are unaffected.

See also:

• “CALL [Condition,] Address — Call Subroutine at Specified Address, Possibly with Conditions,” page 94”

• “RETURN [Condition] — Return from Subroutine Call, Possibly with Conditions,” page 106
Chapter 4

Interrupts

The PicoBlaze™ processor provides a single interrupt input signal. If the application requires multiple interrupt signals, combine the signals using simple FPGA logic to form a single INTERRUPT input signal. After reset, the INTERRUPT input is disabled and must be enabled via the ENABLE INTERRUPT instruction. To disable interrupts at any point in the program, issue a DISABLE INTERRUPT instruction.

Once enabled, the INTERRUPT input signal must be applied for at least two clock cycles to guarantee that it is recognized, generating an INTERRUPT Event.

An active interrupt forces the PicoBlaze processor to immediately execute the CALL 3FF instruction immediately after completing the instruction currently executing. The CALL 3FF instruction is a subroutine call to the last program memory location. The instruction in the last location defines how the application code should handle the interrupt. Typically, the instruction at location 3FF is a jump location to an interrupt service routine (ISR).

The PicoBlaze microcontroller automatically performs other functions. The interrupt process preserves the current ZERO and CARRY flag contents and disables any further interrupts. Likewise, the current program counter (PC) value is pushed onto the CALL/RETURN stack. Interrupts must remain disabled throughout the interrupt handling process.

As shown in Figure 4-3, the PicoBlaze microcontroller asserts its INTERRUPT_ACK signal during the second cycle of the two-cycle Interrupt Event to indicate that the interrupt was recognized. The INTERRUPT_ACK signal may be used to clear external interrupts, as shown in Figure 4-1.

\[\text{Figure 4-1: Simple Interrupt Logic}\]

Once enabled, the INTERRUPT input signal must be applied for at least two clock cycles to guarantee that it is recognized, generating an INTERRUPT Event.

An active interrupt forces the PicoBlaze processor to immediately execute the CALL 3FF instruction immediately after completing the instruction currently executing. The CALL 3FF instruction is a subroutine call to the last program memory location. The instruction in the last location defines how the application code should handle the interrupt. Typically, the instruction at location 3FF is a jump location to an interrupt service routine (ISR).

The PicoBlaze microcontroller automatically performs other functions. The interrupt process preserves the current ZERO and CARRY flag contents and disables any further interrupts. Likewise, the current program counter (PC) value is pushed onto the CALL/RETURN stack. Interrupts must remain disabled throughout the interrupt handling process.

As shown in Figure 4-3, the PicoBlaze microcontroller asserts its INTERRUPT_ACK signal during the second cycle of the two-cycle Interrupt Event to indicate that the interrupt was recognized. The INTERRUPT_ACK signal may be used to clear external interrupts, as shown in Figure 4-1.
A special RETURNI command ensures that the end of an interrupt service routine restores the status of the flags and controls the enable of future interrupts. When the RETURNI instruction is executed, the PC values saved onto the CALL/RETURN stack is automatically reloaded to the PC register. Likewise, the ZERO and CARRY flags are restored and program flow returns to the instruction following the instruction where the interrupt occurred.

If the application does not require an interrupt, tie the INTERRUPT signal Low. Consequently, all 1,024 instruction locations are available.

Example Interrupt Flow

Figure 4-2 shows an example program flow during an interrupt event.

1. By default, the INTERRUPT input is disabled. The Enable Interrupt instruction must execute before the interrupt is recognized.

2. In this example, interrupts are enabled and the PicoBlaze microcontroller is executing the INPUT s1, 01 instruction. Simultaneously to executing this instruction, an interrupt arrives on the INTERRUPT input. The PicoBlaze microcontroller does not act on the interrupt until it finishes executing the INPUT s1, 01 instruction.
3. The PicoBlaze microcontroller recognizes the interrupt and preempts the `ADD s0, s1` instruction. The current PC, which points to the `ADD s0, s1` instruction, is pushed onto the CALL/RETURN stack. Likewise, the ZERO and CARRY flags are preserved. Furthermore, the INTERRUPT_ENABLE flag is cleared disabling any further interrupts. Finally, the PC is loaded with all ones (3FF) and the PicoBlaze microcontroller performs an interrupt service routine call to the last location in the instruction store. If using a 1Kx18 block RAM for instruction store, the last location is 3FF. If using a smaller instruction store, then the interrupt vector is still located in the last instruction location. The PicoBlaze microcontroller also asserts the INTERRUPT_ACK output, indicating that the interrupt is being acknowledged.

4. The interrupt vector is always located in the last location in the instruction store. In this example, the program jumps to the interrupt service routine (ISR) via the `JUMP isr` instruction.

5. When completed, exit the interrupt service routine (ISR) using the special `RETURNI` instruction. Do not use the `RETURN` instruction, which is used with normal subroutine calls. The `RETURNI` instruction returns from the interrupt service routine and re-enables the INTERRUPT input, which was automatically disabled when the interrupt was recognized. Using `RETURNI DISABLE` also returns from the interrupt service routine but leaves the INTERRUPT input disabled.

6. The `RETURNI` instruction restores the preserved ZERO and CARRY flags saved during Step (3). Likewise, the `RETURNI` instruction pops the top of the CALL/RETURN stack into the PC, which causes the PicoBlaze microcontroller to resume program executing the instruction that was preempted by the interrupt, `ADD s0, s1` in this example.

![Interrupt Timing Diagram](image-url)
Figure 4-3 shows the same interrupt procedure but as a timing diagram. With the interrupt enabled, the INTERRUPT input is recognized at Step (2), the same clock cycle where the ADDRESS bus changes value. The address for the instruction ADD s0, s1 appears on the ADDRESS bus and is pushed onto the CALL/RETURN stack. Simultaneously, the interrupt is disabled and the ZERO and CARRY flags are preserved. The ADD s0, s1 instruction is preempted and does not yet execute. Instead, the PicoBlaze microcontroller performs a call to the interrupt vector at location 0x3FF.

An interrupt is undesirable in timing-critical procedures or when predictable timing is a must. Temporarily disable the INTERRUPT input using the DISABLE INTERRUPT instruction, as demonstrated in the critical_timing subroutine in Figure 4-2. Once the critical procedure completes, re-enable the INTERRUPT input with the ENABLE INTERRUPT instruction.
Chapter 5

Scratchpad RAM

The PicoBlaze™ microcontroller contains a 64-byte scratchpad RAM. Two instructions, STORE and FETCH, move data between any data register and the scratchpad RAM. Both direct and indirect addressing are supported. The scratchpad RAM is only supported on PicoBlaze microcontrollers for Spartan®-3, Virtex®-II, and Virtex-II Pro FPGAs.

The scratchpad RAM is unaffected by a RESET Event.

Address Modes

The STORE and FETCH instructions support both direct and indirect addressing modes to access scratchpad RAM data.

Direct Addressing

An immediate constant value directly addresses a specific scratchpad RAM location. In the example in Figure 5-1, register sX directly writes to and reads from scratchpad RAM location 04.

```
scratchpad_transfers:
  STORE sX, 04 ; Write register sX to RAM location 04
  FETCH sX, 04 ; Read RAM location 04 into register sX
```

Figure 5-1: Directly Addressing Scratchpad RAM Locations

Indirect Addressing

Using indirect address, the actual RAM address is the value contained in a specified register. Whereas direct addressing requires the RAM address to be known before assembly, indirect addressing provides additional program flexibility. The application code can compute or modify the RAM address based on other program data. The code in Figure 5-2, for example, initializes all the scratchpad RAM locations to 0 using a simple loop.
Implementing a Look-Up Table

The next few examples demonstrate both the flexibility of the scratchpad RAM and indirect addressing. The example code in Figure 5-3 uses Scratchpad RAM as a look-up table (LUT) to convert four binary inputs to the equivalent hexadecimal character display on a 7-segment LED. The code reads four external switches, resulting in a binary value between 0000 and 1111. The PicoBlaze microcontroller converts each four-bit switch value into the equivalent hexadecimal character as displayed on a 7-segment LED. The scratchpad RAM holds the LED output patterns in the first 16 locations. The input switch value is the address input to the RAM.

---

**Figure 5-2:** Indirect Addressing Initializes All of RAM with a Simple Subroutine

```
NAMEREG s0, ram_data
NAMEREG s1, ram_address

CONSTANT ram_locations, 40 ; there are 64 locations
CONSTANT initial_value, 00 ; initialize to zero

LOAD ram_data, initial_value ; load initial value
LOAD ram_address, ram_locations ; fill from top to bottom

ram_fill: SUB ram_address, 01 ; decrement address
STORE ram_data, (ram_address) ; initialize location
JUMP NZ, ram_fill ; if not address 0, goto ram_fill
```

---

**Figure 5-3:** Using Scratchpad RAM as a Look-Up Table

```
CONSTANT switches, 00 ; read switch values at port 0
CONSTANT LEDs, 01 ; write 7-seg LED at port 1
; Define 7-segment LED pattern {dp,g,f,e,d,c,b,a}
CONSTANT LED_0, C0 ; display '0' on 7-segment display
CONSTANT LED_1, F9 ; display '1' on 7-segment display
; CONSTANT LED_F, 8E ; display 'F' on 7-segment display

NAMEREG s0, switch_value ; read switches into register s0
NAMEREG s1, LED_output ; load LED output data in register s1

; Load 7-segment LED patterns into scratchpad RAM
LOAD LED_output, LED_0 ; grab LED pattern for switches = 0000
STORE LED_output, 00 ; store in RAM[0]
LOAD LED_output, LED_1 ; grab LED pattern for switches = 0001
STORE LED_output, 01 ; store in RAM[1]
; LOAD LED_output, LED_F ; grab LED pattern for switches = 1111
STORE LED_output, 0F ; store in RAM[15]

; Read switch values and display value on 7-segment LED
loop: INPUT switch_value, switches ; read value on switches
AND switch_value, F0 ; mask upper bits to guarantee < 15
FETCH LED_output, (switch_value) ; look up LED pattern in RAM
OUTPUT LED_output, LEDs ; display switch value on 7-segment LED
JUMP loop
```
Stack Operations

Although the PicoBlaze microcontroller has a CALL/RETURN stack, it does not have a dedicated data stack. In some controller architectures, register values are preserved during subroutine calls or interrupts by pushing them or popping them onto a data stack. The equivalent operation is possible in the PicoBlaze microcontroller by reserving some locations in scratchpad RAM.

In the example shown in Figure 5-4, the *my_subroutine* function uses register *s0*. The value of register *s0* is preserved onto a “stack”, which is emulated using scratchpad RAM. When the *my_subroutine* function completes, the preserved value of register *s0* is restored from the stack.

![Figure 5-4: Use Scratchpad RAM to Emulate PUSH and POP Stack Operations](image)

FIFO Operations

In a similar vein, FIFOs can be created using two separate pointers into scratchpad RAM. One pointer tracks data being written into RAM; the other tracks data being read from RAM.

See also:
- “STORE sX, Operand — Write Register sX Value to Scratchpad RAM Location,” page 112.
- “FETCH sX, Operand — Read Scratchpad RAM Location to Register sX,” page 98.
Chapter 6

Input and Output Ports

The PicoBlaze™ microcontroller supports up to 256 input ports and 256 output ports that can also be combined to create input/output ports. The interface signals from Figure 2-1 involved in INPUT and OUTPUT operations are described below.

- The PORT_ID[7:0] output port presents the port identifier number or port address for both INPUT and OUTPUT operations.
- The IN_PORT[7:0] input port captures input data during INPUT operations.
- The OUT_PORT[7:0] output port presents output data during OUTPUT operations.
- The READ_STROBE output is asserted High during the second cycle of the two-cycle INPUT operation.
- The WRITE_STROBE output is asserted High during the second cycle of the two-cycle OUTPUT operation.

In timing critical designs, set timing constraints for the PORT_ID and data paths allowing two clock cycles. Only the read and write strobes need to be constrained to a single clock cycle. For maximum performance and to simplify timing constraints, insert a pipeline register where possible, as described in the following sections.

Thought-out design keeps the interface logic compact with good performance. The following diagrams show circuits suitable for output ports, input ports, and for connecting memory. When using a logic synthesis tool, check that the source code is not describing a circuit that is more complex than is actually required and that the synthesis tool is implementing the intended logic.

PORT_ID Port

The 8-bit PORT_ID port supplies the port identifier or port address for the associated INPUT or OUTPUT operation. The PORT_ID port is valid for two clock cycles, allowing sufficient time for any interface decoding logic and for connections to asynchronous RAM. Similarly, the two-cycle operation allows read operations from synchronous RAM, such as block RAM.

INPUT and OUTPUT operations support both direct and indirect addressing. The port address is supplied as either as an 8-bit immediate constant or specified indirectly as the contents of any of the 16 data registers. Indirect addressing is ideal when accessing a block of memory, either a peripheral at contiguous port addresses or some form of block or distributed memory within or external to the FPGA.

Adding external peripherals to the PicoBlaze microcontroller is relatively straightforward. The only challenge is decoding the PORT_ID value using the minimum required logic for the application. The decoding challenge depends on the number of input, output, or bidirectional ports, as described in Table 6-1 and subsequent text.
INPUT Operations

An INPUT operation transfers the data supplied on the IN_PORT input port to any one of the 16 data registers, defined by register \( sX \), as shown in Figure 6-1. The PORT_ID output port, defined either by register \( sY \) or an 8-bit immediate constant, selects the desired input source. Input sources are generally selected via a multiplexer, using a portion of the bits from the PORT_ID output port to select a specific source. The size of the multiplexer is proportional to the number of possible input sources, which has direct implications on performance.

Table 6-1: Decoding PORT_ID Depending on Number of Ports

<table>
<thead>
<tr>
<th>Number of Ports</th>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 1</td>
<td>No multiplexing required</td>
<td>No decoding required</td>
</tr>
<tr>
<td>2 to 8</td>
<td>Single input multiplexer</td>
<td>“One hot” encode PORT_ID</td>
</tr>
<tr>
<td></td>
<td>Binary encode PORT_ID</td>
<td></td>
</tr>
<tr>
<td>9 to 256</td>
<td>Cascaded multiplexer tree</td>
<td>Binary encode PORT_ID</td>
</tr>
<tr>
<td></td>
<td>Binary encode PORT_ID</td>
<td>Hybrid “one hot”/binary encoded</td>
</tr>
</tbody>
</table>

![Figure 6-1: INPUT Operation and FPGA Interface Logic](image_url)

The INPUT operation asserts the associated READ_STROBE output pulse on the second cycle of the two-cycle INPUT cycle, as shown in Figure 6-2. The READ_STROBE signal is seldom used in applications but it indicates that the PicoBlaze microcontroller has acquired the data. READ_STROBE is critical when reading data from a FIFO, acknowledging receipt of data as shown in Figure 6-4.
In this example, the PicoBlaze microcontroller is reading data from the port address defined by the contents of register s7. The read data is captured in register s0. When the instruction executes, the contents of register S7 appear on the PORT_ID port. The PORT_ID is then decoded by FPGA logic external to the PicoBlaze microcontroller and the requested data is eventually presented on the IN_PORT port. The READ_STROBE signal goes High during the second clock cycle of the instruction, although the READ_STROBE signal is primarily used only by FIFOs so that the FIFO can update its read pointer. The data presented on the IN_PORT port is captured on rising clock edge 2, marking the end of the INPUT instruction. Data needs only be present with sufficient setup time to this clock edge. After rising clock edge 2, the data on the IN_PORT port is captured and available in the target register, register s0 in this case.

Because the PORT_ID is valid for two clock cycles, the input data multiplexer can be registered to maintain performance, as shown in Figure 6-3. In most applications, the actual clock cycle when the PicoBlaze microcontroller reads an input is not critical. Therefore the paths from the various sources can typically be registered. For example, signals arriving from the FPGA pins can be captured using input flip-flops. Registering the input path simplifies timing specifications, avoids reports of ‘false paths’ and leads to more reliable designs.
Failure to include a register anywhere in the path from PORT_ID to IN_PORT is the most common reason for decreased system clock rates. Consequently, make sure that this path is registered at some point.

Applications with Few Input Sources

If the application has 32 or less input ports, then a single multiplexer is ideal to connect the various input signals to the IN_PORT input port, as shown in Figure 6-3. Check the results of synthesis to ensure that the special MUXF5, MUXF6, MUXF7, and MUXF8 are being employed to make the most efficient multiplexer structure.

Refer to UG331 Chapter 8: Using Dedicated Multiplexers (see Reference 5).

READ_STROBE Interaction with FIFOs

Occasionally, the circuit providing data to the PicoBlaze microcontroller needs to know that it was successfully read. Figure 6-4 shows an example using a FIFO buffer. The FIFO only updates its read pointer once the PicoBlaze microcontroller successfully captures data, indicated by the READ_STROBE signal.
OUTPUT Operations

As shown in Figure 6-5, an OUTPUT operation presents the contents of any of the 16 registers to the OUT_PORT output port. The PORT_ID output port, defined either by register sY or an 8-bit immediate constant, selects the desired output destination. The WRITE_STROBE output pulse indicates that data on the OUT_PORT port is valid and ready for capture. Typically, the WRITE_STROBE signal, combined with the decoded PORT_ID port, is used as either a clock enable or a write enable signal to other FPGA logic that captures the output data.

The OUTPUT operation asserts the associated WRITE_STROBE output pulse beginning on rising CLK edge 1 of the two-cycle OUTPUT instruction, as shown in Figure 6-6. In this particular example, the PicoBlaze microcontroller writes the contents of register s0 to hexadecimal port address 65. The contents of register s0 appear on the OUT_PORT port; the port address appears on the PORT_ID port. The WRITE_STROBE goes High on the second clock cycle to indicate that data is valid.
Simple Output Structure for Few Output Destinations

For eight or less simple output ports, use “one-hot” port addresses and only decode the appropriate PORT_ID signal, as shown in Figure 6-7. This technique greatly reduces the address decode logic which lowers cost and maximizes performance. This approach also reduces the loading on the PORT_ID bus, which is often critical to overall system performance.

If the number of decoded PORT_ID bits is three or less, then the decode logic fits in a single level of FPGA logic, maximizing performance.
As shown in Figure 6-8, use CONSTANT directives in the program make the code readable and help ensure that the correct ports are decoded. Because the PORT_ID addresses use “one-hot” encoding, it is also possible to create a single address that incorporates all the individual addresses. This way, the PicoBlaze microcontroller can send a broadcast message to all of the output destinations—in this case, a single instruction clears all destinations.

```plaintext
; Use CONSTANT declarations to define output port addresses
CONSTANT Port_A, 01
CONSTANT Port_B, 02
CONSTANT Port_C, 04
CONSTANT Port_D, 08
CONSTANT Broadcast, FF

; Use assigned port names for better readability
OUTPUT s0, Port_A
OUTPUT s1, Port_B
OUTPUT s2, Port_C
OUTPUT s4, Port_D

; Send broadcast message to all addresses to clear all output register
LOAD s0, 00
OUTPUT s0, Broadcast
```

Figure 6-7: Simple Address Decoding for Designs with Few Output Destinations

Figure 6-8: Use CONSTANT Directives to Declare Output Port Addresses
Pipelining for Maximum Performance

In most applications, the PicoBlaze microcontroller has more than sufficient performance to meet application requirements. However, PicoBlaze designs attached to multiple memory blocks or that have many simple ports may end up using most, if not all, of the 256 available port addresses. Decoding and routing all 256 locations complicates the overall design, especially for designs requiring maximum performance.

Pipelining the PORT_ID decoding function improves overall system performance. During an OUTPUT operation, both the PORT_ID and OUT_PORT ports are valid for two clock cycles while the WRITE_STROBE output is only active during the second of the two cycles, as shown Figure 6-6.

One approach to improving interface performance is to pipeline the PORT_ID decoding logic, as illustrated in Figure 6-9. In designs with many ports, the fanout and loading on the PORT_ID bus limits maximum performance. Fortunately, because the PORT_ID port is active for two clock cycles, the PORT_ID logic can be pipelined. Each decoded PORT_ID value is then captured in a flip-flop. Each pipelined decode value is qualified using the WRITE_STROBE signal during the next clock cycle to actually capture the OUT_PORT data.

![Diagram](Figure 6-9: Pipelining the PORT_ID Decoding Improves Performance)
The pipelining registers on the OUT_PORT and PORT_ID signals, shaded in Figure 6-9, are optional. Both OUT_PORT and PORT_ID are valid for two clock cycles. However, pipelining them decreases the initial fanout and reduces the routing distance, both of which improve performance.

During OUTPUT operations, the PicoBlaze microcontroller has no data dependencies and consequently no dependencies on the FPGA interface logic. If data takes longer than the two-clock instruction cycle to be captured by the FPGA logic, so be it. The PicoBlaze microcontroller initiates the OUTPUT operation but does not need to wait while the FPGA logic captures the data in its ultimate location as long as data is not lost. However, pipelining INPUT operations can be more complicated. During an INPUT operation, the PicoBlaze microcontroller requests data from the FPGA logic and must receive the data to successfully complete the instruction.

Figure 6-10 illustrates the dependency, where the critical timing path is blue. In this example, the PicoBlaze microcontroller is reading data from a dual-port RAM. This example assumes that some other function within the FPGA writes data into the dual-port RAM. When the PicoBlaze microcontroller reads data from the dual-port RAM, the read address appears on the PORT_ID port. The critical path is the delay from the PORT_ID port, through the dual-port RAM read path, through the input select multiplexer, to the setup on the pipelining register. If this path limits performance, add a pipelining register to improve performance. However, where is the best position for the pipeline register, Point A or Point B?

![Figure 6-10: Without Pipelining, the Full Read Path Delay Can Reduce Performance](image)

From Figure 6-2, the read data for INPUT operations must be presented and valid on the IN_PORT port by the end of the second clock cycle. There is already one layer of pipelining immediately following the input select multiplexer feeding the IN_PORT port. Adding a pipelining register at Point A or Point B delays data by an additional clock cycle, too late to meet the PicoBlaze microcontroller’s requirements.

The best place to position the pipeline register is at Point B, which splits the read path roughly in half. However, the input select multiplexer structure must be modified to accommodate the extra register layer, as shown in Figure 6-11.
Repartitioning the Design for Maximum Performance

Another approach to maximizing performance is to re-evaluate the system requirements. If the number of I/O ports is the bottleneck in the system, ask if all the ports are actually required as part of a single application or whether a single PicoBlaze microcontroller is performing multiple tasks. If multiple tasks share a single PicoBlaze core, consider partitioning the design into multiple PicoBlaze applications, each with a reduced number of I/O ports. Partitioning the design may have additional benefits such as simplifying the application code and reducing resource requirements.
Instruction Storage Configurations

The PicoBlaze™ microcontroller executes code from memory resources embedded within the FPGA. Figure 7-1 shows that the PicoBlaze microcontroller actually consists of two subfunctions. The KCPSM3 module contains the PicoBlaze ALU, register file, scratchpad RAM, etc. Some form of internal memory, typically a block RAM, provides the PicoBlaze instruction store. To effectively create an on-chip ROM, the block RAM’s write enable pin, WE, is held Low, disabling any potential write operations.

However, the PicoBlaze microcontroller supports other implementations that have advantages for specific applications as described below. Many of these alternate implementations leverage the extra port provided by the dual-port block RAM on Spartan®-3, Virtex®-II, and Virtex-II Pro FPGAs.

Figure 7-1: Standard Implementation using a Single 1Kx18 Block RAM as the Instruction Store

Standard Configuration – Single 1Kx18 Block RAM

In most applications, PicoBlaze instructions are stored in a single FPGA block RAM, configured as a 1Kx18 ROM shown in Figure 7-2. The application code is assembled and ultimately compiled as part of the FPGA design. The instruction store is automatically loaded into the attached block RAM during the FPGA configuration process.
Chapter 7: Instruction Storage Configurations

Standard Configuration with UART or JTAG Programming Interface

The second read/write port on the block RAM provides a convenient means to update the PicoBlaze instruction store without recompiling the entire FPGA design. While the processor is halted, application code can be updated via a simple UART or via the FPGA’s JTAG port, as shown in Figure 7-3.

Two PicoBlaze Microcontrollers Share a 1Kx18 Code Image

As shown in Figure 7-4, two PicoBlaze microcontrollers can share a single dual-port block RAM to store a common or mostly common code image. The two microcontrollers operate entirely independently of one another although they each independently execute the same or mostly the same code. The clock input, I/O ports, and interrupt input are unique to each microcontroller.
Two PicoBlaze Microcontrollers with Separate 512x18 Code Images in a Block RAM

Two PicoBlaze microcontrollers can also share a single dual-port RAM but each with a separate 512-instruction area, as shown in Figure 7-5. The most-significant address bit of one block RAM port is tied Low while the other same bit on the other port is tied High. This limits each port to half of the 1Kx18 memory, or 512x18. The two microcontrollers operate independently.

![Figure 7-5: Two PicoBlaze Microcontrollers with Separate 512-Instruction Memory in one Block RAM](image)

Despite that both PicoBlaze microcontrollers use half the normal instruction store, the interrupt vectors for both remain the same. When an interrupt occurs, the associated KCPSM3 block presents all ones on the ADDRESS bus, which is truncated to the last memory location in its half of the block RAM memory (address 1FF hexadecimal).

Figure 7-5 shows the block RAM split into two equal halves. If one microcontroller requires more than the other, then tie the upper address lines as appropriate. Practically any partition is allowed as long as the combined code size is 1,024x18 or less.

Distributed ROM Instead of Block RAM

Block RAM is the most efficient method to store PicoBlaze application code. However, if all the block RAM within the FPGA is already committed to other functions then the PicoBlaze code can be stored within the FPGAs Configurable Logic Blocks (CLBs), as shown in Figure 7-6.

![Figure 7-6: Using Distributed ROM for Instruction Memory](image)

This technique is only roughly efficient if the program size is 128 instructions or less. Although larger instruction stores are possible, they quickly consume CLB logic. Table 7-1 shows the number of FPGA slices required for various instruction stores. Distributed ROM essentially uses the Look-Up Tables (LUTs) within its FPGA logic block as a small ROM instead of for logic.
To maintain compatibility with block RAM, the distributed ROM must have a registered output using CLB flip-flops.

Table 7-1: Slices Required when Using CLBs for ROM

<table>
<thead>
<tr>
<th>Instructions</th>
<th>ROM Slices</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 16</td>
<td>9</td>
</tr>
<tr>
<td>≤ 32</td>
<td>18</td>
</tr>
<tr>
<td>≤ 64</td>
<td>36</td>
</tr>
<tr>
<td>≤ 128</td>
<td>72</td>
</tr>
<tr>
<td>≤ 256</td>
<td>144</td>
</tr>
<tr>
<td>≤ 512</td>
<td>297</td>
</tr>
<tr>
<td>≤ 1,024</td>
<td>594</td>
</tr>
</tbody>
</table>

The CORE Generator software can create all of the above distributed ROM functions using the coefficients file generated by the PicoBlaze assembler.
Chapter 8

Performance

Input Clock Frequency

Table 8-1 shows the maximum available performance for the PicoBlaze™ microcontroller using various FPGA families and speed grades. The Virtex®-II and Virtex-II Pro FPGA families are optimized for maximum performance. The Spartan®-3 FPGA family is optimized for lowest cost.

<table>
<thead>
<tr>
<th>FPGA Family (Speed Grade)</th>
<th>Maximum Clock Frequency</th>
<th>Maximum Execution Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spartan-3 (-4) FPGA</td>
<td>88 MHz</td>
<td>44 MIPS</td>
</tr>
<tr>
<td>Virtex-II (-6) FPGA</td>
<td>152 MHz</td>
<td>76 MIPS</td>
</tr>
<tr>
<td>Virtex-II Pro (-7) FPGA</td>
<td>200 MHz</td>
<td>100 MIPS</td>
</tr>
</tbody>
</table>

Unless the end application requires absolute performance, there is no need to operate the PicoBlaze microcontroller at its maximum clock frequency. In fact, operating slower is advantageous. Often, the PicoBlaze microcontroller is managing slower peripheral operations like serial communications or monitoring keyboard buttons, neither of which stresses the FPGA’s performance. A lower clock frequency reduces the number of idle instruction cycles and reduces total system power consumption.

The PicoBlaze microcontroller is a fully static design and operates down to DC (0 MHz).

Predicting Executing Performance

All instructions always execute in two clock cycles, resulting in predictable execution performance. In real-time applications, a constant execution rate simplifies calculating program execution times.
Chapter 9

PicoBlaze Development Tools

There are three primary development environments for creating PicoBlaze™ processor application code, as summarized in Table 9-1. Xilinx offers two PicoBlaze environments. The PicoBlaze reference design includes the KCPSM3 command-line assembler that executes in a Windows DOS box or command window. The Xilinx System Generator for DSP development environment includes both a PicoBlaze assembler and a simulation model for the Math Works MATLAB/Simulink environment. The Mediatronix pBlazIDE software is a graphical development environment including an assembler and full-featured instruction-set simulator (ISS).

Table 9-1: PicoBlaze Development Environments

<table>
<thead>
<tr>
<th></th>
<th>Xilinx KCPSM3</th>
<th>Mediatronix pBlazIDE</th>
<th>Xilinx System Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembler</td>
<td>Command-line in DOS window</td>
<td>Graphical</td>
<td>Command-line within System Generator</td>
</tr>
<tr>
<td>Instruction Syntax</td>
<td>KCPSM3</td>
<td>PBlazIDE</td>
<td>KCPSM3</td>
</tr>
<tr>
<td>Instruction Set Simulator</td>
<td>Facilities provided for VHDL simulation</td>
<td>Graphical/Interactive</td>
<td>Graphical/Interactive</td>
</tr>
<tr>
<td>Simulator Breakpoints</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Register Viewer</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Memory Viewer</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

KCPSM3

Assembler

The KCPSM3 Assembler is provided as a simple DOS executable file together with three template files. Copy all the files KCPSM3 . EXE, ROM_form. vhd, ROM_form. v, and ROM_form. coe into your working directory.

Programs are best written with either the standard Notepad or Wordpad tools available on most Windows computers. However, any PC-format text editor is sufficient. Save the PicoBlaze assembly program with a PSM file extension (eight-character name limit).
Open a DOS box and navigate to the working directory. To assemble the PicoBlaze program, type:

```
kcpsm3 <filename>.psm
```

### Assembly Errors

The assembler halts as soon as an error is detected. A short message indicates the reason for any error. The assembler also displays the line that it was analyzing when it detected the problem. Fix each reported problem in turn and re-execute the assembler.

Since the execution of the assembler is very fast, it is unlikely that you will be able to ‘see’ it making progress, and the display will appear to be immediate. To review everything that the assembler has written to the screen, the DOS output can be redirected to a text file using:

```
kcpsm3 <filename>.psm > screen_dump.txt
```

### Input and Output Files

The KCPSM3 assembler reads four input files and creates 15 output files as shown in Figure 9-1. The KCPSM3 assembler reads the PicoBlaze source program, `<filename>.psm`, and three template files that instantiate and initialize a block RAM in various design flows, `ROM_form.*`.

All five assembler passes are recorded in the `pass*.dat` output files. Should an error occur during assembly, these files may contain additional details on the error.

If the source program is free of errors, the KCPSM3 assembler generates an object code output, formatted for a variety of design flows, based on the initial template files. These output files generate the code ROM, instantiated as a block RAM, and properly initialized with the PicoBlaze object code. The assembler also generates equivalent raw decimal and hexadecimal output files for other utilities.

---

**Figure 9-1:** KCPSM3 Assembler Files

All five assembler passes are recorded in the `pass*.dat` output files. Should an error occur during assembly, these files may contain additional details on the error.

If the source program is free of errors, the KCPSM3 assembler generates an object code output, formatted for a variety of design flows, based on the initial template files. These output files generate the code ROM, instantiated as a block RAM, and properly initialized with the PicoBlaze object code. The assembler also generates equivalent raw decimal and hexadecimal output files for other utilities.
The assembler also produces a log file plus files that show the assignments for various labels and constants found in the source code. The log file shows the instruction address, the opcode for each instruction, and the source code instruction and comments for the associated instruction address. The assigned values for register names, labels, and constants appear immediately following the associated symbolic name.

Finally, the KCPSM3 assembler generates a formatted version of the source program (“pretty print” output). The formatted output file formats all labels and comments, converts all commands and hexadecimal constants to upper case, and consistently spaces operands.

Mediatronix pBlazIDE

The Mediatronix pBlazIDE software, shown in Figure 12-1, page 83, is a free, graphical, integrated development environment for Windows-based computers. Its features are as follows:

- Syntax color highlighting
- Instruction set simulator (ISS)
  - Breakpoints
  - Register display
  - Memory display
- Source code formatter (“pretty print”)
- KCPSM3-to-pBlazIDE import function/syntax conversion
- HTML output, including color highlighting

Download the pBlazIDE software directly from the Mediatronix website:

http://www.mediatronix.com/pBlazeIDE.htm

Configuring pBlazIDE for the PicoBlaze Microcontroller

The pBlazIDE development software supports all four variants of the PicoBlaze architecture. To use the PicoBlaze microcontroller for Spartan®-3, Virtex®-II, or Virtex-II Pro FPGAs, choose Settings → PicoBlaze 3 from the pBlazIDE menu, as shown in Figure 9-2.
Importing KCPSM3 Code into pBlazIDE

The pBlazIDE syntax and instruction mnemonics are different than the Xilinx KCPSM3 syntax. The pBlazIDE software provides an import function to convert KCPSM3 code to the pBlazIDE syntax.

From the pBlazIDE menu, choose File ➔ Import, then select the KCPSM3-format *.psm file, as shown in Figure 9-3. The pBlazIDE software automatically translates and formats the source code, as shown in Figure 9-4.

**Figure 9-3:** Converting Xilinx Syntax PicoBlaze Source Code to pBlazIDE Syntax

**Figure 9-4:** Example of How KCPSM Source Code Converts to pBlazIDE Code

**Table:**

<table>
<thead>
<tr>
<th>KCPSM Source Code</th>
<th>Code Imported/Converted into pBlazIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSTANT myconstant, A5</td>
<td>myconstant       EQU       $A5</td>
</tr>
<tr>
<td>NAMEREG s0, count16_lsb</td>
<td>count16_lsb       EQU       s0</td>
</tr>
<tr>
<td>NAMEREG s1, count16_msb</td>
<td>count16_msb       EQU       s1</td>
</tr>
<tr>
<td>ADDRESS 000</td>
<td>ORG                0</td>
</tr>
<tr>
<td><strong>main:</strong> ; initialize 16-bit counter, enable interrupts</td>
<td>main: ; initialize 16-bit counter, enable interrupts</td>
</tr>
<tr>
<td>LOAD count16_lsb, myconstant</td>
<td>LOAD        count16_lsb, myconstant</td>
</tr>
<tr>
<td>ENABLE INTERRUPT</td>
<td>EINT</td>
</tr>
<tr>
<td><strong>loop:</strong> ; continuously increment 16-bit counter</td>
<td><strong>loop:</strong> ; continuously increment 16-bit counter</td>
</tr>
<tr>
<td>JUMP loop</td>
<td>JUMP                  loop</td>
</tr>
<tr>
<td><strong>end_main:</strong></td>
<td><strong>end_main:</strong></td>
</tr>
<tr>
<td>increment_count: ; add 1 to LSB of 16-bit counter</td>
<td>increment_count: ; add 1 to LSB of 16-bit counter</td>
</tr>
<tr>
<td>ADD count16_lsb, 01</td>
<td>ADD        count16_lsb, 01</td>
</tr>
<tr>
<td>only add one to MSB if carry generated by LSB</td>
<td>ADDC       count16_msb, 0</td>
</tr>
<tr>
<td>RETURN</td>
<td>RETURN</td>
</tr>
<tr>
<td><strong>isr:</strong> ; decrement 16-bit counter by one on interrupt</td>
<td><strong>isr:</strong> ; decrement 16-bit counter by one on interrupt</td>
</tr>
<tr>
<td>SUB count16_lsb, 1</td>
<td>SUB        count16_lsb, 1</td>
</tr>
<tr>
<td>only subtract one from MSB if borrow generated by LSB</td>
<td>SUBC       count16_msb, 0</td>
</tr>
<tr>
<td>RETURN</td>
<td>RETI                  ENABLE</td>
</tr>
<tr>
<td>interrupt vector is always in last memory location</td>
<td>interrupt vector is always in last memory location</td>
</tr>
<tr>
<td><strong>JUMP ISR</strong></td>
<td><strong>JUMP ISR</strong></td>
</tr>
<tr>
<td>JUMP isr</td>
<td>JUMP isr</td>
</tr>
</tbody>
</table>
Differences Between the KCPSM3 Assembler and pBlazIDE

Table 9-2 details the differences between the KCPSM3 and pBlazIDE instruction mnemonics.

### Table 9-2: Instruction Mnemonic Differences between KCPSM3 and pBlazIDE

<table>
<thead>
<tr>
<th>KCPSM3 Instruction</th>
<th>pBlazIDE Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>RETURN</td>
<td>RET</td>
</tr>
<tr>
<td>RETURN C</td>
<td>RET C</td>
</tr>
<tr>
<td>RETURN NC</td>
<td>RET NC</td>
</tr>
<tr>
<td>RETURN Z</td>
<td>RET Z</td>
</tr>
<tr>
<td>RETURN NZ</td>
<td>RET NZ</td>
</tr>
<tr>
<td>RETURNI ENABLE</td>
<td>RETI ENABLE</td>
</tr>
<tr>
<td>RETURNI DISABLE</td>
<td>RETI DISABLE</td>
</tr>
<tr>
<td>ADDCY</td>
<td>ADDC</td>
</tr>
<tr>
<td>SUBCY</td>
<td>SUBC</td>
</tr>
<tr>
<td>INPUT sX, (sY)</td>
<td>IN sX, sY</td>
</tr>
<tr>
<td></td>
<td>(no parentheses)</td>
</tr>
<tr>
<td>INPUT sX, kk</td>
<td>IN sX, kk</td>
</tr>
<tr>
<td>OUTPUT sX, (sY)</td>
<td>OUT sX, sY</td>
</tr>
<tr>
<td></td>
<td>(no parentheses)</td>
</tr>
<tr>
<td>OUTPUT sX, kk</td>
<td>OUT sX, kk</td>
</tr>
<tr>
<td>ENABLE INTERRUPT</td>
<td>EINT</td>
</tr>
<tr>
<td>DISABLE INTERRUPT</td>
<td>DINT</td>
</tr>
<tr>
<td>COMPARE</td>
<td>COMP</td>
</tr>
<tr>
<td>STORE sX, (sY)</td>
<td>STORE sX, sY</td>
</tr>
<tr>
<td></td>
<td>(no parentheses)</td>
</tr>
<tr>
<td>FETCH sX, (sY)</td>
<td>FETCH sX, sY</td>
</tr>
<tr>
<td></td>
<td>(no parentheses)</td>
</tr>
</tbody>
</table>

### Directives

Table 9-3 lists the KCPSM3 and PBlazIDE directives for various functions.

### Table 9-3: Directives

<table>
<thead>
<tr>
<th>Function</th>
<th>KCPSM3 Directive</th>
<th>PBlazIDE Directive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locating Code</td>
<td>ADDRESS 3FF</td>
<td>ORG $3FF</td>
</tr>
<tr>
<td>Aliasing Register Names</td>
<td>NAMEREG s5, myregname</td>
<td>myregname EQU s5</td>
</tr>
<tr>
<td>Declaring Constants</td>
<td>CONSTANT myconstant, 80</td>
<td>myconstant EQU $80</td>
</tr>
<tr>
<td>Naming the program ROM file</td>
<td>Named using the same base filename as the assembler source file</td>
<td>VHDL &quot;template.vhd&quot;, &quot;target.vhd&quot;, &quot;entity_name&quot;</td>
</tr>
</tbody>
</table>
Chapter 10

Using the PicoBlaze Microcontroller in an FPGA Design

The PicoBlaze™ microcontroller is primarily designed for use in a VHDL design flow. However, both Verilog and black box instantiation are also supported, as described below. Similarly, Xilinx XST/ISE® 6.2i and later versions support mixed language support where both VHDL and Verilog can be mixed in a single project. There is also support for the Xilinx System Generator design environment.

VHDL Design Flow

The PicoBlaze microcontroller is supplied as a VHDL source file, called KCPSM3.vhd, which is optimized for efficient and predictable implementation in a Spartan®-3, Virtex®-II, or Virtex-II Pro FPGA. The code is suitable for both synthesis and simulation and was developed and tested using the Xilinx Synthesis Tool (XST) for logic synthesis and ModelSim for simulation. Designers have also successfully used other logic synthesis and simulation tools. The VHDL source code must not be modified in any way.

KCPSM3 Module

The KCPSM3 module contains the PicoBlaze ALU, register file, scratchpad, RAM, etc. The only function not included is the instruction store. The component declaration for the KCPSM3 module appears in Figure 10-1. Figure 10-2 lists the KCPSM3 component instantiation.

```vhdl
component KCPSM3
port (  
  address : out std_logic_vector( 9 downto 0);  
  instruction : in std_logic_vector(17 downto 0);  
  port_id : out std_logic_vector( 7 downto 0);  
  write_strobe : out std_logic;  
  out_port : out std_logic_vector( 7 downto 0);  
  read_strobe : out std_logic;  
  in_port : in std_logic_vector( 7 downto 0);  
  interrupt : in std_logic;  
  interrupt_ack : out std_logic;  
  reset : in std_logic;  
  clk : in std_logic  
);  
end component;
```

Figure 10-1: VHDL Component Declaration of KCPSM3
Connecting the Program ROM

The PicoBlaze program ROM is used within a VHDL design flow. The PicoBlaze assembler generates a VHDL file in which a block RAM and its initial contents are defined. This VHDL file can be used for both logic synthesis and simulation of the processor.

Figure 10-3 shows the component declaration for the program ROM, and Figure 10-4 shows the component instantiation. The name of the program ROM, shown as "prog_rom" in the following figures, is derived from the name of the PicoBlaze assembler source file. For example, if the assembler source file is named phone.psm, then the assembler generates a program ROM definition file called phone.vhd.

To speed development, a VHDL file called embedded_KCPSM3.vhd is provided. In this file, the PicoBlaze macro is connected to its associated block RAM program ROM. This entire module can be embedded in the design application, or simply used to cut and paste the component declaration and instantiation information into the user’s design files.
Black Box Instantiation of KCPSM3 using KCPSM3.ngc

The Xilinx NGC file included with the reference design was generated by synthesizing the KCPSM3.vhd file using the Xilinx Synthesis Tool (XST), without inserting I/O buffers.

When used as a “black box” in a Spartan-3, Virtex-II or Virtex-II Pro FPGA design, the PicoBlaze microcontroller is merged with the remainder of the FPGA design during the translate phase (ngdbuild).

Note that buses are defined in the style IN_PORT<7:0> with individual signals defined as in_port_0 through in_port_7.

Generating the Program ROM using prog_rom.coe

The KCPSM assembler generates a memory coefficients file (*.coe). Using the Xilinx CORE Generator™ system, create a block ROM using the *.coe file.

The file defines the initial contents of a block ROM. The output files created by the CORE Generator system can then be used in the normal design flow and connected to the PicoBlaze “black box” instantiation of the KCPSM3 module.

Generating an ESC Schematic Symbol

To generate an ESC schematic symbol, use the embedded_KCPSM3.vhd file.

Verilog Design Flow

Beginning with XST/ISE 6.2i, the Xilinx development software allows mixed-language design projects using both VHDL and Verilog. Consequently, the KCPSM3 VHDL source can be included within a Verilog project. The KCPSM3 assembler generates a Verilog file named <filename>.v that defines the initial contents (see assembler notes for more detail). This Verilog file is used to implement and simulate the PicoBlaze instruction store.

The details of mixed VHDL and Verilog language support in the Xilinx ISE software is described in detail in Chapter 8, “Mixed Language Support”, in the XST User Guide.

- XST User Guide

Black-box instantiation is an alternative Verilog design approach. Instantiate the kcspm3.ngc black box file within the Verilog design to define the remainder of the processor.
Chapter 11

Assembler Directives

Both the KCPSM3 and pBlazIDE assemblers include directives that provide advanced control.

Locating Code at a Specific Address

In some cases, application code must be assigned to a specific instruction address. Examples include the code located at the reset vector, 0, and the interrupt vector, 3FF.

As an example, Table 11-1 shows the PicoBlaze™ processor assembler directive to locate code at the interrupt vector for both the KCPSM3 and pBlazIDE formats.

<table>
<thead>
<tr>
<th></th>
<th>KCPSM3</th>
<th>pBlazIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADDRESS</td>
<td>3FF</td>
<td>ORG $3FF</td>
</tr>
</tbody>
</table>

Table 11-1: Assembler Directives to Locate Code

Naming or Aliasing Registers

The PicoBlaze microcontroller has 16 general-purpose registers named s0 through sF. To improve code clarity and to enable easy code re-use, re-name or alias the PicoBlaze register with a variable name. Naming registers also prevents unintended use of a register and the associated data corruption, both improving code quality and reducing debugging efforts.

Table 11-2 shows how to alias a register, s5 in this case, to a variable name, myregname. Both KCPSM3 and pBlazIDE formats are shown.

<table>
<thead>
<tr>
<th></th>
<th>KCPSM3</th>
<th>pBlazIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAMEREG</td>
<td>s5, myregname</td>
<td>myregname EQU s5</td>
</tr>
</tbody>
</table>

Table 11-2: Assembler Directives to Name or Alias Registers

In the KCPSM3 assembler, the NAMEREG directive is applied in-line with the code. Before the NAMEREG directive, the register is named using the ‘sX’ style. Following the directive, only the new name applies. It is also possible to rename a register again (i.e., NAMEREG old_regnname, new_regnname) and only the new name applies in the subsequent program lines.
Defining Constants

Similar to renaming registers, assign names to constant values. By defining names for constants, it is easier to understand and document the PicoBlaze code rather than using the constant values in the code. Similarly, assigning names to registers and constants simplifies code maintenance. Updating the value assigned to a constant is easier if the constant is declared just once rather than searching for each occurrence in the application code.

Table 11-3 shows how to define a constant called `myconstant` and assign the value 80 hexadecimal. Both KCPSM3 and pBlazIDE formats are shown.

| Table 11-3: Assembler Directives to Name or Alias Registers |
|-----------------|-----------------|
| **KCPSM3**      | **pBlazIDE**    |
| CONSTANT myconstant, 80 | myconstant EQU $80 |

Naming the Program ROM Output File

The PicoBlaze assembler generates object code and formats the results for some form of internal memory within the FPGA. In general, the internal memory is block RAM, as described in Chapter 7, “Instruction Storage Configurations.”

**KCPSM3**

The output files from the KCPSM3 assembler are always named according to the source program name. For example, an assembly program named `myprog.psm` produces output files called `myprog.vhd`, `myprog.v`, etc. for the various output formats.

**pBlazIDE**

The pBlazIDE assembler provides a directive, using the keyword `VHDL`, to explicitly name the target output file and the VHDL entity name, as shown in Figure 11-1. The `template.vhd` file contains the VHDL template for the program ROM. The `target.vhd` file is the output VHDL file, derived from the `template.vhd` file, which contains the initialization values created by assembling the PicoBlaze code. Finally, `entity_name` is the VHDL entity name used to name program ROM.

```
VHDL "template.vhd", "target.vhd", "entity_name"
```

**Figure 11-1: pBlazIDE Directive to Name the VHDL Output File**

Defining I/O Ports (pBlazIDE)

To aid modeling and debugging of the interaction between the PicoBlaze microcontroller and the remainder of the FPGA, the pBlazIDE assembler supports some additional directives to describe and define I/O ports. These directives are particularly useful during instruction set simulation, as shown in Figure 12-1.
Input Ports

The DSIN directive defines the name and the port address (or port identification number) for a read-only input port. The DSIN directive models an input port that only connects to the PicoBlaze microcontroller’s IN_PORT port. An optional field specifies a text file containing input values used during instruction set simulation. Figure 11-2 provides an example.

```
; pBlazIDE syntax to define an input port
; input_port_name DSIN <port_id#>[, "<input_file_name>"
;
switches    DSIN  $00, "switch_inputs.txt"
readport    DSIN  $1F
```

**Figure 11-2: Example of pBlazIDE DSIN Directive**

As shown in Figure 11-3, the stimulus contained in the specified `switch_inputs.txt` is rather simple. Each line defines the data for an input (read) operation from the specified port address. Each line represents a single port input operation. Data is specified as decimal, unless prepended with a dollar sign ($), which indicates the data is hexadecimal. If the simulation reads through all the values provided, the last value is persistent until the end of simulation.

```
$FF
01
02
03
$A5
$5A
```

**Figure 11-3: Example File (switch_inputs.txt) to Describe Input Values for Simulation**

During instruction set simulation, pBlazIDE displays the input port as shown in Figure 11-4. Edit the input port values during simulation by checking the individual bit values or, to modify the entire byte value, double-click the current port value.

**Output Ports**

The DSOUT directive defines the name and the port address (or port identification number) for a write-only output port. The DSOUT directive models an output port that only connects to the PicoBlaze microcontroller’s OUT_PORT port. An optional field
specifies a text file that records the result of any output operations to this during instruction set simulation. Figure 11-5 provides an example.

```
; pBlazIDE syntax to define a write-only output port
; output_port_name DSOUT <port_id#>[, "<output_file_name>" ]
;
LEDs          DSOUT $01, "output_values.txt"
writeport     DSOUT $1E
```

Figure 11-5: Example of pBlazIDE DSOUT Directive

The values recorded in the optional output file are always written as hexadecimal values. During instruction set simulation, pBlazIDE displays the write-only output port as shown in Figure 11-6. Output ports are write-only and cannot be modified from the graphical interface.

```
; pBlazIDE syntax to define a readable output port
; input_output_port_name DSIO <port_id#>["<output_file_name>"

mailbox        DSIO $02, "mailbox_out.txt"
readwrite      DSIO $1D
```

Figure 11-7: Example of pBlazIDE DSIO Directive

The values recorded in the optional output file are always written as hexadecimal values.
Custom Instruction Op-Codes

During instruction set simulation, pBlazIDE displays the readable output port as shown in Figure 11-8. The port value can be modified from the graphical interface.

Figure 11-8: The pBlazIDE DSIO Directive Defines an Output Port That Can Be Read Back

Custom Instruction Op-Codes

The pBlazIDE environment supports the INST directive to force the assembler to generate a custom in-line instruction op-code. The INST directive is used when adding custom capabilities to the PicoBlaze reference design. However, adding custom capabilities requires modifications to PicoBlaze hardware.
Simulating PicoBlaze Code

Various tools support PicoBlaze code simulation, each with distinct strengths and weaknesses as described in Table 12-1. For example, the pBlazIDE Instruction Set Simulator (ISS) is best for simulating PicoBlaze operation during code development. As shown in Figure 12-1, the pBlazIDE ISS provides a seamless development environment where assembly code can be quickly tested with full observability. Registers, flags, and memory values appear on the graphical display. Likewise, each of these resources can be modified to enhance testing.

Table 12-1: PicoBlaze Code Simulation Options

<table>
<thead>
<tr>
<th>Verification Tool</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
</table>
| pBlazIDE          | • Ideal for rapid code development  
                  • Cycle-accurate Instruction Set Simulation (ISS)  
                  • Single-step  
                  • Breakpoints  
                  • Intimate interaction with PicoBlaze registers, flags, and memory values  
                  • Code coverage indicator  
                  • Software timing  
                  • Basic system-level simulation via file I/O functions  
                  • Free! | • No modeling of custom logic attached to the PicoBlaze microcontroller |
| ModelSim          | • Holistic simulation of PicoBlaze microcontroller with associated FPGA logic  
                  • VHDL and Verilog logic and timing simulation  
                  • Cycle and timing accurate with FPGA hardware | • Requires simulator setup and stimulus files  
                  • Digital simulator, not an ideal Instruction Set Simulation environment |
Furthermore, the pBlazIDE ISS offers full single-step and breakpoint support while viewing the PicoBlaze assembly source code. Evaluate the software timing for end application. Observe code coverage. Simulate basic FPGA interaction using the pBlazIDE DSIN, DSOUT, and DSIO directives (see “Defining I/O Ports (pBlazIDE),” page 76 for more information).

Best of all, the pBlazIDE graphical development environment is free! Download the latest version directly from the Mediatronix website:

http://www.mediatronix.com/pBlazeIDE.htm

The pBlazIDE ISS does not support full simulation of the PicoBlaze microcontroller embedded with all the other FPGA logic. Fortunately, the PicoBlaze core source files support both VHDL and Verilog simulation using the ModelSim simulator. ModelSim allows the entire design to be simulated, including accurate timing information and textual disassembly features.

If using the Xilinx System Generator software, there is full development and system-level simulation support for the PicoBlaze microcontroller. Refer to “Designing PicoBlaze Microcontroller Application” in the Xilinx System Generator User Guide (see Reference 3) for more information.

### Table 12-1: PicoBlaze Code Simulation Options

<table>
<thead>
<tr>
<th>Verification Tool</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
</table>
| Xilinx System Generator  | • Full PicoBlaze system-level simulation with the System Generator environment  
                           | • Cycle-accurate Instruction Set Simulation (ISS)  
                           | • Single-step  
                           | • Breakpoints  
                           | • Register and memory viewer | • Primarily only useful is already using Xilinx System Generator |
| In-system on FPGA        | • Fast, real-time performance  
                           | • Ideal for complex interactions  
                           | • Integrated with peripherals, displays, UARTs, etc. | • Poor visibility of register contents |

Instruction Set Simulation with pBlazIDE

The Mediatronix pBlazIDE instruction set simulator (ISS), shown in Figure 12-1, provides complete internal observability during code development. Begin simulation by clicking **Assemble**, as shown in Table 12-2. The pBlazIDE ISS also provides instruction breakpoints, single-stepping, register and RAM observation, code coverage, and software timing.
Figure 12-1: The pBlazIDE Instruction Set Simulator (ISS)

Simulator Control Buttons

Table 12-2 shows the various pBlazIDE control buttons and describes their functions.

Table 12-2: pBlazIDE Simulator Control Buttons

<table>
<thead>
<tr>
<th>Button</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assemble</td>
<td>Assemble the open document. If no errors are encountered, the simulator is invoked and the other simulation control buttons are enabled.</td>
</tr>
<tr>
<td>Edit</td>
<td>Leave simulator and return to editor. All the simulation control buttons are disabled.</td>
</tr>
</tbody>
</table>
### Table 12-2: pBlazIDE Simulator Control Buttons (Continued)

<table>
<thead>
<tr>
<th>Button</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reset</strong></td>
<td>Reset the simulator. Reset the Program Counter (PC) and Stack Pointer (SP). Register and RAM values are not reset.</td>
</tr>
<tr>
<td><strong>Run</strong></td>
<td>Run the program. The program continues running until an active breakpoint is encountered or if the Reset or Pause button is pressed.</td>
</tr>
<tr>
<td><strong>Single Step</strong></td>
<td>Execute a single instruction. The active register, memory, and I/O displays are updated and the cursor arrow advances to the next instruction. The next instruction to be executed is highlighted in blue and a blue arrow appears to the left of the instruction line. After executing an instruction, the code coverage indicator changes from blue to green. If executing a valid CALL instruction, the program steps into the subroutine function.</td>
</tr>
<tr>
<td><strong>Step Over</strong></td>
<td>Behaves like the Single Step button except that the simulator does not step into CALL instructions. If executing a valid CALL instruction, the program executes the entire subroutine and the display advances to the instruction following the CALL instruction.</td>
</tr>
<tr>
<td><strong>Run to Cursor</strong></td>
<td>Run the program until the program advances to the current cursor location.</td>
</tr>
<tr>
<td><strong>Pause</strong></td>
<td>Pause a running simulation and display the current state of the PicoBlaze microcontroller. Continue the simulation using any of the green action buttons.</td>
</tr>
<tr>
<td><strong>Toggle Breakpoint</strong></td>
<td>Set or remove a breakpoint on the instruction at the current cursor location. The instruction line is highlighted in red and a breakpoint indicator appears to the left of the line. Multiple breakpoints may be simultaneously active. If the simulation reaches an instruction with an active breakpoint, the simulation automatically pauses.</td>
</tr>
<tr>
<td><strong>Remove All Breakpoints</strong></td>
<td>Clear all active breakpoints.</td>
</tr>
</tbody>
</table>

### Using the pBlazIDE Instruction Set Simulator with KCPSM3 Programs

The pBlazIDE software primarily supports only a VHDL design flow, which is sufficient for many applications. The KCPSM3 assembler supports Verilog, black box, and Xilinx System Generator design flows in addition to the VHDL flow.

Fortunately, pBlazIDE has an import function that translates a KCPSM3-syntax program into the pBlazIDE syntax. Consequently, it is possible to use the pBlazIDE instruction set simulator to simulate KCPSM3 programs.

### Simulating FPGA Interaction with the pBlazIDE Instruction Set Simulator

Although pBlazIDE does not simulate FPGA logic, it does provide basic capabilities to test the PicoBlaze INPUT and OUTPUT operations that connect to FPGA logic. The DSIN, DSOUT, and DSIO directives declare input and output ports, and also provide simple file I/O functions. A stimulus file associated with a DSIN statement simulates data reads during a PicoBlaze INPUT operation. Similarly, the DSOUT statement specifies an output file where PicoBlaze OUTPUT operations are recorded.
Turbocharging Simulation using FPGAs!

Hardware simulators track results with picosecond or nanosecond resolution. In contrast, the PicoBlaze microcontroller is often employed in applications that are less time critical or deliberately slow. For example, a real-time clock is impractical to simulate using a hardware or software simulator. Even UART-based communication is desperately slow relative to a 50 MHz system clock. Likewise, VHDL and Verilog simulation requires accurate stimulus to drive the application.

In test cases, the solution is to simply use the FPGA hardware directly as the testing and debugging medium. While in-system “simulation” is not a replacement for worst-case timing analysis or code-coverage testing, it is possible to recompile a small design in less than a minute and make iterative changes to code and hardware. Using the download interface described in “Standard Configuration with UART or JTAG Programming Interface” in Chapter 7, rapid code changes can be quickly downloaded into the FPGA without recompiling the FPGA hardware design. Likewise, testing happens in the actual environment, along with the other support circuitry, which reduces the burden to create detailed and accurate stimulus models. For example, UART interaction can be tested using the HyperTerminal program on the PC, not just simulated using a VHDL model.

Furthermore, the PicoBlaze microcontroller itself is ideal for an internal test pattern generator, either to test another PicoBlaze core or to test integrated FPGA logic. The PicoBlaze microcontroller can output a test vector, calculate the result expected back from the FPGA, read the actual value from the FPGA, and verify that the actual and expected values match.
Related Materials and References

This appendix provides links to additional information relevant to a PicoBlaze™ processor design.

1. **PicoBlaze 8-bit Embedded Microcontroller**
   Download PicoBlaze reference designs and additional files.
   http://www.xilinx.com/ipcenter/processor_central/picoblaze

2. Mediatronix pBlazIDE Integrated Development Environment for PicoBlaze
   http://www.mediatronix.com/pBlazeIDE.htm


4. MicroBlaze 32-bit Soft Processor Core
   http://www.xilinx.com/microblaze


Appendix B

Example Program Templates

The following code templates provide the basic recommended structure for PicoBlaze™ processor application programs. Both KCPSM3 and pBlazIDE templates are provided.

If reading this document in Adobe Acrobat, use the Select Text tool to select code snippets, then copy and paste the text into your text editor.

Figure B-1 provides a code template for creating PicoBlaze applications using the KCPSM3 assembler.

### KCPSM3 Syntax

Figure B-1 provides a code template for creating PicoBlaze applications using the KCPSM3 assembler.

```
NAMEREG sX, <name> ; Rename register sX with <name>
CONSTANT <name>, 00 ; Define constant <name>, assign value

; ROM output file is always called
;   <filename>.vhd

ADDRESS 000 ; Programs always start at reset vector 0

ENABLE INTERRUPT ; If using interrupts, be sure to enable
;   the INTERRUPT input

BEGIN:
; << your code here >>

JUMP BEGIN ; Embedded applications never end

ISR: ; An Interrupt Service Routine (ISR) is
; required if using interrupts
; Interrupts are automatically disabled
; when an interrupt is recognized
; Never re-enable interrupts during the ISR

RETURNI ENABLE ; Return from interrupt service routine
; Use RETURNI DISABLE to leave interrupts
; disabled

ADDRESS 3FF ; Interrupt vector is located at highest
; instruction address

JUMP ISR ; Jump to interrupt service routine, ISR
```

*Figure B-1: PicoBlaze Application Program Template for KCPSM3 Assembler*
pBlazIDE Syntax

Figure B-2 provides a code template for creating PicoBlaze applications using the pBlazIDE assembler.

```
{name} EQU sX ; Rename register sX with <name>
{name} EQU $00 ; Define constant <name>, assign value

; name ROM output file generated by pBlazIDE assembler
VHDL "template.vhd", "target.vhd", "entity_name"

{name} DSIN <port_id> ; Create input port, assign port address
{name} DSOUT <port_id> ; Create output port, assign port address
{name} DSIO <port_id> ; Create readable output port,
                       ; assign port address

ORG 0; Programs always start at reset vector 0
EINT ; If using interrupts, be sure to enable
      ; the INTERRUPT input

BEGIN:
   ; <<< your code here >>>

    JUMP BEGIN ; Embedded applications never end

ISR: ; An Interrupt Service Routine (ISR) is
      ; required if using interrupts
      ; Interrupts are automatically disabled
      ; when an interrupt is recognized
      ; Never re-enable interrupts during the ISR

    RETI ENABLE ; Return from interrupt service routine
                  ; Use RETURNI DISABLE to leave interrupts
                  ; disabled

ORG $3FF ; Interrupt vector is located at highest
          ; instruction address
JUMP ISR ; Jump to interrupt service routine, ISR
```

*Figure B-2: PicoBlaze Application Program Template for KCPSM3 Assembler*
Appendix C

PicoBlaze Instruction Set and Event Reference

This appendix provides a detailed operational description of each PicoBlaze™ processor instruction and the Interrupt and Reset events, including pseudocode for each instruction. The pseudocode assumes that all variable to the right of an assignment symbol (\(\equiv\)) have the original value before the instruction is executed. The values for variables to the left of an assignment symbol are assigned at the end of the instruction and all assignments occur in parallel, similar to VHDL.

ADD sX, Operand —Add Operand to Register sX

The ADD instruction performs an 8-bit addition of two operands, as shown in Figure C-1. The first operand is any register, which also receives the result of the operation. A second operand is also any register or an 8-bit constant value. The ADD instruction does not use the CARRY as an input, and hence, there is no need to condition the flags before use. Flags are affected by this operation.

Example

Operand is a register location, \(sY\), or an immediate byte-wide constant, \(kk\).

\[
\begin{align*}
\text{ADD } sX, sY; \text{ Add register.} & \quad sX = sX + sY. \\
\text{ADD } sX, kk; \text{ Add immediate.} & \quad sX = sX + kk.
\end{align*}
\]

Description

Operand is added to register \(sX\). The ZERO and CARRY flags are set appropriately.
Pseudocode

\[
\begin{align*}
\text{sX} & \leftarrow (\text{sX} + \text{Operand}) \mod 256; \text{ always an 8-bit result} \\
\text{if } ( (\text{sX} + \text{Operand}) > 255 ) \text{ then} & \\
\quad \text{CARRY} & \leftarrow 1 \\
\text{else} & \\
\quad \text{CARRY} & \leftarrow 0 \\
\text{endif} & \\
\text{if } ( ((\text{sX} + \text{Operand}) = 0) \text{ or } ((\text{sX} + \text{Operand}) = 256) ) \text{ then} & \\
\quad \text{ZERO} & \leftarrow 1 \\
\text{else} & \\
\quad \text{ZERO} & \leftarrow 0 \\
\text{endif} & \\
\text{PC} & \leftarrow \text{PC} + 1
\end{align*}
\]

Registers/Flags Altered

Registers: sX, PC

Flags: CARRY, ZERO

ADDCY sX, Operand — Add Operand to Register sX with Carry

The ADCCY instruction performs an addition of two 8-bit operands and adds an additional ‘1’ if the CARRY flag was set by a previous instruction, as shown in Figure C-2. The first operand is any register, which also receives the result of the operation. A second operand is also any register or an 8-bit constant value. Flags are affected by this operation.

Example

Operand is a register location, sY, or an immediate byte-wide constant, kk.

\[
\begin{align*}
\text{ADDCY sX, sY; Add register. } & \quad \text{sX} = \text{sX} + \text{sY} + \text{CARRY} \\
\text{ADDCY sX, kk; Add immediate. } & \quad \text{sX} = \text{sX} + \text{kk} + \text{CARRY}
\end{align*}
\]

Description

Operand and CARRY flag are added to register sX. The ZERO and CARRY flags are set appropriately.
Pseudocode

if (CARRY = 1) then
    sX ← (sX + Operand + 1) mod 256; always an 8-bit result
else
    sX ← (sX + Operand) mod 256 ; always an 8-bit result
end if

if ( (sX + Operand + CARRY) > 255 ) then
    CARRY ← 1
else
    CARRY ← 0
endif

if ( ((sX + Operand + CARRY) = 0) or ((sX + Operand + CARRY) = 256) ) then
    ZERO ← 1
else
    ZERO ← 0
endif

PC ← PC + 1

Registers/Flags Altered

Registers: sX, PC
Flags: CARRY, ZERO

Notes

pBlazIDE Equivalent: ADDC

AND sX, Operand — Logical Bitwise AND Register sX with Operand

The AND instruction performs a bitwise logical AND operation between two operands, as shown in Figure C-3. The first operand is any register, which also receives the result of the operation. A second operand is also any register or an 8-bit immediate constant. The ZERO flag is set if the resulting value is zero. The CARRY flag is always cleared by an AND instruction.

![Figure C-3: AND Operation](image_url)

The AND operation can be used to perform tests on the contents of a register. The status of the ZERO flag then controls the flow of the program.
Examples

\[
\text{AND } \text{sX}, \text{sY} ; \text{ Logically AND the individual bits of register sX with } \\
\text{the corresponding bits in register sY} \\
\text{AND } \text{sX}, \text{kk} ; \text{ Logically AND the individual bits of register sX with } \\
\text{the corresponding bits in the immediate constant kk}
\]

Pseudocode

\[
; \text{logically AND the corresponding bits in sX and the Operand} \\
\text{for } (i=0; i<7; i=i+1) \\
\{ \\
\quad \text{sX}(i) \leftarrow \text{sX}(i) \text{ AND Operand}(i) \\
\} \\
\text{CARRY } \leftarrow 0 \\
\text{if } (\text{sX} = 0) \text{ then} \\
\quad \text{ZERO } \leftarrow 1 \\
\text{else} \\
\quad \text{ZERO } \leftarrow 0 \\
\text{end if} \\
\text{PC } \leftarrow \text{PC} + 1
\]

Registers/Flags Altered

Registers: sX, PC

Flags: ZERO, CARRY is always 0

CALL [Condition,] Address — Call Subroutine at Specified Address, Possibly with Conditions

The CALL instruction modifies the normal program execution sequence by jumping to a specified program address. Each CALL instruction must specify the 10-bit address as a three-digit hexadecimal value or a label that the assembler resolves to a three-digit hexadecimal value.

The CALL instruction has both conditional and unconditional variants. A conditional CALL is only performed if a test performed against either the ZERO flag or CARRY flag is true. If unconditional or if the condition is true, the CALL instruction pushes the current value the PC to the top of the CALL/RETURN stack. Simultaneously, the specified CALL location is loaded into the PC.

A subroutine function must exist at the specified address. The subroutine function requires a RETURN instruction to return from the subroutine.

The CALL instruction does not affect the ZERO or CARRY flags. However, if a CALL is performed, the resulting subroutine instructions may modify the flags.

Examples

\[
\text{CALL MYSUB; Unconditionally call MYSUB subroutine} \\
\text{CALL C, MYSUB; If CARRY flag set, call MYSUB subroutine} \\
\text{CALL NC, MYSUB; If CARRY flag not set, call MYSUB subroutine} \\
\text{CALL Z, MYSUB; If ZERO flag set, call MYSUB subroutine} \\
\text{CALL NZ, MYSUB; If ZERO flag not set, call MYSUB subroutine}
\]
CALL [Condition,] Address — Call Subroutine at Specified Address, Possibly with Conditions

Condition

Depending on the specified Condition, the program calls the subroutine beginning at the specified Address. If the specified Condition is not met, the program continues to the next instruction.

Table C-1: CALL Instruction Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;none&gt;</td>
<td>Always true. Call subroutine unconditionally.</td>
</tr>
<tr>
<td>C</td>
<td>CARRY = 1. Call subroutine if CARRY flag is set.</td>
</tr>
<tr>
<td>NC</td>
<td>CARRY = 0. Call subroutine if CARRY flag is cleared.</td>
</tr>
<tr>
<td>Z</td>
<td>ZERO = 1. Call subroutine if ZERO flag is set.</td>
</tr>
<tr>
<td>NZ</td>
<td>ZERO = 0. Call subroutine if ZERO flag is cleared.</td>
</tr>
</tbody>
</table>

Pseudocode

if (Condition = TRUE) then
  ; push current PC onto top of the CALL/RETURN stack
  TOS = Top of Stack
  TOS ← PC
  ; load PC with specified Address
  PC ← Address
else
  PC ← PC + 1
endif

Registers/Flags Altered

Registers: PC, CALL/RETURN stack
Flags: Not affected

Notes

The maximum number of nested subroutine calls is 31 levels, due to the depth of the CALL/RETURN stack.
COMPARE sX, Operand — Compare Operand with Register sX

The COMPARE instruction performs an 8-bit comparison of two operands, as shown in Figure C-4. The first operand, sX, is any register and this register is NOT affected by the COMPARE operation. The second operand is also any register or an 8-bit immediate constant value. Only the flags are affected by this operation.

Register sX is compared against Operand. The ZERO flag is set when Register sX and Operand are identical. The CARRY flag is set when Operand is larger than Register sX, where both Operand and Register sX are evaluated as unsigned integers.

Example

Operand is a register location, sY, or an immediate byte-wide constant, kk.

```
COMPARE sX, sY; Compare sX against sY.
COMPARE sX, kk; Compare sX against immediate constant, kk.
```

Pseudocode

```
if ( Operand > sX ) then
  CARRY ← 1
else
  CARRY ← 0
endif

if ( sX = Operand ) then
  ZERO ← 1
else
  ZERO ← 0
endif

PC ← PC + 1
```

Registers/Flags Altered

Registers: PC only. No data registers affected.

Flags: CARRY, ZERO

Notes

pBlazIDE Equivalent: COMP

The COMPARE instruction is only supported on PicoBlaze microcontrollers for Spartan®-3, Virtex®-II, and Virtex-II Pro FPGAs.
DISABLE INTERRUPT — Disable External Interrupt Input

The DISABLE INTERRUPT instruction clears the interrupt enable (IE) flag. Consequently, the PicoBlaze microcontroller ignores the INTERRUPT input. Use this instruction to temporarily disable interrupts during timing-critical code segments. Use the ENABLE INTERRUPT instruction to re-enable interrupts.

Example

DISABLE INTERRUPT; Disable interrupts

Pseudocode

```
DISABLE INTERRUPT;
```

```
INTERRUPT_ENABLE ← 0
PC ← PC + 1
```

Registers/Flags Altered

Registers: PC
Flags: INTERRUPT_ENABLE

Notes

PBlazIDE Equivalent: DINT

ENABLE INTERRUPT — Enable External Interrupt Input

The ENABLE INTERRUPT instruction sets the interrupt enable (IE) flag. Consequently, the PicoBlaze microcontroller recognizes the INTERRUPT input. Before using this instruction, a suitable interrupt service routine (ISR) must be associated with the interrupt vector address, 3FF.

Never issue the ENABLE INTERRUPT instruction from within an ISR.

Example

ENABLE INTERRUPT; Enable interrupts

Pseudocode

```
ENABLE INTERRUPT;
```

```
INTERRUPT_ENABLE ← 1
PC ← PC + 1
```

Registers/Flags Altered

Registers: PC
Flags: INTERRUPT_ENABLE

Notes

PBlazIDE Equivalent: EINT
FETCH sX, Operand — Read Scratchpad RAM Location to Register sX

The FETCH instruction reads scratchpad RAM location specified by Operand into register sX, as shown in Figure C-5. There are 64 scratchpad RAM locations. The two most-significant bits of Operand, bits 7 and 6, are discarded and the RAM address is truncated to the least-significant six bits ofOperand, bits 5 to bit 0. Consequently, a FETCH operation from address FF is equivalent to a FETCH operation from address 3F.

Examples

FETCH sX, (sY) ; Read scratchpad RAM location specified by the ; contents of register sY into register sX

FETCH sX, kk ; Read scratchpad RAM location specified by the ; immediate constant kk into register sX

Pseudocode

sX ← Scratchpad_RAM [Operand[5:0]]
PC ← PC + 1

Registers/Flags Altered

Registers: PC
Flags: None

Notes

pBlazIDE Equivalent: The instruction mnemonic, FETCH, is the same for both KCPSM3 and pBlazIDE. However, the instruction syntax for indirect addressing is slightly different. The KCPSM3 syntax places parentheses around the indirect address while the pBlazIDE syntax uses no parentheses.

<table>
<thead>
<tr>
<th>KCPSM3 Instruction</th>
<th>PBlazIDE Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>FETCH sX, (sY)</td>
<td>FETCH sX, sY</td>
</tr>
</tbody>
</table>

The FETCH instruction is only supported on PicoBlaze microcontrollers for Spartan-3, Virtex-II, and Virtex-II Pro FPGAs.
INPUT sX, Operand — Set PORT_ID to Operand, Read value on IN_PORT into Register sX

The INPUT instruction sets the PORT_ID output port to either the value specified by register sY or by the immediate constant kk. The instruction then reads the value on the IN_PORT input port into register sX. Flags are not affected by this operation.

Interface logic decodes the PORT_ID address to provide the correct value on IN_PORT.

Examples

\[
\text{INPUT sX, sY ; Read the value on IN_PORT into register sX, set PORT_ID}
\]
\[
\text{; to the contents of sY}
\]
\[
\text{INPUT sX, kk ; Read the value on IN_PORT into register sX, set PORT_ID}
\]
\[
\text{; to the immediate constant kk}
\]

Pseudocode

\[
\text{PORT_ID \leftarrow Operand}
\]
\[
\text{sX \leftarrow IN_PORT}
\]
\[
\text{PC \leftarrow PC + 1}
\]

Registers/Flags Altered

Registers: sX, PC
Flags: None

Notes

pBlazIDE Equivalent: IN

The READ_STROBE output is asserted during the second CLK cycle of the two-cycle INPUT operation.
INTERRUPT Event, When Enabled

The interrupt event is not an instruction but the response of the PicoBlaze microcontroller to an external interrupt input. If the INTERRUPT_ENABLE flag is set, then a recognized logic level on the INTERRUPT input generates an Interrupt Event. The action essentially generates a subroutine CALL to the most-significant instruction address, location 1023 ($3FF). The currently executing instruction is allowed to complete. Once the PicoBlaze microcontroller recognizes the interrupt input, the INTERRUPT_ENABLE flag is automatically reset. The next instruction in the normal program flow is preempted by the Interrupt Event and the current PC is pushed onto the CALL/RETURN stack. The PC is loaded with all ones and the program calls the instruction at the most-significant address.

The instruction at the most-significant address must jump to the interrupt service routine (ISR).

Pseudocode

```plaintext
; only respond to INTERRUPT input if INTERRUPT_ENABLE flag is set
if ( (INTERRUPT_ENABLE = 1)and (INTERRUPT input = High) ) then
    ; clear the INTERRUPT_ENABLE flag
    INTERRUPT_ENABLE ← 0

    ; push the current program counter (PC) to the stack
    TOS = Top of Stack
    TOS ← PC

    ; preserve the current CARRY and ZERO flags
    PRESERVED_CARRY ← CARRY
    PRESERVED_ZERO ← ZERO

    ; load program counter (PC) with interrupt vector ($3FF)
    PC ← $3FF
endif
```

Registers/Flags Altered

Registers: PC, CALL/RETURN stack

Flags: CARRY, ZERO, INTERRUPT_ENABLE

Notes

The PicoBlaze microcontroller asserts the INTERRUPT_ACK output on the second CLK cycle of the two-cycle Interrupt Event, as shown in Figure 4-3, page 43. This signal is optionally used to clear any hardware interrupt flags.

The programmer must ensure that a RETURNI instruction is only performed in response to a previous interrupt. Otherwise, the PC stack may not contain a valid return address.

Do not use the RETURNI instruction to return from a subroutine CALL. Instead, use the RETURN instruction.

Because an interrupt event may happen at any time, the values of the CARRY and ZERO flags cannot be predetermined. Consequently, the corresponding Interrupt Service Routine (ISR) must not depend on specific values for the CARRY and ZERO flags.
The **JUMP** instruction modifies the normal program execution sequence by jumping to a specified program address. Each **JUMP** instruction must specify the 10-bit jumping address as a three-digit hexadecimal value or a label that the assembler resolves to a three-digit hexadecimal value.

The **JUMP** instruction has both conditional and unconditional variants. A conditional **JUMP** is only performed if a test performed against either the ZERO flag or CARRY flag is true. If unconditional or if the condition is true, the **JUMP** instruction loads the specified jump address into the Program Counter (PC).

The **JUMP** instruction does not affect the CALL/RETURN stack.

The **JUMP** instruction does not affect the ZERO or CARRY flags.

**Example**

```plaintext
JUMP     NEW_LOCATION; Unconditionally jump to NEW_LOCATION
JUMP C,  NEW_LOCATION; If CARRY flag set, jump to NEW_LOCATION
JUMP NC, NEW_LOCATION; If CARRY flag not set, jump to NEW_LOCATION
JUMP Z,  NEW_LOCATION; If ZERO flag set, jump to NEW_LOCATION
JUMP NZ, NEW_LOCATION; If ZERO flag not set, jump to NEW_LOCATION
```

**Condition**

Depending on the specified condition, the program jumps to the instruction at the specified address. If the specified condition is not met, the program continues on to the next instruction.

**Table C-2: JUMP Instruction Conditions**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;none&gt;</td>
<td>Always true. Jump unconditionally.</td>
</tr>
<tr>
<td>C</td>
<td>CARRY = 1. Jump if CARRY flag is set.</td>
</tr>
<tr>
<td>NC</td>
<td>CARRY = 0. Jump if CARRY flag is cleared.</td>
</tr>
<tr>
<td>Z</td>
<td>ZERO = 1. Jump if ZERO flag is set.</td>
</tr>
<tr>
<td>NZ</td>
<td>ZERO = 0. Jump if ZERO flag is cleared.</td>
</tr>
</tbody>
</table>

**Pseudocode**

```
if (Condition = TRUE) then
   PC ← Address
else
   PC ← PC + 1
endif
```

**Registers/Flags Altered**

Registers: PC

Flags: Not affected
LOAD sX, Operand — Load Register sX withOperand

The LOAD instruction loads the contents of any register. The new value is either the contents of any other register or an immediate constant. The LOAD instruction has no effect on the status flags.

Because the LOAD instruction does not affect the flags, use it to reorder and assign register contents at any stage of the program execution. Loading a constant into a register via the LOAD instruction has no impact on program size or performance and is the easiest method to assign a value or to clear a register.

Examples

LOAD sX, sY; Move the contents of register sY to register sX
LOAD sX, kk; Load register sX with the immediate constant kk

Pseudocode

sX ← Operand
PC ← PC + 1

Registers/Flags Altered

Registers: sX, PC
Flags: Not affected
OR sX, Operand — Logical Bitwise OR Register sX with Operand

The OR instruction performs a bitwise logical OR operation between two operands, as shown in Figure C-6. The first operand is any register, which also receives the result of the operation. A second operand is also any register or an 8-bit immediate constant. The ZERO flag is set if the resulting value is zero. The CARRY flag is always cleared by an OR instruction.

The OR instruction provides a way to force the setting any bit of the specified register, which can be used to form control signals.

Examples

OR sX, sY ; Logically OR the individual bits of register sX with the ; corresponding bits in register sY
OR sX, kk ; Logically OR the individual bits of register sX with the ; corresponding bits in the immediate constant kk

Pseudocode

; logically OR the corresponding bits in sX and the Operand
for (i=0; i< 7; i=i+1)
{
    sX(i) ← sX(i) OR Operand(i)
}

CARRY ← 0

if (sX = 0) then
    ZERO ← 1
else
    ZERO ← 0
end if

PC ← PC + 1

Registers/Flags Altered

Registers: sX, PC
Flags: ZERO, CARRY is always 0
OUTPUT sX, Operand — Write Register sX Value to OUT_PORT, Set PORT_ID to Operand

The OUTPUT instruction sets the PORT_ID port address to the value specified by either the register sY or the immediate constant kk. The instruction writes the contents of register sX to the OUT_PORT output port. FPGA logic captures the output value by decoding the PORT_ID value and WRITE_STROBE output, as shown in Figure C-7.

Examples

OUTPUT sX, sY; Write register sX to OUT_PORT, set PORT_ID to the ; contents of sY

OUTPUT sX, kk; Write register sX to OUT_PORT, set PORT_ID to the ; immediate constant kk

Pseudocode

PORT_ID ← Operand

OUT_PORT ← sX

PC ← PC + 1

Registers/Flags Altered

Registers: PC

Flags: None

Notes

pBlazIDE Equivalent: OUT

The WRITE_STROBE output is asserted during the second CLK cycle of the two-cycle OUTPUT operation.

Figure C-7: OUTPUT Operation and FPGA Interface Logic
The reset event is not an instruction but the response of the PicoBlaze microcontroller when the RESET input is High. A RESET Event restarts the PicoBlaze microcontroller and clears various hardware elements, as shown in Table C-3.

A RESET Event is automatically generated immediately following FPGA configuration, initiated by the FPGA’s internal Global Set/Reset (GSR) signal. After configuration, the FPGA application generates RESET Event by asserting the RESET input before a rising CLK clock edge.

**Table C-3: PicoBlaze Reset Values**

<table>
<thead>
<tr>
<th>Resource</th>
<th>RESET Event Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>General-purpose Registers</td>
<td>Unaffected.</td>
</tr>
<tr>
<td>Program Counter</td>
<td>0</td>
</tr>
<tr>
<td>ZERO Flag</td>
<td>0</td>
</tr>
<tr>
<td>CARRY Flag</td>
<td>0</td>
</tr>
<tr>
<td>INTERRUPT_ENABLE Flag</td>
<td>0</td>
</tr>
<tr>
<td>Scratchpad RAM</td>
<td>Unaffected.</td>
</tr>
<tr>
<td>Program Store</td>
<td>Unaffected.</td>
</tr>
<tr>
<td>CALL/RETURN Stack</td>
<td>Stack Pointer reset.</td>
</tr>
</tbody>
</table>

The general-purpose registers, the scratchpad RAM, and the program store are not affected by a RESET Event. The CALL/RETURN stack is a circular buffer, although a RESET Event essentially resets the CALL/RETURN stack pointer.

**Pseudocode**

```plaintext
if (RESET input = High) then
  ; clear Program Counter
  PC ← 0

  ; disable the INTERRUPT input by clearing the INTERRUPT_ENABLE flag
  INTERRUPT_INPUT ← 0

  ; clear the ZERO and CARRY flags
  ZERO ← 0
  CARRY ← 0
endif
```

**Registers/Flags Altered**

Registers: PC, CALL/RETURN stack

Flags: CARRY, ZERO, INTERRUPT_ENABLE
RETURN [Condition] — Return from Subroutine Call, Possibly with Conditions

The RETURN instruction is the complement to the CALL instruction. The RETURN instruction is also conditional. The new PC value is formed internally by incrementing the last value on the program address stack, ensuring that the program executes the instruction following the CALL instruction that called the subroutine. The RETURN instruction has no effect on the status of the flags.

The RETURN instruction has both conditional and unconditional variants. A conditional RETURN is only performed if a test performed against either the ZERO flag or CARRY flag is true. If unconditional or if the condition is true, the RETURN instruction pops the return address from the top of the CALL/RETURN stack into the PC. The popped value forces the program to return to the instruction immediately following the original subroutine CALL.

Ensure that a RETURN is only performed in response to a previous CALL instruction so that the CALL/RETURN stack contains a valid address.

The RETURN instruction does not affect the ZERO or CARRY flags. The flag values set prior to the RETURN instruction are maintained and available after the return from the subroutine call.

Condition

Depending on the specified condition, the program returns from a subroutine call. If the specified condition is not met, the program continues on to the next instruction.

Table C-4: RETURN Instruction Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;none&gt;</td>
<td>Always true. Return from called subroutine unconditionally.</td>
</tr>
<tr>
<td>C</td>
<td>CARRY = 1. Return from called subroutine if CARRY flag is set.</td>
</tr>
<tr>
<td>NC</td>
<td>CARRY = 0. Return from called subroutine if CARRY flag is cleared.</td>
</tr>
<tr>
<td>Z</td>
<td>ZERO = 1. Return from called subroutine if ZERO flag is set.</td>
</tr>
<tr>
<td>NZ</td>
<td>ZERO = 0. Return from called subroutine if ZERO flag is cleared.</td>
</tr>
</tbody>
</table>

Pseudocode

if (Condition = TRUE) then
    ; pop the top of the CALL/RETURN stack into PC
    ; TOS = Top of Stack
    PC ← TOS + 1; incremented value from Top of Stack
else
    PC ← PC + 1
endif

Registers/Flags Altered

Registers: PC, CALL/RETURN stack
Flags: Not affected

Notes

Do not use the RETURN instruction to return from an interrupt. Instead, use the RETURNI instruction.
RETURNI [ENABLE/DISABLE] — Return from Interrupt Service Routine and Enable or Disable Interrupts

The RETURNI instruction is a special variation of the RETURN instruction. It concludes an interrupt service routine. The RETURNI instruction is unconditional and pops the return address from the top of the CALL/RETURN stack into the PC. The return address points to the instruction preempted by an Interrupt Event. The RETURNI instruction restores the CARRY and ZERO flags to the values preserved by the Interrupt Event.

The ENABLE or DISABLE operand defines whether the INTERRUPT input is re-enabled or remains disabled when returning from the interrupt service routine (ISR).

Example

```
RETURNI ENABLE; Return from interrupt, re-enable interrupts
RETURNI DISABLE; Return from interrupt, leave interrupts disabled
```

Pseudocode

```
; pop the top of the CALL/RETURN stack into PC
PC ← TOS

; restore the flags to their pre-interrupt values
CARRY ← PRESERVED_CARRY
ZERO ← PRESERVED_ZERO

; if "ENABLE" specified, re-enable interrupts
if (ENABLE = TRUE) then
    INTERRUPT_ENABLE ← 1
else
    INTERRUPT_ENABLE ← 0
endif
```

Registers/Flags Altered

Registers: PC, CALL/RETURN stack
Flags: CARRY, ZERO, INTERRUPT_ENABLE

Notes

Do not use the RETURNI instruction to return from a subroutine CALL. Instead, use the RETURN instruction.

PBlazIDE Equivalent: RETI ENABLE, RETI DISABLE
RL sX — Rotate Left Register sX

The rotate left instruction operates on any single data register. Each bit in the specified register is shifted left by one bit position, as shown in Table C-5. The most-significant bit, bit 7, shifts both into the CARRY bit and into the least-significant bit, bit 0.

**Table C-5: Rotate Left (RL) Operation**

<table>
<thead>
<tr>
<th>Rotate Left</th>
<th>RL sX</th>
<th>CARRY</th>
<th>Register sX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>6 5 4 3 2 1 0</td>
</tr>
</tbody>
</table>

**Example**

RL sX; Rotate left. Bit sX[7] copied into CARRY.

**Pseudocode**

```
CARRY ← sX[7]
sX ← { sX[6:0], sX[7] }
if ( sX = 0 ) then
  ZERO ← 1
else
  ZERO ← 0
endif
PC ← PC + 1
```

**Registers/Flags Altered**

Registers: sX, PC

Flags: CARRY, ZERO

RR sX — Rotate Right Register sX

The rotate right instruction operates on any single data register. Each bit in the specified register is shifted right by one bit position, as shown in Table C-6. The least-significant bit, bit 0, shifts both into the CARRY bit and into the most-significant bit, bit 7.

**Table C-6: Rotate Right (RR) Operation**

<table>
<thead>
<tr>
<th>Rotate Right</th>
<th>RR sX</th>
<th>Register sX</th>
<th>CARRY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
</tbody>
</table>


Example

RR sX; Rotate right. Bit sX[0] copied into CARRY

Pseudocode

CARRY ← sX[0]

sX ← {sX[0], sX[7:1]}

if (sX = 0) then
  ZERO ← 1
else
  ZERO ← 0
endif

PC ← PC + 1

Registers/Flags Altered

Registers: sX, PC

Flags: CARRY, ZERO

\textbf{SL[0 | 1 | X | A] sX — Shift Left Register sX}

There are four variants of the shift left instruction, as shown in Table C-7, that operate on any single data register. Each bit in the specified register is shifted left by one bit position. The most-significant bit, bit 7, shifts into the CARRY bit. The last character of the instruction mnemonic—i.e., ‘0’, ‘1’, ‘X’, or ‘A’—indicates the value shifted into the least-significant bit, bit 7.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Shift Left} & \textbf{Shift Left Operations} \\
\hline
\textbf{SL0 sX} & Shift Left with ‘0’ fill. \\
& \begin{array}{c}
\text{CARRY} \\
\text{Register sX}
\end{array} \\
& \begin{array}{c|c|c|c|c|c|c|c}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\text{‘0’}
\end{array} \\
\hline
\textbf{SL1 sX} & Shift Left with ‘1’ fill. \\
& \begin{array}{c}
\text{CARRY} \\
\text{Register sX}
\end{array} \\
& \begin{array}{c|c|c|c|c|c|c|c}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\text{‘1’}
\end{array} \\
\hline
\textbf{SLX sX} & Shift Left, eXtend bit 0. \\
& \begin{array}{c}
\text{CARRY} \\
\text{Register sX}
\end{array} \\
& \begin{array}{c|c|c|c|c|c|c|c}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\end{array} \\
\hline
\textbf{SLA sX} & Shift Left through All bits, including CARRY. \\
& \begin{array}{c}
\text{CARRY} \\
\text{Register sX}
\end{array} \\
& \begin{array}{c|c|c|c|c|c|c|c}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\end{array} \\
\hline
\end{tabular}
\end{table}

The ZERO flag is always 0 after executing the SL1 instruction because register sX is never zero.
Examples

\[ \text{SL0} \ sX; \text{ Shift left. 0 shifts into LSB, MSB shifts into CARRY.} \]
\[ \text{SL1} \ sX; \text{ Shift left. 1 shifts into LSB, MSB shifts into CARRY.} \]
\[ \text{SLX} \ sX; \text{ Shift left. LSB shifts into LSB, MSB shifts into CARRY.} \]
\[ \text{SLA} \ sX; \text{ Shift left. CARRY shifts into LSB, MSB shifts into CARRY.} \]

Pseudocode

\[
\begin{align*}
\text{case (INSTRUCTION)} \\
&\text{when "SL0" } \\
&\quad \text{LSB} \leftarrow 0 \\
&\text{when "SL1" } \\
&\quad \text{LSB} \leftarrow 1 \\
&\text{when "SLX" } \\
&\quad \text{LSB} \leftarrow sX(7) \\
&\text{when "SLA" } \\
&\quad \text{LSB} \leftarrow \text{CARRY}
\end{align*}
\]
\[
\begin{align*}
&\text{end case} \\
&\text{CARRY} \leftarrow sX[7] \\
&sX \leftarrow \{sX[6:0], \text{LSB}\}
\end{align*}
\]
\[
\begin{align*}
&\text{if ( sX = 0 ) then} \\
&\quad \text{ZERO} \leftarrow 1 \\
&\text{else} \\
&\quad \text{ZERO} \leftarrow 0
\end{align*}
\]
\[
\begin{align*}
&\text{endif} \\
&\text{PC} \leftarrow \text{PC} + 1
\end{align*}
\]

Registers/Flags Altered

Registers: \( sX, \text{PC} \)

Flags: CARRY, ZERO

\textbf{SR[ 0 | 1 | X | A ] sX — Shift Right Register sX}

There are four variants of the shift right instruction, as shown in Table C-8, that operate on any single data register. Each bit in the specified register is shifted right by one bit position. The least-significant bit, bit 0, shifts into the CARRY bit. The last character of the instruction mnemonic—i.e., ‘0’, ‘1’, ‘X’, or ‘A’—indicates the value shifted into the most-significant bit, bit 7.
SR[ 0 | 1 | X | A ] sX — Shift Right Register sX

**Table C-8: Shift Right Operations**

<table>
<thead>
<tr>
<th>Shift Right</th>
<th>SR0 sX</th>
<th>SR1 sX</th>
<th>SRX sX</th>
<th>SRA sX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift Right with ‘0’ fill.</td>
<td><strong>Register sX</strong></td>
<td><strong>CARRY</strong></td>
<td>‘0’</td>
<td>7 6 5 4 3 2 1 0</td>
</tr>
<tr>
<td>Shift Right with ‘1’ fill.</td>
<td><strong>Register sX</strong></td>
<td><strong>CARRY</strong></td>
<td>‘1’</td>
<td>7 6 5 4 3 2 1 0</td>
</tr>
<tr>
<td>Shift Right, sign eXtend.</td>
<td><strong>Register sX</strong></td>
<td><strong>CARRY</strong></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
<tr>
<td>Shift Right through All bits, including CARRY.</td>
<td><strong>Register sX</strong></td>
<td><strong>CARRY</strong></td>
<td>7 6 5 4 3 2 1 0</td>
<td></td>
</tr>
</tbody>
</table>

The ZERO flag is always 0 after executing the SR1 instruction because register sX is never zero.

**Example**
- SR0 sX; Shift right. 0 shifts into MSB, LSB shifts into CARRY.
- SR1 sX; Shift right. 1 shifts into MSB, LSB shifts into CARRY.
- SRX sX; Shift right MSB shifts into MSB, LSB shifts into CARRY.
- SRA sX; Shift right CARRY shifts into MSB, LSB shifts into CARRY.

**Pseudocode**

```python
case (INSTRUCTION)
  when "SR0"
    MSB ← 0
  when "SR1"
    MSB ← 1
  when "SRX"
    MSB ← sX(7)
  when "SRA"
    MSB ← CARRY
end case

CARRY ← sX[0]

sX ← {MSB, sX[7:1]}

if ( sX = 0 ) then
  ZERO ← 0
else
  ZERO ← 1
endif

PC ← PC + 1
```
Registers/Flags Altered

Registers: sX, PC
Flags: CARRY, ZERO

STORE sX, Operand — Write Register sX Value to Scratchpad RAM Location

The STORE instruction writes register sX to the scratchpad RAM location specified by Operand, as shown in Figure C-8. There are 64 scratchpad RAM locations. The two most-significant bits of Operand, bits 7 and 6, are discarded and the RAM address is truncated to the least-significant six bits of Operand, bits 5 to bit 0. Consequently, a STORE operation to address FF is equivalent to a STORE operation to address 3F.

**Examples**

STORE sX, (sY)  ; Write register sX to scratchpad RAM location
                 ; specified by the contents of register sY

STORE sX, kk    ; Write register sX to scratchpad RAM location
                 ; specified by the immediate constant kk

**Pseudocode**

\[
\text{Scratchpad\_RAM[Operand[5:0]]} \leftarrow \text{sX}
\]

\[
\text{PC} \leftarrow \text{PC} + 1
\]

**Registers/Flags Altered**

Registers: sX, PC
Flags: None

**Notes**

pBlazIDE Equivalent: The instruction mnemonic, STORE, is the same for both KCPSM3 and pBlazIDE. However, the instruction syntax for indirect addressing is slightly different. The KCPSM3 syntax places parentheses around the indirect address while the pBlazIDE syntax uses no parentheses.
SUB sX, Operand — Subtract Operand from Register sX

The STORE instruction is only supported on PicoBlaze microcontrollers for Spartan-3, Virtex-II, and Virtex-II Pro FPGAs.

SUB sX, Operand — Subtract Operand from Register sX

The SUB instruction performs an 8-bit subtraction of two operands, as shown in Figure C-9. The first operand is any register, which also receives the result of the operation. The second operand is also any register or an 8-bit constant value. Flags are affected by this operation. The SUB instruction does not use the CARRY as an input, and therefore there is no need to condition the flags before use.

The CARRY flag, when set, indicates when an underflow (borrow) occurred.

**Examples**

Operand is a register location, sY, or an immediate byte-wide constant, kk.

\[
\begin{align*}
\text{SUB } sX, sY; & \text{ Subtract register. } sX = sX - sY. \\
\text{SUB } sX, kk; & \text{ Subtract immediate. } sX = sX - kk.
\end{align*}
\]

**Description**

Operand is subtracted from register sX. The ZERO and CARRY flags are set appropriately.
Pseudocode

\[ sX \leftarrow (sX - \text{Operand}) \mod 256; \text{always an 8-bit result} \]

if \((sX - \text{Operand}) < 0\) then
  \(\text{CARRY} \leftarrow 1\)
else
  \(\text{CARRY} \leftarrow 0\)
endif

if \((sX - \text{Operand}) = 0\) then
  \(\text{ZERO} \leftarrow 1\)
else
  \(\text{ZERO} \leftarrow 0\)
endif

\(\text{PC} \leftarrow \text{PC} + 1\)

Registers/Flags Altered
- Registers: \(sX, \text{PC}\)
- Flags: \(\text{CARRY}, \text{ZERO}\)

SUBCY \(sX, \text{Operand}\) —Subtract Operand from Register \(sX\) with Borrow

The SUBCY instruction performs an 8-bit subtraction of two operands and subtracts an additional ‘1’ if the CARRY (borrow) flag was set by a previous instruction, as shown in Figure C-10. The first operand is any register, which also receives the result of the operation. The second operand is also any register or an 8-bit constant value. Flags are affected by this operation.

Examples

Operand is a register location, \(sY\), or an immediate byte-wide constant, \(kk\).

- \(\text{SUBCY } sX, sY; \text{ Subtract register. } sX = sX - sY - \text{CARRY}\)
- \(\text{SUBCY } sX, kk; \text{ Subtract immediate. } sX = sX - kk - \text{CARRY}\)
SUBCY sX, Operand — Subtract Operand from Register sX with Borrow

Description
Operand and CARRY flag are subtracted from register sX. The ZERO and CARRY flags are set appropriately.

Pseudocode
if (CARRY = 1) then
    sX ← (sX - Operand - 1) mod 256; always an 8-bit result
else
    sX ← (sX - Operand) mod 256 ; always an 8-bit result
endif

if ( (sX - Operand - CARRY) < 0 ) then
    CARRY ← 1
else
    CARRY ← 0
endif

if ( ((sX - Operand - CARRY) = 0) or ((sX - Operand - CARRY) = -256) ) then
    ZERO ← 1
else
    ZERO ← 0
endif

PC ← PC + 1

Registers/Flags Altered
Registers: sX
Flags: CARRY, ZERO

Notes
pBlazIDE Equivalent: SUBC
TEST sX, Operand — Test Bit Location in Register sX, Generate Odd Parity

The TEST instruction performs two related but separate operations. The ZERO flag indicates the result of a bitwise logical AND operation between register sX and the specified Operand. The ZERO flag is set if the resulting bitwise AND is zero, as shown in Figure C-11. The CARRY flag indicates the XOR of the result, as shown in Figure C-12, which behaves like an odd parity generator.

Examples

TEST sX, sY ; Test register sX using register sY as the test mask
TEST sX, kk ; Test register sX using the immediate constant kk as the ; test mask
Pseudocode

; logically AND the corresponding bits in sX and the Operand
for (i=0; i<= 7; i=i+1)
{
    AND_TEST(i) ← sX(i) AND Operand(i)
}

if (AND_TEST = 0) then
    ZERO ← 1
else
    ZERO ← 0
end if

; logically XOR the corresponding bits in sX and the Operand
XOR_TEST = 0
for (i=0; i<= 7; i=i+1)
{
    XOR_TEST ← AND_TEST(i) XOR XOR_TEST
}

if (XOR_TEST = 1) then; generate odd parity
    CARRY ← 1 ; odd number of one’s, CARRY=1 for odd parity
else
    CARRY ← 0 ; even number of one’s, CARRY=0 for odd parity
end if

PC ← PC + 1

Registers/Flags Altered

Registers: PC
Flags: ZERO, CARRY

The TEST instruction is only supported on PicoBlaze microcontrollers for Spartan-3, Virtex-II, and Virtex-II Pro FPGAs.
XOR sX, Operand — Logical Bitwise XOR Register sX with Operand

The XOR instruction performs a bitwise logical XOR operation between two operands, as shown in Figure C-13. The first operand is any register, which also receives the result of the operation. A second operand is also any register or an 8-bit immediate constant. The ZERO flag is set if the resulting value is zero. The CARRY flag is always cleared by an XOR instruction.

The XOR operation inverts bits contained in a register, which is used in forming control signals.

Examples

XOR sX, sY ; Logically XOR the individual bits of register sX with ; the corresponding bits in register sY
XOR sX, kk ; Logically XOR the individual bits of register sX with ; the corresponding bits in the immediate constant kk

Pseudocode

; logically XOR the corresponding bits in sX and the Operand
for (i=0; i<= 7; i=i+1)
{
    sX(i) ← sX(i) XOR Operand(i)
}

CARRY ← 0

if (sX = 0) then
    ZERO ← 1
else
    ZERO ← 0
end if

PC ← PC + 1

Registers/Flags Altered

Registers: sX, PC
Flags: ZERO, CARRY is always 0

Figure C-13: XOR Operation

The XOR operation inverts bits contained in a register, which is used in forming control signals.
### Appendix D

# Instruction Codes

Table D-1 provides the 18-bit instruction code for every PicoBlaze™ processor instruction.

| Instruction   | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  | 0  |
|---------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| ADD sX,kk     | 0  | 1  | 1  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  |
| ADD sX,sY     | 0  | 1  | 1  | 0  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  |
| ADDCY sX,kk   | 0  | 1  | 1  | 0  | 1  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  | k  |
| ADDCY sX,sY   | 0  | 1  | 1  | 0  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  | 0  |
| AND sX,kk     | 0  | 0  | 1  | 0  | 1  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  | k  |
| AND sX,sY     | 0  | 0  | 1  | 0  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  | 0  |
| CALL          | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | a  | a  | a  | a  | a  | a  | a  | a  |
| CALL C        | 1  | 1  | 0  | 0  | 0  | 1  | 1  | 0  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| CALL NC       | 1  | 1  | 0  | 0  | 0  | 1  | 1  | 1  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| CALL NZ       | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| CALL Z        | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 0  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| COMPARE sX,kk | 0  | 1  | 0  | 1  | 0  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| COMPARE sX,sY | 0  | 1  | 0  | 1  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  | 0  |
| DISABLE INTERRUPT | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| ENABLE INTERRUPT | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| FETCH sX,ss   | 0  | 0  | 0  | 1  | 1  | 0  | x  | x  | x  | x  | 0  | 0  | s  | s  | s  | s  | s  | s  | s  |
| FETCH sX,(sY) | 0  | 0  | 0  | 1  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  | 0  |
| INPUT sX,(sY) | 0  | 0  | 0  | 1  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | 0  | 0  | 0  | 0  | 0  |
| INPUT sX,pp   | 0  | 0  | 0  | 1  | 0  | 0  | x  | x  | x  | x  | p  | p  | p  | p  | p  | p  | p  | p  |
| JUMP          | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 0  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| JUMP C        | 1  | 1  | 0  | 1  | 0  | 1  | 1  | 0  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| JUMP NC       | 1  | 1  | 0  | 1  | 0  | 1  | 1  | 1  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| JUMP NZ       | 1  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |

Table D-1: PicoBlaze Instruction Codes
### Table D-1: PicoBlaze Instruction Codes (Continued)

| Instruction | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  | 0  |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| JUMP Z      | 1  | 1  | 0  | 1  | 0  | 1  | 0  | 0  | a  | a  | a  | a  | a  | a  | a  | a  | a  | a  |
| LOAD sX,kk  | 0  | 0  | 0  | 0  | 0  | 1  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| LOAD sX,sY  | 0  | 0  | 0  | 0  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| OR sX,kk    | 0  | 0  | 1  | 1  | 0  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| OR sX,sY    | 0  | 0  | 1  | 1  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| OUTPUT sX,(sY) | 1  | 0  | 1  | 1  | 0  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| OUTPUT sX,pp | 1  | 0  | 1  | 1  | 0  | 0  | x  | x  | x  | x  | p  | p  | p  | p  | p  | p  | p  | p  |
| RETURN      | 1  | 0  | 1  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURN C    | 1  | 0  | 1  | 0  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURN NC   | 1  | 0  | 1  | 0  | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURN NZ   | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURN Z    | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURNI DISABLE | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RETURNI ENABLE | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| RL sX       | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  |
| RR sX       | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 1  | 1  | 0  | 0  |
| SL0 sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 1  | 0  |
| SL1 sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 1  | 1  |
| SLA sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| SLX sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  |
| SR0 sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 1  | 1  | 1  | 0  |
| SR1 sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 1  | 1  |
| SRA sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  |
| SRX sX      | 1  | 0  | 0  | 0  | 0  | 0  | x  | x  | x  | x  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 1  |
| STORE sX, ss| 1  | 0  | 1  | 1  | 1  | 1  | 0  | x  | x  | x  | x  | 0  | 0  | s  | s  | s  | s  | s  |
| STORE sX,(sY) | 1  | 0  | 1  | 1  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| SUB sX,kk   | 0  | 1  | 1  | 1  | 1  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| SUB sX,sY   | 0  | 1  | 1  | 1  | 1  | 0  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| SUBCY sX,kk | 0  | 1  | 1  | 1  | 1  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| SUBCY sX,sY | 0  | 1  | 1  | 1  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
| TEST sX,kk  | 0  | 1  | 0  | 0  | 1  | 0  | x  | x  | x  | x  | k  | k  | k  | k  | k  | k  | k  | k  |
| TEST sX,sY  | 0  | 1  | 0  | 0  | 1  | 1  | x  | x  | x  | x  | y  | y  | y  | y  | y  | y  | y  | y  |
### Table D-1:  PicoBlaze Instruction Codes (Continued)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>17</th>
<th>16</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>XOR sX,kk</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>k</td>
<td>k</td>
<td>k</td>
<td>k</td>
<td>k</td>
<td>k</td>
<td>k</td>
<td>k</td>
</tr>
<tr>
<td>XOR sX,sY</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **a**: Absolute instruction address
- **x**: Register sX
- **y**: Register sY
- **k**: Immediate constant
- **p**: Port address
- **s**: Scratchpad RAM address
Register and Scratchpad RAM Planning Worksheets

This appendix provides worksheets to plan register assignment and allocation for a PicoBlaze™ processor application. A similar worksheet is also provided to plan scratchpad RAM assignment and allocation.

Registers

<table>
<thead>
<tr>
<th>Reg.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>s0</td>
<td></td>
</tr>
<tr>
<td>s1</td>
<td></td>
</tr>
<tr>
<td>s2</td>
<td></td>
</tr>
<tr>
<td>s3</td>
<td></td>
</tr>
<tr>
<td>s4</td>
<td></td>
</tr>
<tr>
<td>s5</td>
<td></td>
</tr>
<tr>
<td>s6</td>
<td></td>
</tr>
<tr>
<td>s7</td>
<td></td>
</tr>
<tr>
<td>s8</td>
<td></td>
</tr>
<tr>
<td>s9</td>
<td></td>
</tr>
<tr>
<td>sA</td>
<td></td>
</tr>
<tr>
<td>sB</td>
<td></td>
</tr>
<tr>
<td>sC</td>
<td></td>
</tr>
<tr>
<td>sD</td>
<td></td>
</tr>
<tr>
<td>sE</td>
<td></td>
</tr>
<tr>
<td>sF</td>
<td></td>
</tr>
</tbody>
</table>
## Scratchpad RAM

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Description</th>
<th>Loc.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>01</td>
<td></td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td></td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td></td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>07</td>
<td></td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td></td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>0A</td>
<td></td>
<td>2A</td>
<td></td>
</tr>
<tr>
<td>0B</td>
<td></td>
<td>2B</td>
<td></td>
</tr>
<tr>
<td>0C</td>
<td></td>
<td>2C</td>
<td></td>
</tr>
<tr>
<td>0D</td>
<td></td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>0E</td>
<td></td>
<td>2E</td>
<td></td>
</tr>
<tr>
<td>0F</td>
<td></td>
<td>2F</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td></td>
<td>3A</td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td></td>
<td>3B</td>
<td></td>
</tr>
<tr>
<td>1C</td>
<td></td>
<td>3C</td>
<td></td>
</tr>
<tr>
<td>1D</td>
<td></td>
<td>3D</td>
<td></td>
</tr>
<tr>
<td>1E</td>
<td></td>
<td>3E</td>
<td></td>
</tr>
<tr>
<td>1F</td>
<td></td>
<td>3F</td>
<td></td>
</tr>
</tbody>
</table>