

PicoBlaze 8-bit Embedded Microcontroller User Guide

*for Spartan-3, Virtex-II, and
Virtex-II Pro FPGAs*

UG129 (v1.1.2) June 24, 2008

PicoBlazeTM





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 HEREUNDER FOR USE OF THE DESIGN. YOU ACKNOWLEDGE THAT THE FEES, IF ANY, REFLECT THE ALLOCATION OF RISK SET FORTH IN THIS AGREEMENT ^{cc} 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...

	Version	Revision
05/20/04	1.0	Initial Xilinx release.
06/10/04	1.1	Various minor corrections, updates, and enhancements throughout.
11/21/05	1.1.1	Minor updates.
06/24/08	1.1.2	Corrected typo in example for “LOAD sX, Operand — Load Register sX with Operand”. Updated trademarks and links.

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.



About This Guide

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

2: 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
Repertitioning 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

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.

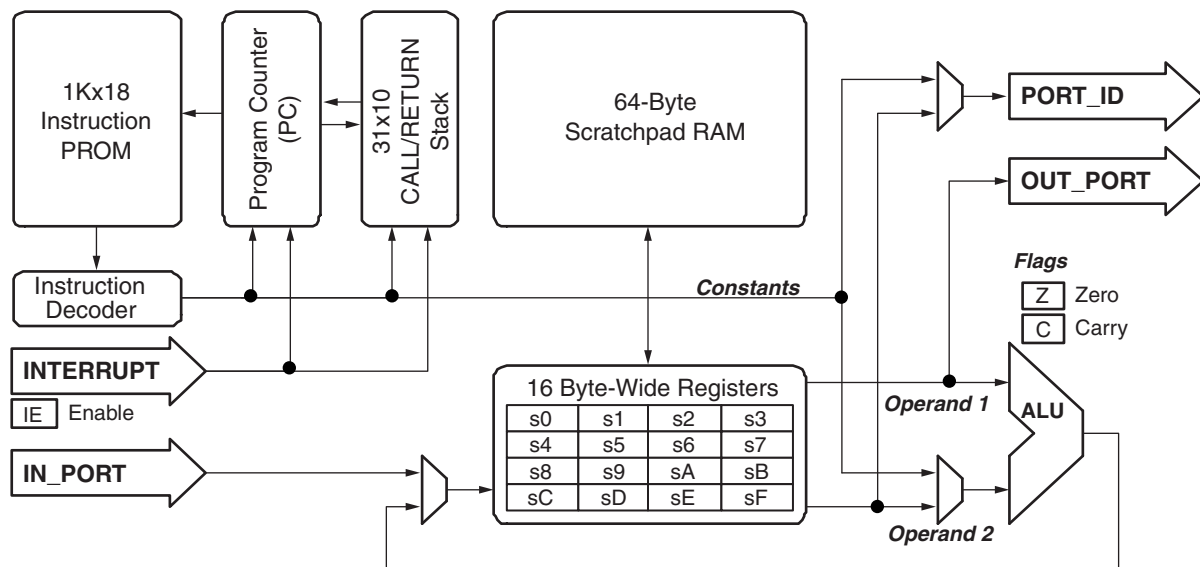
The various PicoBlaze code examples throughout this application note are written for the Xilinx KCPSM3 assembler. The Mediatronix pBlazIDE assembler has a code import function that reads the KCPSM3 syntax.

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

- 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



UG129_c1_01_051204

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.

The data registers and scratchpad RAM are not affected by Reset.

See “RESET Event” in Appendix C for more information.

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 1-1: PicoBlaze Microcontroller Embedded within an FPGA Provides the Optimal Balance between Microcontroller and FPGA Solutions

	PicoBlaze Microcontroller	FPGA Logic
Strengths	<ul style="list-style-type: none"> • Easy to program, excellent for control and state machine applications • Resource requirements remain constant with increasing complexity • Re-uses logic resources, excellent for lower-performance functions 	<ul style="list-style-type: none"> • Significantly higher performance • Excellent at parallel operations • Sequential vs. parallel implementation trade-offs optimize performance or cost • Fast response to multiple, simultaneous inputs
Weaknesses	<ul style="list-style-type: none"> • Executes sequentially • Performance degrades with increasing complexity • Program memory requirements increase with increasing complexity • Slower response to simultaneous inputs 	<ul style="list-style-type: none"> • Control and state machine applications more difficult to program • Logic resources grow with increasing complexity

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.

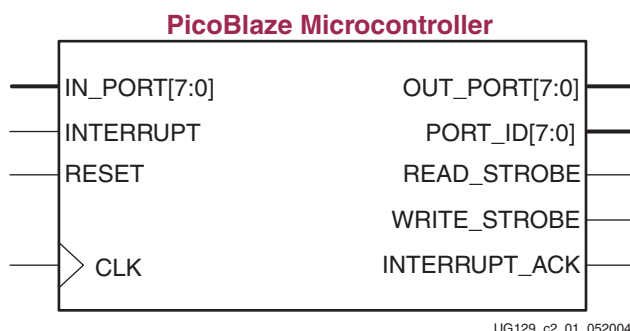


Figure 2-1: PicoBlaze Interface Connections

Table 2-1: PicoBlaze Interface Signal Descriptions

Signal	Direction	Description
IN_PORT[7:0]	Input	Input Data Port: Present valid input data on this port during an INPUT instruction. The data is captured on the rising edge of CLK.
INTERRUPT	Input	Interrupt Input: 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.
RESET	Input	Reset Input: 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.
CLK	Input	Clock Input: 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.
OUT_PORT[7:0]	Output	Output Data Port: 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.

Table 2-1: PicoBlaze Interface Signal Descriptions (*Continued*)

Signal	Direction	Description
PORT_ID[7:0]	Output	Port Address: The I/O port address appears on this port for two CLK cycles during an INPUT or OUTPUT instruction.
READ_STROBE	Output	Read Strobe: 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.
WRITE_STROBE	Output	Write Strobe: 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.
INTERRUPT_ACK	Output	Interrupt Acknowledge: 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.

PicoBlaze Instruction Set



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 3-1: PicoBlaze Instruction Set (alphabetical listing)

Instruction	Description	Function	ZERO	CARRY
ADD sX, kk	Add register sX with literal kk	$sX \leftarrow sX + kk$?	?
ADD sX, sY	Add register sX with register sY	$sX \leftarrow sX + sY$?	?
ADDCY sX, kk (ADDC)	Add register sX with literal kk with CARRY bit	$sX \leftarrow sX + kk + \text{CARRY}$?	?
ADDCY sX, sY (ADDC)	Add register sX with register sY with CARRY bit	$sX \leftarrow sX + sY + \text{CARRY}$?	?
AND sX, kk	Bitwise AND register sX with literal kk	$sX \leftarrow sX \text{ AND } kk$?	0
AND sX, sY	Bitwise AND register sX with register sY	$sX \leftarrow sX \text{ AND } sY$?	0
CALL aaa	Unconditionally call subroutine at aaa	$\text{TOS} \leftarrow \text{PC}$ $\text{PC} \leftarrow \text{aaa}$	-	-
CALL C, aaa	If CARRY flag set, call subroutine at aaa	If $\text{CARRY}=1$, $\{\text{TOS} \leftarrow \text{PC}, \text{PC} \leftarrow \text{aaa}\}$	-	-
CALL NC, aaa	If CARRY flag not set, call subroutine at aaa	If $\text{CARRY}=0$, $\{\text{TOS} \leftarrow \text{PC}, \text{PC} \leftarrow \text{aaa}\}$	-	-
CALL NZ, aaa	If ZERO flag not set, call subroutine at aaa	If $\text{ZERO}=0$, $\{\text{TOS} \leftarrow \text{PC}, \text{PC} \leftarrow \text{aaa}\}$	-	-
CALL Z, aaa	If ZERO flag set, call subroutine at aaa	If $\text{ZERO}=1$, $\{\text{TOS} \leftarrow \text{PC}, \text{PC} \leftarrow \text{aaa}\}$	-	-
COMPARE sX, kk (COMP)	Compare register sX with literal kk. Set CARRY and ZERO flags as appropriate. Registers are unaffected.	If $sX=kk$, $\text{ZERO} \leftarrow 1$ If $sX < kk$, $\text{CARRY} \leftarrow 1$?	?
COMPARE sX, sY (COMP)	Compare register sX with register sY. Set CARRY and ZERO flags as appropriate. Registers are unaffected.	If $sX=sY$, $\text{ZERO} \leftarrow 1$ If $sX < sY$, $\text{CARRY} \leftarrow 1$?	?
DISABLE INTERRUPT (DINT)	Disable interrupt input	$\text{INTERRUPT_ENABLE} \leftarrow 0$	-	-

Table 3-1: PicoBlaze Instruction Set (alphabetical listing)

Instruction	Description	Function	ZERO	CARRY
ENABLE INTERRUPT (EINT)	Enable interrupt input	$\text{INTERRUPT_ENABLE} \leftarrow 1$	-	-
Interrupt Event	Asynchronous interrupt input. Preserve flags and PC. Clear INTERRUPT_ENABLE flag. Jump to interrupt vector at address 3FF.	$\text{Preserved ZERO} \leftarrow \text{ZERO}$ $\text{Preserved CARRY} \leftarrow \text{CARRY}$ $\text{INTERRUPT_ENABLE} \leftarrow 0$ $\text{TOS} \leftarrow \text{PC}$ $\text{PC} \leftarrow 3\text{FF}$	-	-
FETCH sX, (sY) (FETCH sX, sY)	Read scratchpad RAM location pointed to by register sY into register sX	$\text{sX} \leftarrow \text{RAM}[(\text{sY})]$	-	-
FETCH sX, ss	Read scratchpad RAM location ss into register sX	$\text{sX} \leftarrow \text{RAM}[\text{ss}]$	-	-
INPUT sX, (sY) (IN sX, sY)	Read value on input port location pointed to by register sY into register sX	$\text{PORT_ID} \leftarrow \text{sY}$ $\text{sX} \leftarrow \text{IN_PORT}$	-	-
INPUT sX, pp (IN)	Read value on input port location pp into register sX	$\text{PORT_ID} \leftarrow \text{pp}$ $\text{sX} \leftarrow \text{IN_PORT}$	-	-
JUMP aaa	Unconditionally jump to aaa	$\text{PC} \leftarrow \text{aaa}$	-	-
JUMP C, aaa	If CARRY flag set, jump to aaa	If $\text{CARRY}=1$, $\text{PC} \leftarrow \text{aaa}$	-	-
JUMP NC, aaa	If CARRY flag not set, jump to aaa	If $\text{CARRY}=0$, $\text{PC} \leftarrow \text{aaa}$	-	-
JUMP NZ, aaa	If ZERO flag not set, jump to aaa	If $\text{ZERO}=0$, $\text{PC} \leftarrow \text{aaa}$	-	-
JUMP Z, aaa	If ZERO flag set, jump to aaa	If $\text{ZERO}=1$, $\text{PC} \leftarrow \text{aaa}$	-	-
LOAD sX, kk	Load register sX with literal kk	$\text{sX} \leftarrow \text{kk}$	-	-
LOAD sX, sY	Load register sX with register sY	$\text{sX} \leftarrow \text{sY}$	-	-
OR sX, kk	Bitwise OR register sX with literal kk	$\text{sX} \leftarrow \text{sX OR kk}$?	0
OR sX, sY	Bitwise OR register sX with register sY	$\text{sX} \leftarrow \text{sX OR sY}$?	0
OUTPUT sX, (sY) (OUT sX, sY)	Write register sX to output port location pointed to by register sY	$\text{PORT_ID} \leftarrow \text{sY}$ $\text{OUT_PORT} \leftarrow \text{sX}$	-	-
OUTPUT sX, pp (OUT sX, pp)	Write register sX to output port location pp	$\text{PORT_ID} \leftarrow \text{pp}$ $\text{OUT_PORT} \leftarrow \text{sX}$	-	-
RETURN (RET)	Unconditionally return from subroutine	$\text{PC} \leftarrow \text{TOS}+1$	-	-
RETURN C (RET C)	If CARRY flag set, return from subroutine	If $\text{CARRY}=1$, $\text{PC} \leftarrow \text{TOS}+1$	-	-
RETURN NC (RET NC)	If CARRY flag not set, return from subroutine	If $\text{CARRY}=0$, $\text{PC} \leftarrow \text{TOS}+1$	-	-
RETURN NZ (RET NZ)	If ZERO flag not set, return from subroutine	If $\text{ZERO}=0$, $\text{PC} \leftarrow \text{TOS}+1$	-	-
RETURN Z (RET Z)	If ZERO flag set, return from subroutine	If $\text{ZERO}=1$, $\text{PC} \leftarrow \text{TOS}+1$	-	-

Table 3-1: PicoBlaze Instruction Set (alphabetical listing)

Instruction	Description	Function	ZERO	CARRY
RETURNI DISABLE (RETI DISABLE)	Return from interrupt service routine. Interrupt remains disabled.	PC \leftarrow TOS ZERO \leftarrow Preserved ZERO CARRY \leftarrow Preserved CARRY INTERRUPT_ENABLE \leftarrow 0	?	?
RETURNI ENABLE (RETI ENABLE)	Return from interrupt service routine. Re-enable interrupt.	PC \leftarrow TOS ZERO \leftarrow Preserved ZERO CARRY \leftarrow Preserved CARRY INTERRUPT_ENABLE \leftarrow 1	?	?
RL sX	Rotate register sX left	sX \leftarrow {sX[6:0],sX[7]} CARRY \leftarrow sX[7]	?	?
RR sX	Rotate register sX right	sX \leftarrow {sX[0],sX[7:1]} CARRY \leftarrow sX[0]	?	?
SL0 sX	Shift register sX left, zero fill	sX \leftarrow {sX[6:0],0} CARRY \leftarrow sX[7]	?	?
SL1 sX	Shift register sX left, one fill	sX \leftarrow {sX[6:0],1} CARRY \leftarrow sX[7]	0	?
SLA sX	Shift register sX left through all bits, including CARRY	sX \leftarrow {sX[6:0],CARRY} CARRY \leftarrow sX[7]	?	?
SLX sX	Shift register sX left. Bit sX[0] is unaffected.	sX \leftarrow {sX[6:0],sX[0]} CARRY \leftarrow sX[7]	?	?
SR0 sX	Shift register sX right, zero fill	sX \leftarrow {0,sX[7:1]} CARRY \leftarrow sX[0]	?	?
SR1 sX	Shift register sX right, one fill	sX \leftarrow {1,sX[7:1]} CARRY \leftarrow sX[0]	0	?
SRA sX	Shift register sX right through all bits, including CARRY	sX \leftarrow {CARRY,sX[7:1]} CARRY \leftarrow sX[0]	?	?
SRX sX	Arithmetic shift register sX right. Sign extend sX. Bit sX[7] is unaffected.	sX \leftarrow {sX[7],sX[7:1]} CARRY \leftarrow sX[0]	?	?
STORE sX, (sY) (STORE sX, sY)	Write register sX to scratchpad RAM location pointed to by register sY	RAM[(sY)] \leftarrow sX	-	-
STORE sX, ss	Write register sX to scratchpad RAM location ss	RAM[ss] \leftarrow sX	-	-
SUB sX, kk	Subtract literal kk from register sX	sX \leftarrow sX - kk	?	?
SUB sX, sY	Subtract register sY from register sX	sX \leftarrow sX - sY	?	?
SUBCY sX, kk (SUBC)	Subtract literal kk from register sX with CARRY (borrow)	sX \leftarrow sX - kk - CARRY	?	?
SUBCY sX, sY (SUBC)	Subtract register sY from register sX with CARRY (borrow)	sX \leftarrow sX - sY - CARRY	?	?

Table 3-1: PicoBlaze Instruction Set (alphabetical listing)

Instruction	Description	Function	ZERO	CARRY
TEST sX, kk	Test bits in register sX against literal kk. Update CARRY and ZERO flags. Registers are unaffected.	If (sX AND kk) = 0, ZERO \leftarrow 1 CARRY \leftarrow odd parity of (sX AND kk)	?	?
TEST sX, sY	Test bits in register sX against register sY. Update CARRY and ZERO flags. Registers are unaffected.	If (sX AND sY) = 0, ZERO \leftarrow 1 CARRY \leftarrow odd parity of (sX AND sY)	?	?
XOR sX, kk	Bitwise XOR register sX with literal kk	sX \leftarrow sX XOR kk	?	0
XOR sX, sY	Bitwise XOR register sX with register sY	sX \leftarrow sX XOR sY	?	0

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

Address Space	Size (Depth x Width)	Addressing Modes	Instructions that Operate on Address Space
Instruction	1Kx18	Direct	<ul style="list-style-type: none"> • JUMP • CALL • RETURN • RETURNI • INTERRUPT event • RESET event <p>All others increment the PC to the next location</p>
Register File	16x8	Direct	<ul style="list-style-type: none"> • LOAD • AND • OR • XOR • TEST (read only) • ADD • ADDCY • SUB • SUBCY • COMPARE (read only) • SR0 • SR1 • SRX • SRA • RR • SL0 • SL1 • SLX • SLA • RL • INPUT • OUTPUT (read only) • STORE (read only) • FETCH
Scratchpad RAM	64x8	Direct Indirect	<ul style="list-style-type: none"> • STORE • FETCH
I/O	256x8	Direct Indirect	<ul style="list-style-type: none"> • INPUT • OUTPUT
CALL/RETURN Stack	31x10	N/A	<ul style="list-style-type: none"> • CALL • Enabled INTERRUPT event • RETURN • RETURNI • RESET event

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.

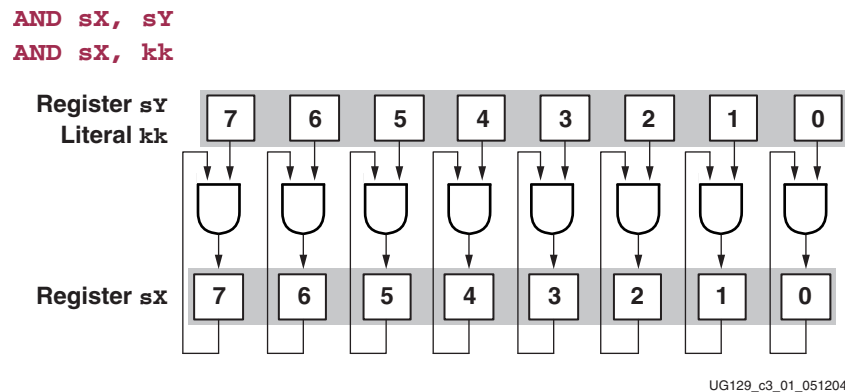


Figure 3-1: Bitwise AND Instruction

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](#).



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.

```
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.

```

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

See also:

- [“ADD sX, Operand —Add Operand to Register sX,” page 91](#)
- [“ADDCY sX, Operand —Add Operand to Register sX with Carry,” page 92](#)

SUB and SUBCY Subtract Instructions

The PicoBlaze microcontroller provides two subtract instructions, SUB and 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 SUBCY instruction is a subtract operation with borrow. If the CARRY flag is set, then SUBCY subtracts an additional one from the resulting difference.

The 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.

```

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](#)

Increment/Decrement

The PicoBlaze microcontroller does not have a dedicated increment or decrement instruction. However, adding or subtracting one using the ADD or SUB instructions provides the equivalent operation, as shown in [Figure 3-10](#).

```

ADD sX,01 ; increment register sX
SUB sX,01 ; decrement register sX

```

Figure 3-10: Incrementing and Decrementing a Register

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.

```

inc_16:
    ; increment low byte
    ADD lo_byte,01

    ; increment high byte only if CARRY bit set when incrementing low byte
    ADDCY hi_byte,00

```

Figure 3-11: Incrementing a 16-bit Value

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.

```

Negate:
    ; invert all bits in the register performing a one's complement
    XOR sX,FF
    ; add one to sX
    ADD sX,01
    RETURN

```

Figure 3-12: Destructive Negate (2's Complement) Function Overwrites Original Value

Another possible implementation that does not overwrite the value appears in Figure 3-13.

```

Negate:
    NAMEREG sY, value
    NAMEREG sX, complement
    ; Clear 'complement' to zero
    LOAD complement, 00
    ; subtract value from 0 to create two's complement
    SUB complement, value
    RETURN

```

Figure 3-13: Non-destructive Negate Function Preserves Original Value

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.

```

; Multiplier Routine (8-bit x 8-bit = 16-bit product)
; =====
; Shift and add algorithm
;
mult_8x8:
    NAMEREG s0, multiplicand    ; preserved
    NAMEREG s1, multiplier      ; preserved
    NAMEREG s2, bit_mask        ; modified
    NAMEREG s3, result_msb      ; most-significant byte (MSB) of result,
                                ; modified
    NAMEREG s4, result_lsb      ; least-significant byte (LSB) of result,
                                ; modified

    ;
    LOAD bit_mask, 01           ; start with least-significant bit (lsb)
    LOAD result_msb, 00         ; clear product MSB
    LOAD result_lsb, 00         ; clear product LSB (not required)
    ;
    ; loop through all bits in multiplier
mult_loop: TEST multiplier, bit_mask ; check if bit is set
            JUMP Z, no_add          ; if bit is not set, skip addition
            ;
            ADD result_msb, multiplicand ; addition only occurs in MSB
            ;
no_add:    SRA result_msb          ; shift MSB right, CARRY into bit 7,
                                ; lsb into CARRY
            SRA result_lsb        ; shift LSB right,
                                ; lsb from result_msb into bit 7
            ;
            SLO bit_mask          ; shift bit_mask left to examine
                                ; next bit in multiplier
            ;
            JUMP NZ, mult_loop     ; if all bit examined, then bit_mask = 0,
                                ; loop if not 0
            ;
            RETURN                ; multiplier result now available in
                                ; result_msb and result_lsb

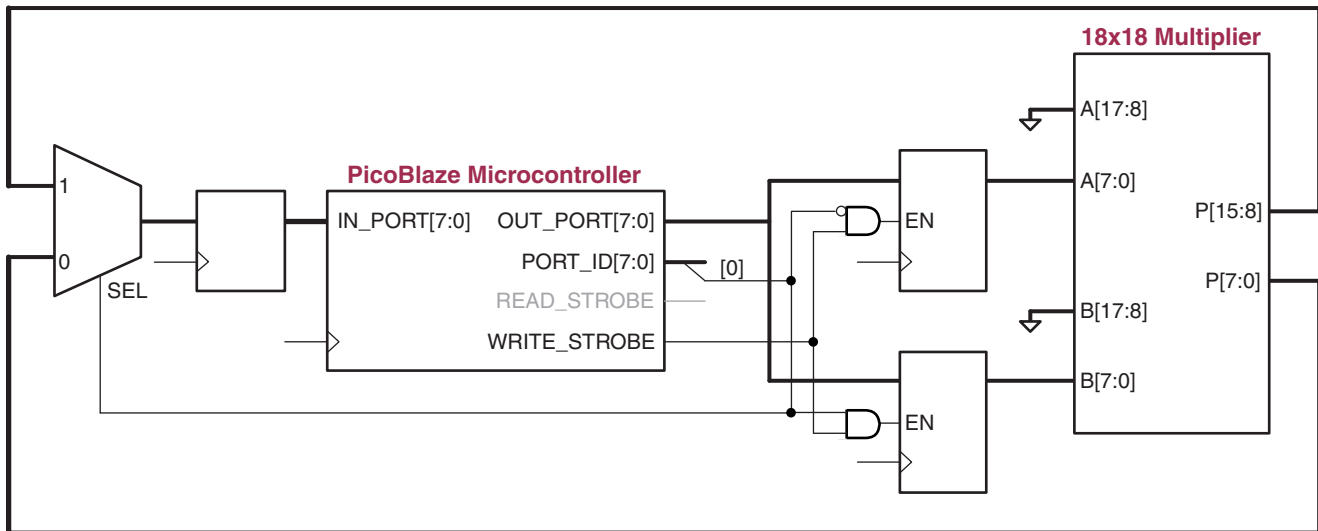
```

Figure 3-14: 8-bit by 8-bit Multiplier Routine Produces a 16-bit Product

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.



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.



UG129_c3_02_052004

Figure 3-15: 8-bit by 8-bit Hardware Multiplier Using the FPGA's 18x18 Multipliers

```

; Multiplier Routine (8-bit x 8-bit = 16-bit product)
; =====
; Connects to embedded 18x18 Hardware Multiplier via ports
;
mult_8x8io:
    NAMEREG s0, multiplicand    ; preserved
    NAMEREG s1, multiplier      ; preserved
    NAMEREG s3, result_msb      ; most-significant byte (MSB) of result, modified
    NAMEREG s4, result_lsb      ; least-significant byte (LSB) of result, modified
    ;
    ; Define the port ID numbers as constants for better clarity
    CONSTANT multiplier_lsb, 00
    CONSTANT multiplier_msb, 01
    ;
    ; Output multiplicand and multiplier to FPGA registers connected to the inputs of
    ; the embedded multiplier.
    OUTPUT multiplicand, multiplier_lsb
    OUTPUT multiplier, multiplier_msb
    ;
    ; Input the resulting product from the embedded multiplier.
    INPUT result_lsb, multiplier_lsb
    INPUT result_msb, multiplier_msb
    ;
    RETURN                      ; multiplier result now available in result_msb
                                ; and result_lsb

```

Figure 3-16: 8-bit by 8-bit Multiply Routine Using Hardware Multiplier

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.

```

; 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
    SLO 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:
    SRO 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 3-17: 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.

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.

```

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.

```
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.

```
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.

```
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.

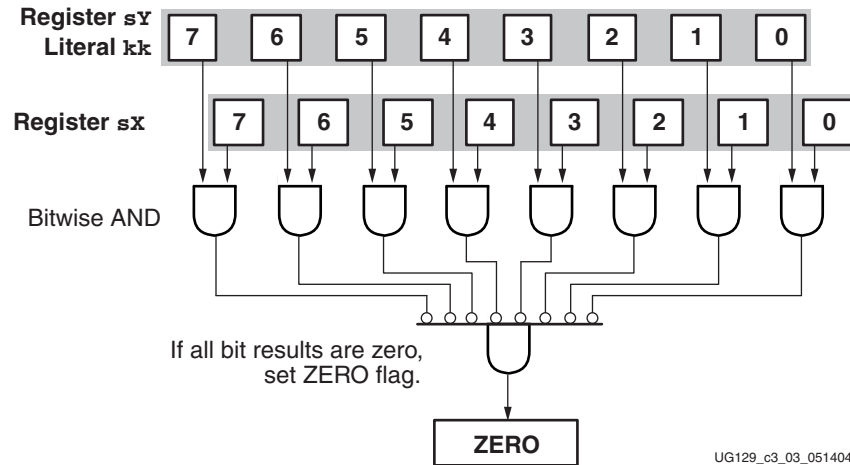


Figure 3-22: The TEST Instruction Affects the ZERO Flag

Each bit of register *sX* is logically ANDed with either the contents of register *sY* 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 *sX* is '1' as shown in the example in Figure 3-23.

```
LOAD s0, 05 ;    s0 = 00000101
TEST s0, 04 ;    mask = 00000100
                ; CARRY = 1, ZERO = 0
```

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

In a broader application, the CARRY bit generates the odd parity for the included bits in register *sX*, 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 *sX* is not included in the generated parity value. If a bit in the second operand is '1', then the corresponding bit in register *sX* is included in the final parity value.

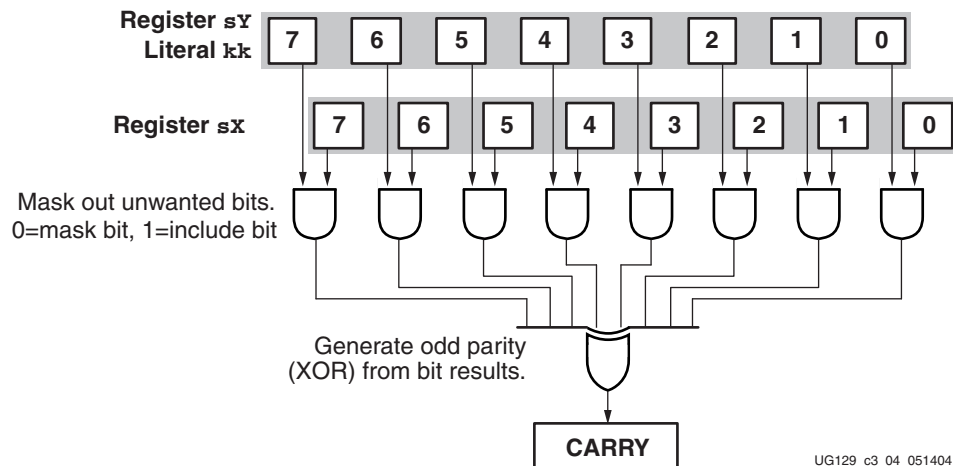


Figure 3-24: The TEST Instruction Affects the CARRY Flag

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 3-3: COMPARE Instruction Flag Operations

Flag	When Flag=0	When Flag=1
ZERO	Operand_1 \neq Operand_2	Operand_1 = Operand_2
CARRY	Operand_1 \geq Operand_2	Operand_1 < Operand_2

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.

Table 3-4: PicoBlaze Shift Instructions

	Shift Left		Shift Right
SL0	Shift Left with '0' fill. 	SR0	Shift Right with '0' fill. 
SL1	Shift Left with '1' fill. 	SR1	Shift Right with '1' fill. 
SLX	Shift Left, eXtend bit 0. 	SRX	Shift Right, sign eXtend. 
SLA	Shift Left through All bits, including CARRY. 	SRA	Shift Right through All bits, including CARRY. 



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

	Rotate Left		Rotate Right
RL		RR	

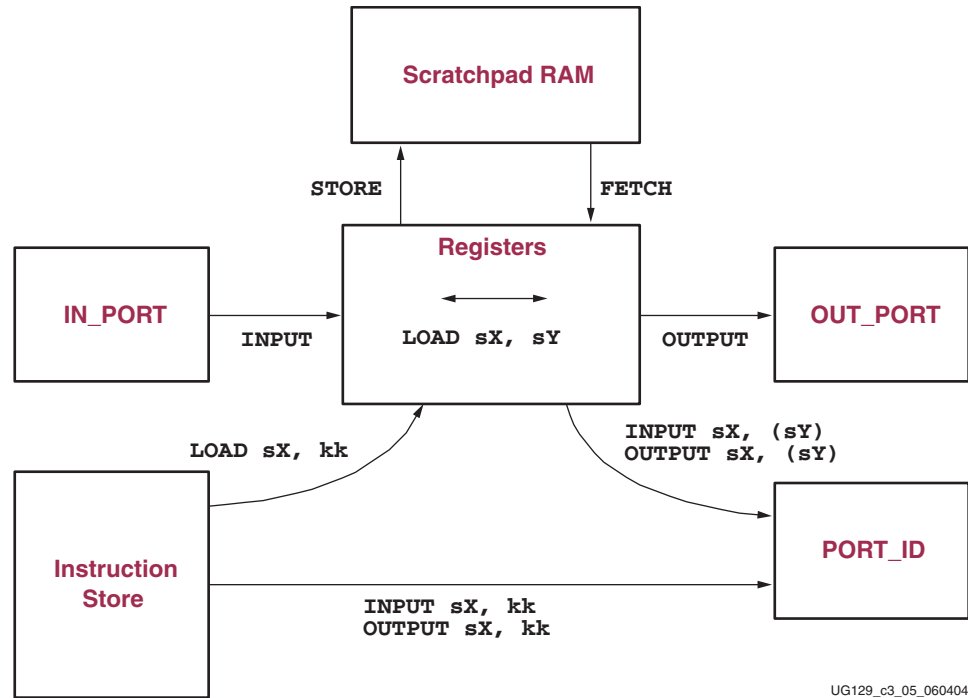
See also:

- “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.



UG129_c3_05_060404

Figure 3-26: Data Movement Instructions

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

Condition	Description
<none>	Always true. Execute instruction unconditionally.
C	CARRY = 1. Execute instruction if CARRY flag is set.
NC	CARRY = 0. Execute instruction if CARRY flag is cleared.
Z	ZERO = 1. Execute instruction if ZERO flag is set.
NZ	ZERO = 0. Execute instruction if ZERO flag is cleared.

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.

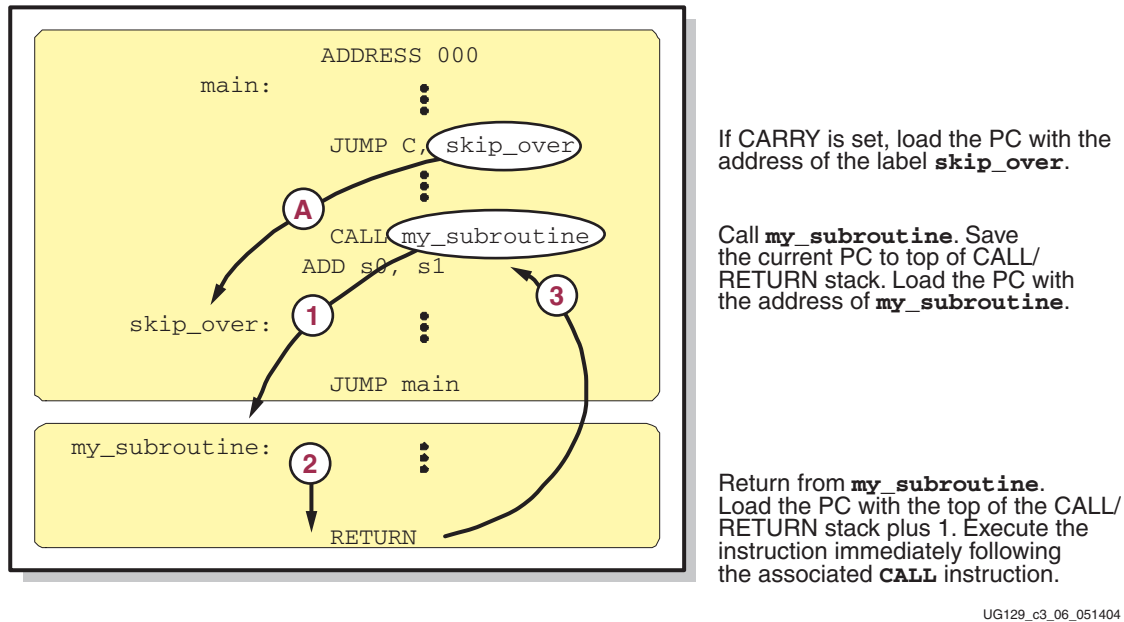


Figure 3-27: Example JUMP and CALL/RETURN Procedures

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.

CALL/RETURN

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

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](#)

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.

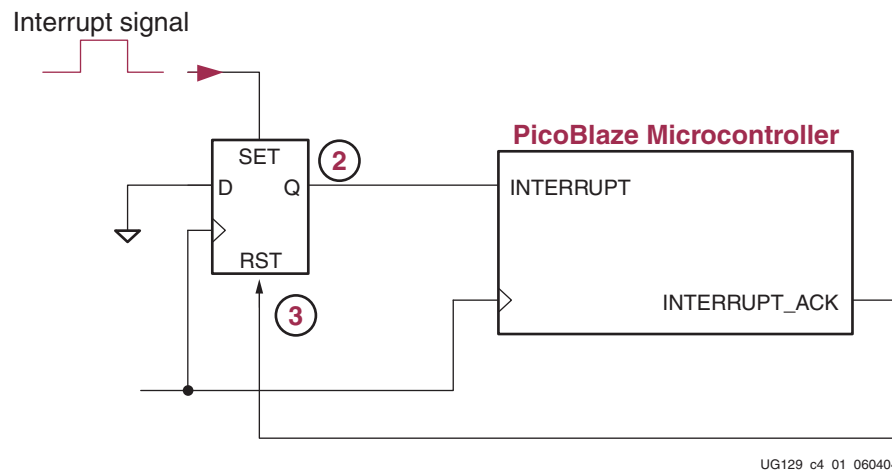


Figure 4-1: Simple Interrupt Logic

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).

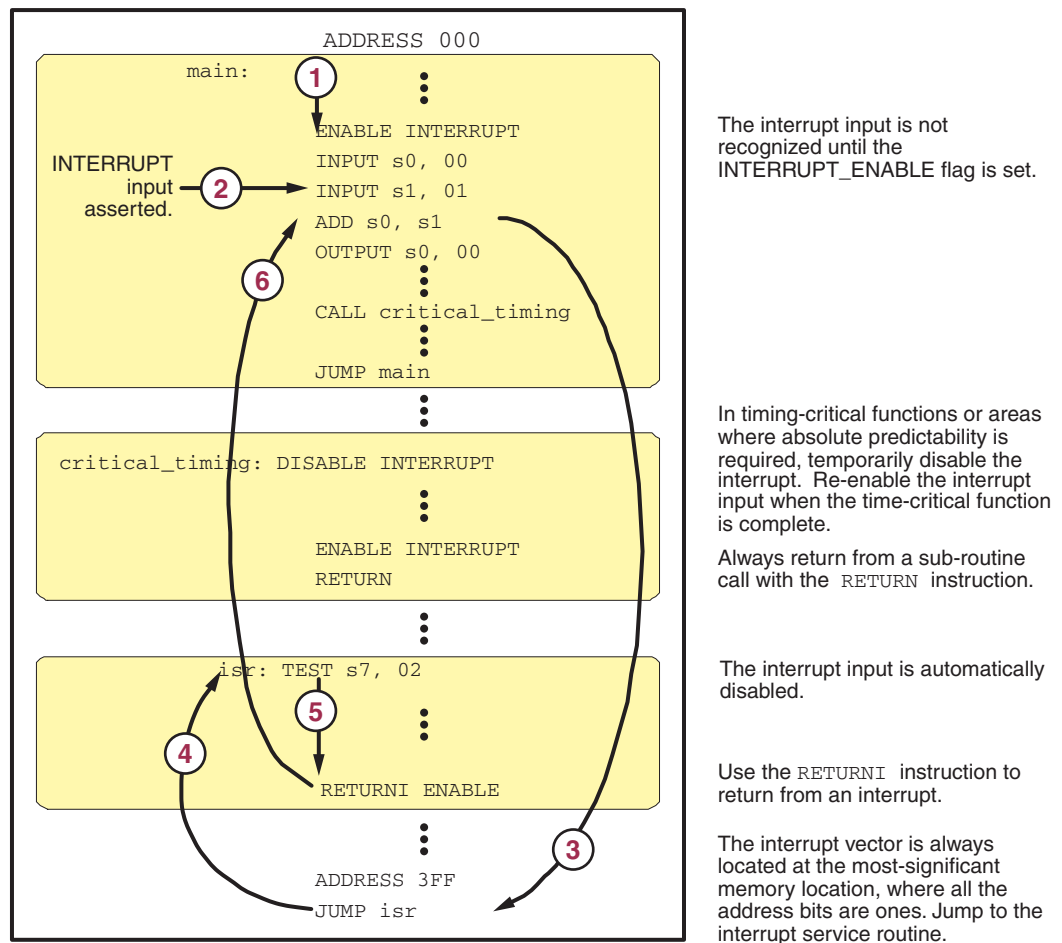
The PicoBlaze microcontroller automatically performs other functions. The interrupt process preserves the current ZERO and CARRY flag contents and disables any further interrupts. Likewise, the current program counter (PC) value is pushed onto the CALL/RETURN stack. Interrupts must remain disabled throughout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



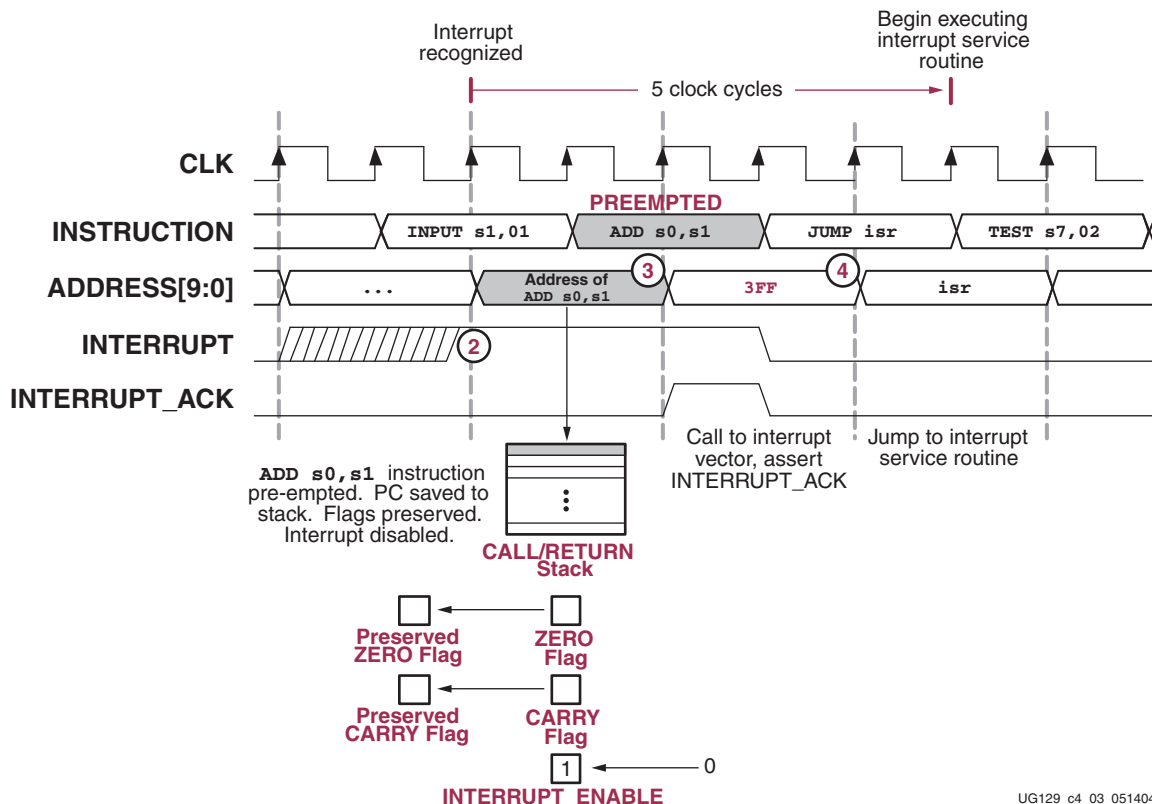
UG129_c4_02_051404

Figure 4-2: 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 ENABLE` 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.



UG129_c4_03_051404

Figure 4-3: Interrupt Timing Diagram

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.

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.

```

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

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.

```

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[F]

; 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 < 16
FETCH LED_output, (switch_value) ; look up LED pattern in RAM

OUTPUT LED_output, LEDs         ; display switch value on 7-segment LED
JUMP loop

```

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

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.

```

NAMEREG sF, stack_ptr ; reserve register sF for the stack pointer

; Initialize stack pointer to location 32 in the scratchpad RAM
LOAD sF, 20

my_subroutine:
; preserve register s0
CALL push_s0

; *** remainder of subroutine algorithm ***

; restore register s0
CALL pop_s0
RETURN

push_s0:
STORE s0, stack_ptr ; preserve register s0 onto "stack"
ADD stack_ptr, 01 ; increment stack pointer
RETURN

pop_s0:
SUB stack_ptr, 01 ; decrement stack pointer
FETCH s0, stack_ptr ; restore register s0 from "stack"
RETURN

```

Figure 5-4: Use Scratchpad RAM to Emulate PUSH and POP Stack Operations

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.

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.

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

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

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.

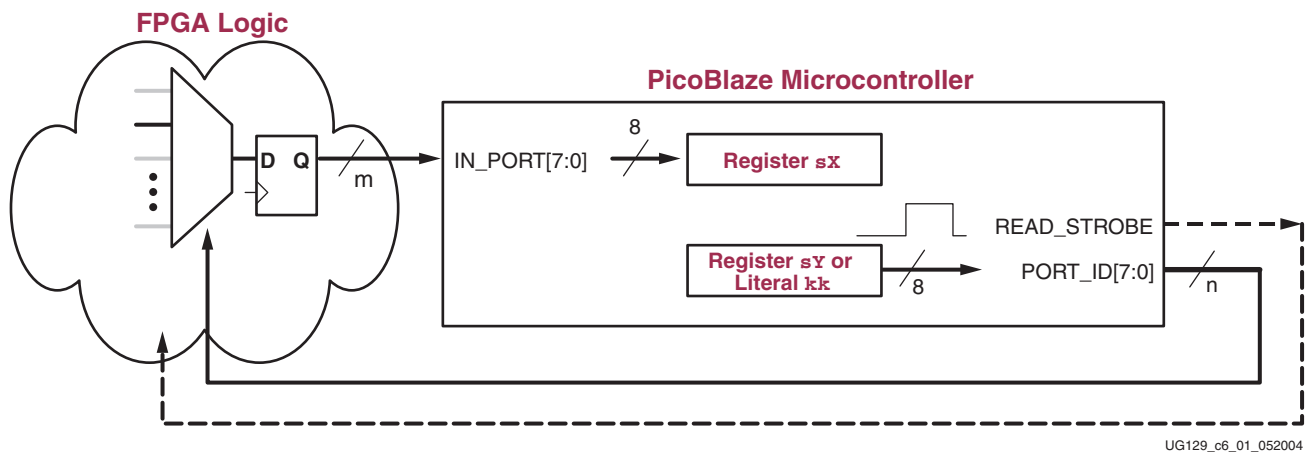


Figure 6-1: INPUT Operation and FPGA Interface Logic

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.

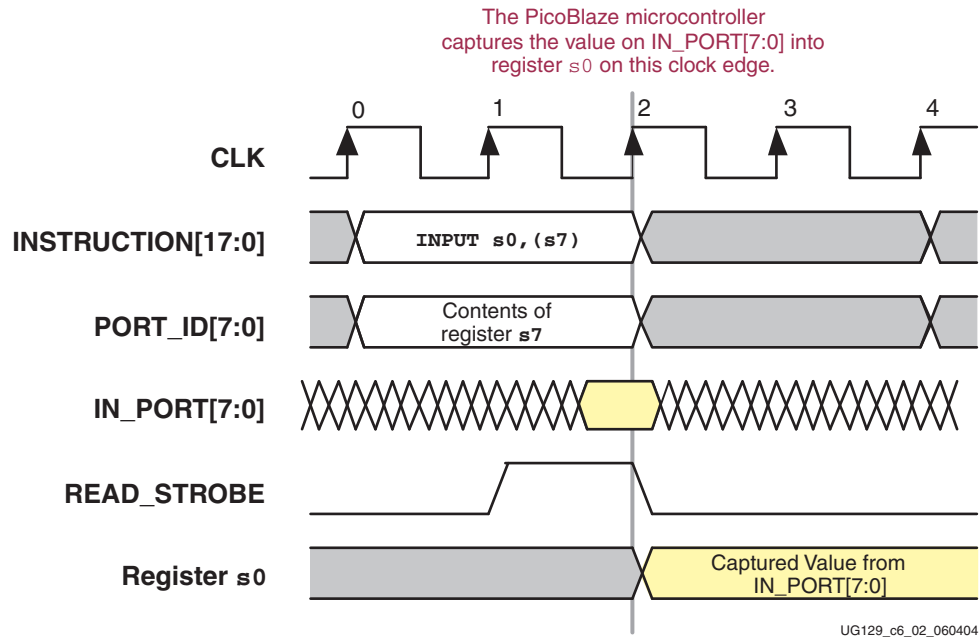


Figure 6-2: Port Timing for INPUT Instruction

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.

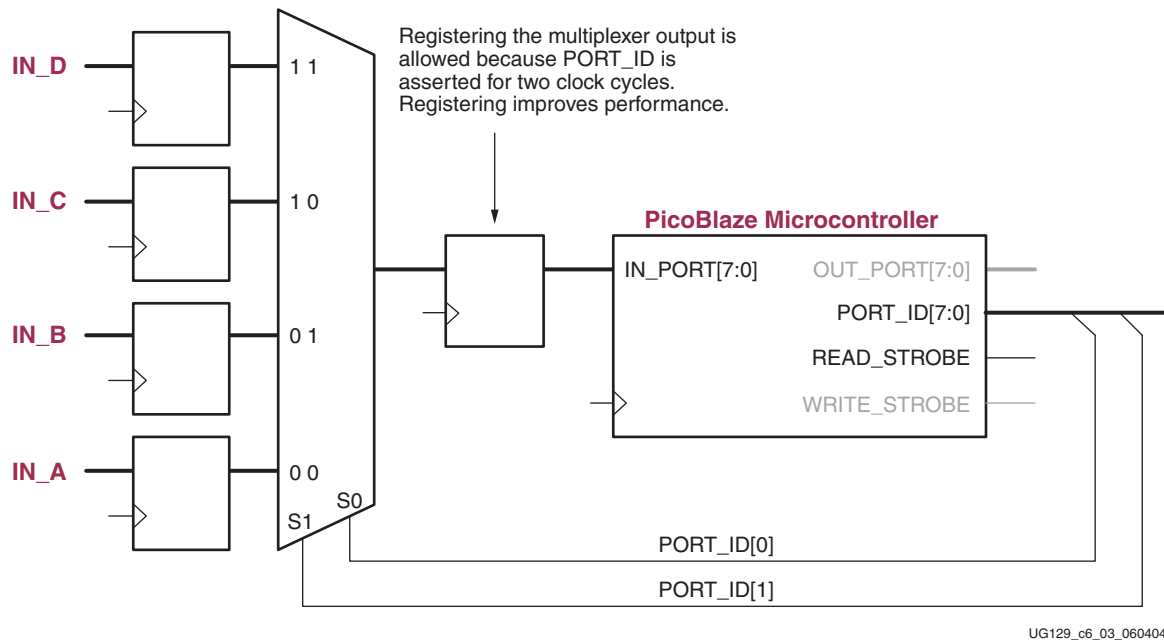


Figure 6-3: Multiplex Multiple Input Sources to Form a Single IN_PORT Port

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.

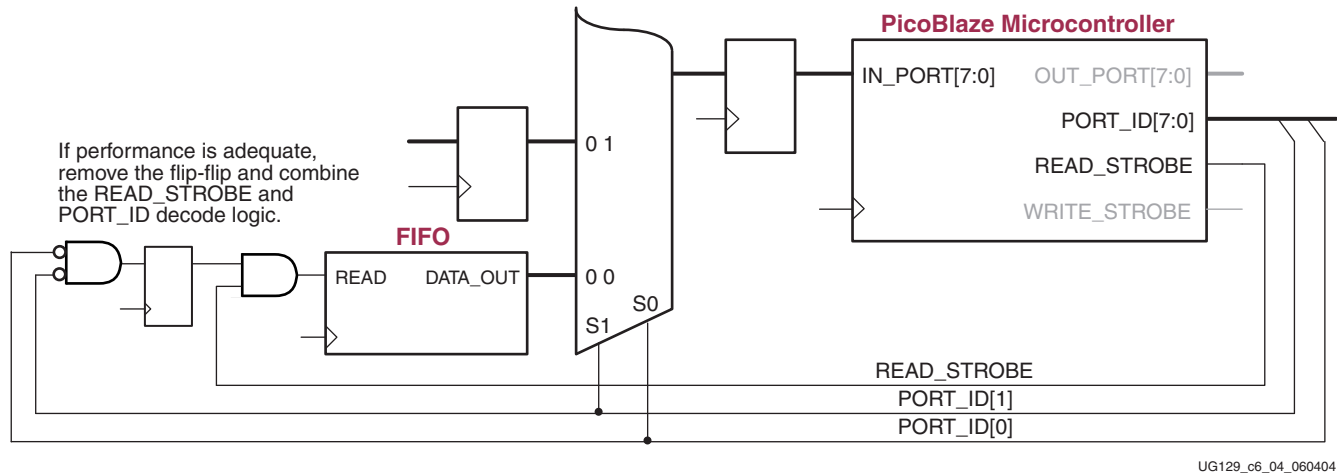


Figure 6-4: READ_STROBE Indicates a Successful INPUT Operation

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.

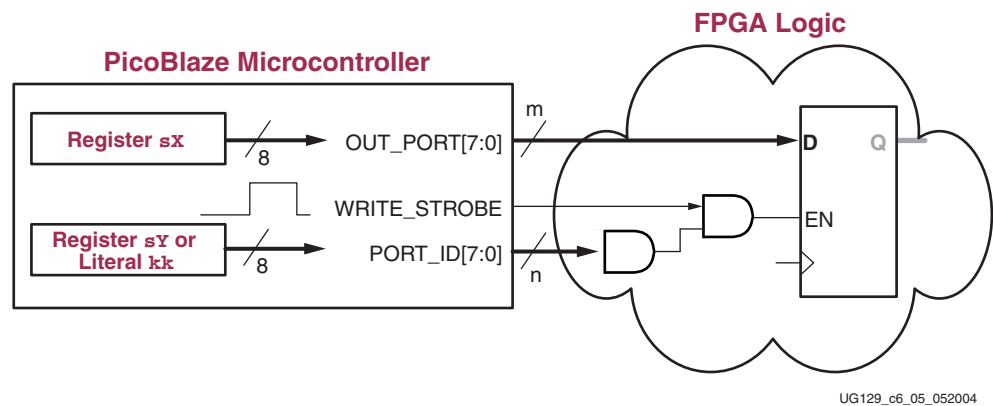


Figure 6-5: OUTPUT Operation and FPGA Interface

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.

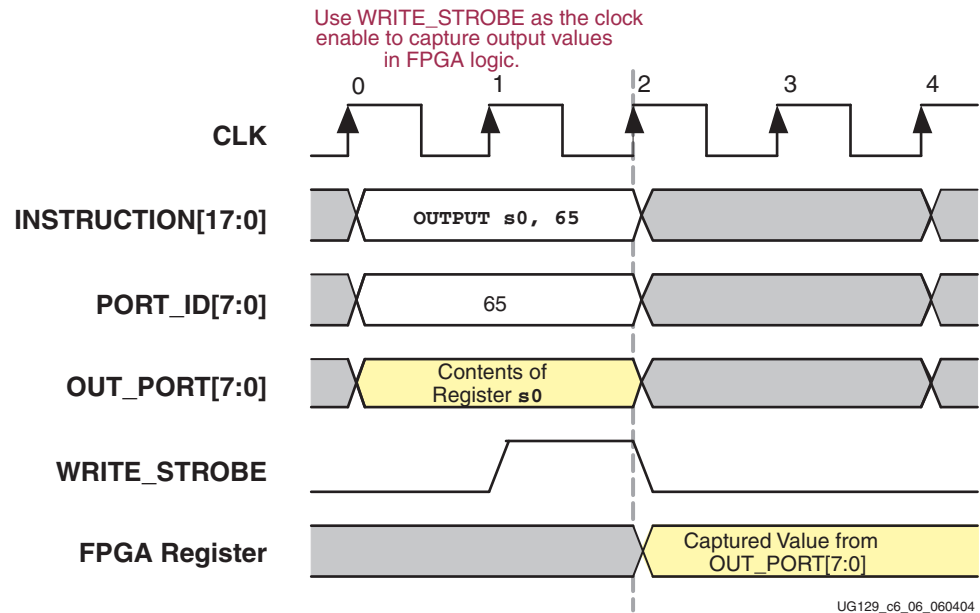
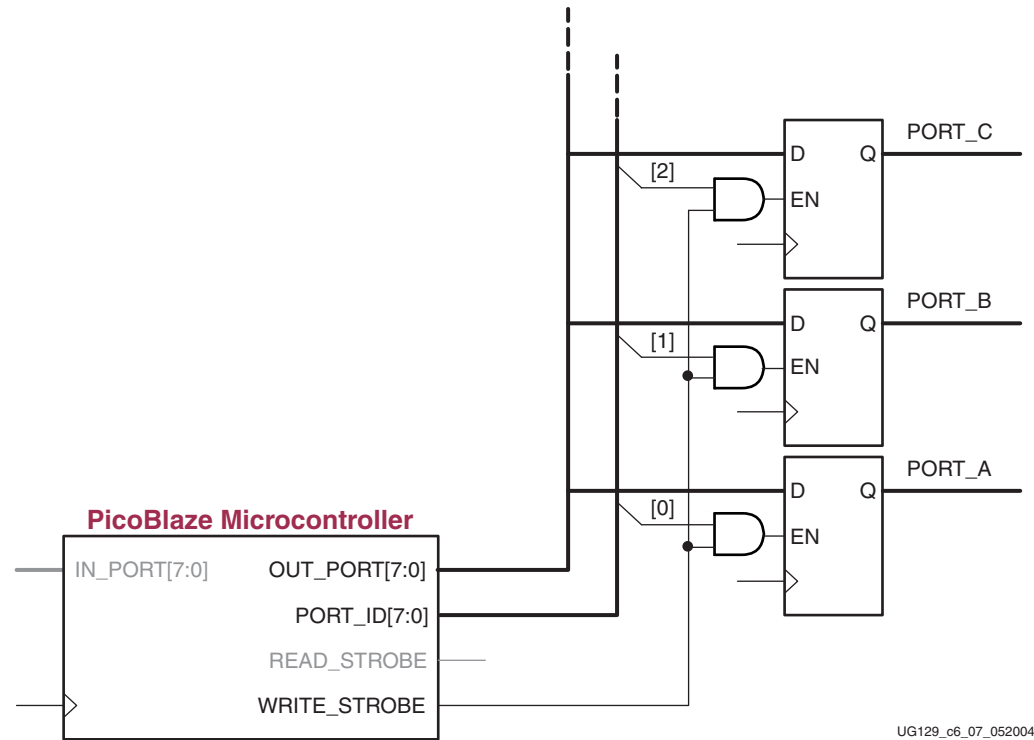


Figure 6-6: Port Timing for OUTPUT Instruction

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.



UG129_c6_07_052004

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

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.

```
; 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 6-8: 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.

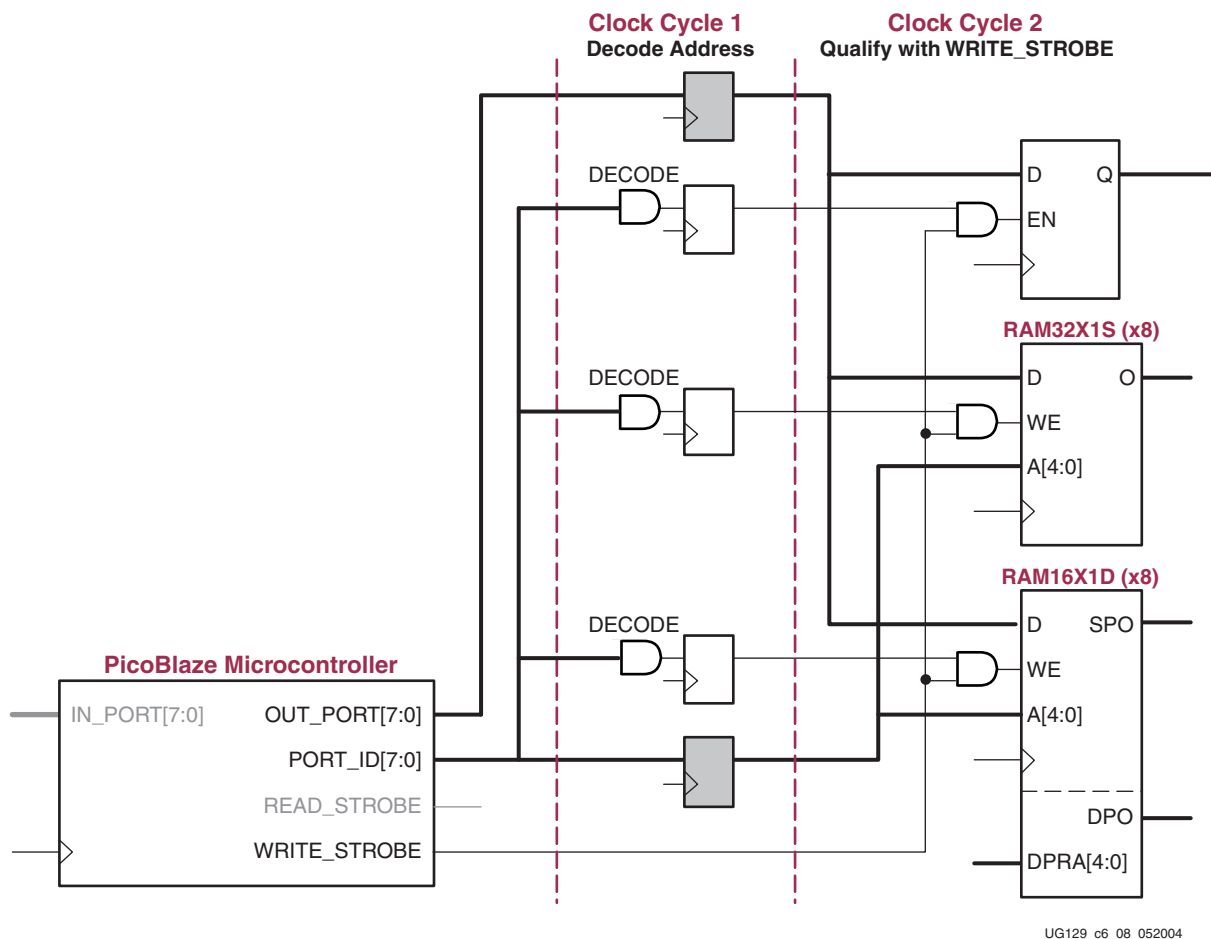
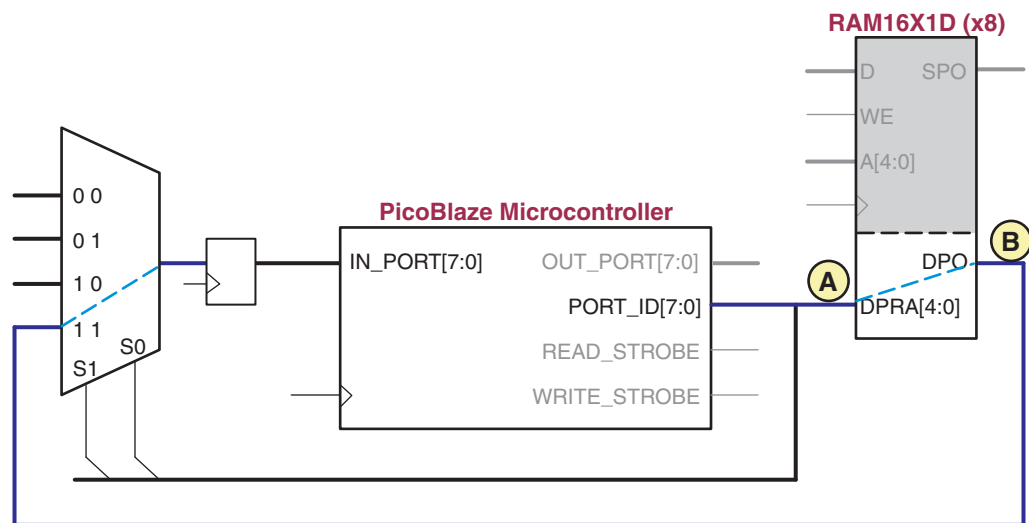


Figure 6-9: Pipelining the PORT_ID Decoding Improves Performance

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?

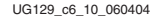


UG129_c6_09_052004

Figure 6-10: Without Pipelining, the Full Read Path Delay Can Reduce Performance

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.



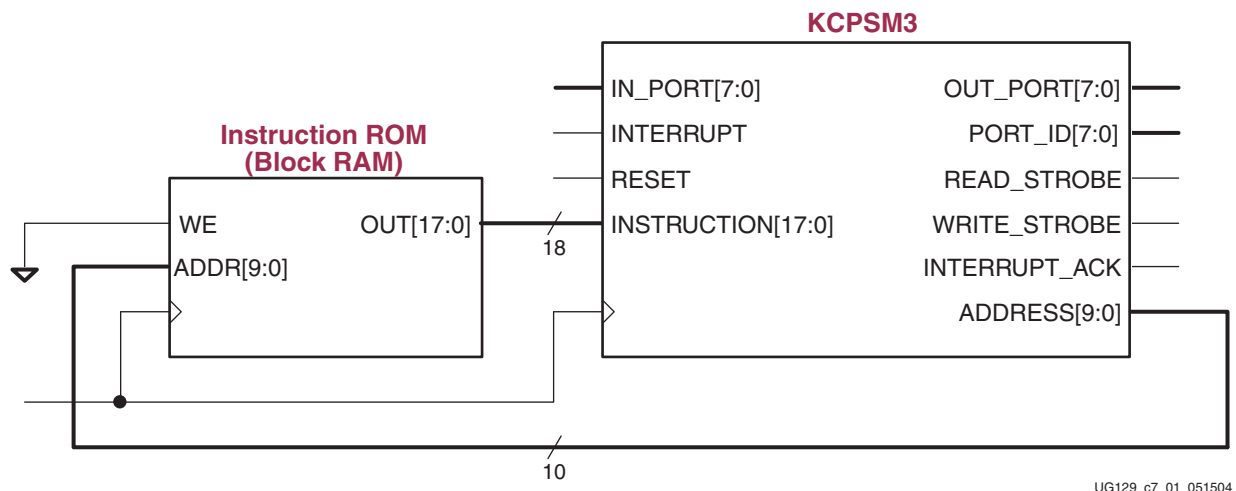
Repartitioning the Design for Maximum Performance

58

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.



UG129_c7_01_051504

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.

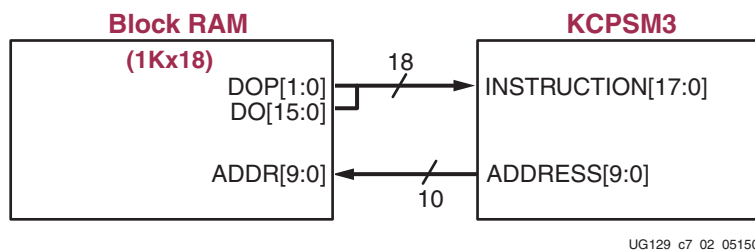


Figure 7-2: Standard Configuration using a Single 1Kx18 Block RAM

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.

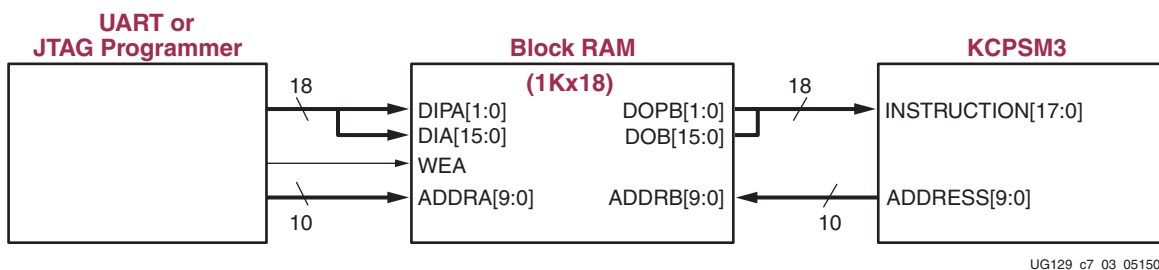


Figure 7-3: Standard Configuration with UART or JTAG Program Loader

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.

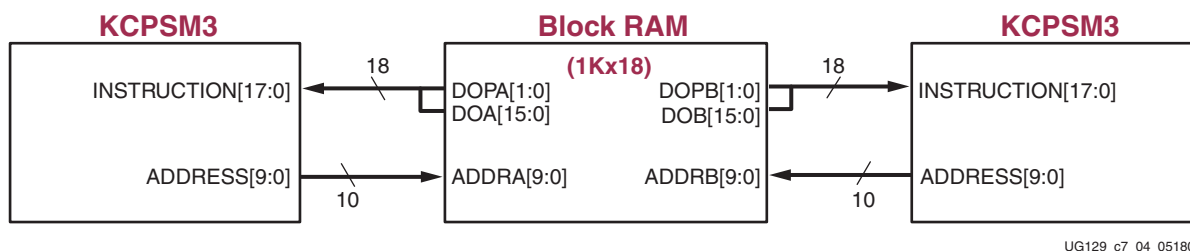
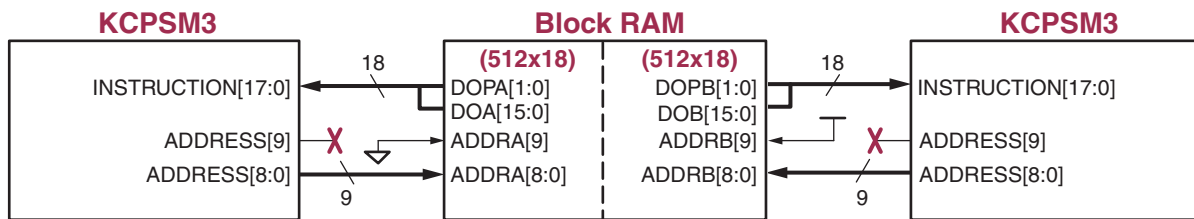


Figure 7-4: Two PicoBlaze Microcontrollers Sharing a Common Code Image

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.



UG129_c7_05_051504

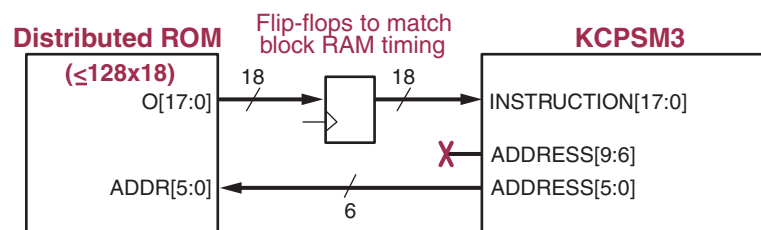
Figure 7-5: Two PicoBlaze Microcontrollers with Separate 512-Instruction Memory in one Block RAM

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.



UG129_c7_06_060404

Figure 7-6: Using Distributed ROM for Instruction Memory

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

Instructions	ROM Slices
≤ 16	9
≤ 32	18
≤ 64	36
≤ 128	72
≤ 256	144
≤ 512	297
$\leq 1,024$	594

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

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 8-1: PicoBlaze Performance Using Slowest Speed Grade

FPGA Family (Speed Grade)	Maximum Clock Frequency	Maximum Execution Performance
Spartan-3 (-4) FPGA	88 MHz	44 MIPS
Virtex-II (-6) FPGA	152 MHz	76 MIPS
Virtex-II Pro (-7) FPGA	200 MHz	100 MIPS

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.

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

	Xilinx KCPSM3	Mediatronix pBlazIDE	Xilinx System Generator
Platform Support	Windows	Windows 98, Windows 2000, Windows NT, Windows ME, Windows XP	Windows 2000, Windows XP
Assembler	Command-line in DOS window	Graphical	Command-line within System Generator
Instruction Syntax	KCPSM3	PBlazIDE	KCPSM3
Instruction Set Simulator	Facilities provided for VHDL simulation	Graphical/Interactive	Graphical/Interactive
Simulator Breakpoints	N/A	Yes	Yes
Register Viewer	N/A	Yes	Yes
Memory Viewer	N/A	Yes	Yes

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.*`.

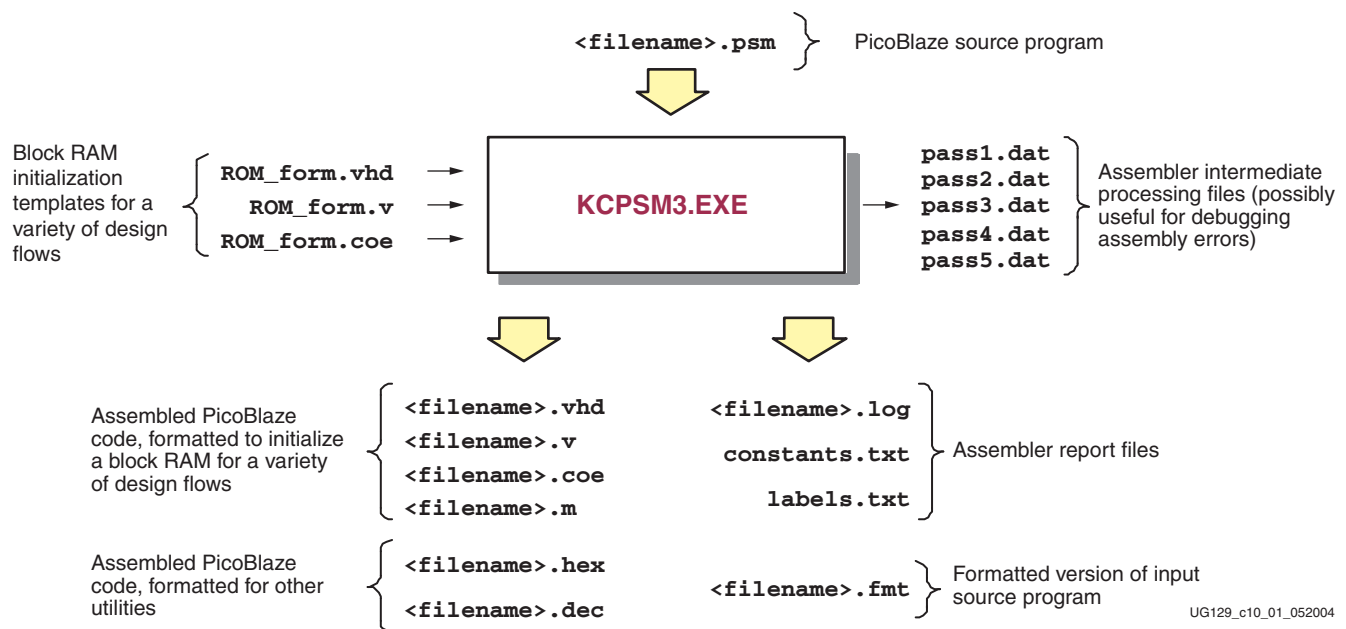


Figure 9-1: KCPSM3 Assembler Files

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:

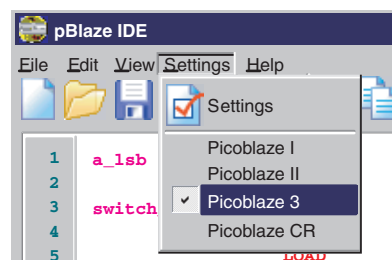
- Syntax color highlighting
- Instruction set simulator (ISS)
 - ♦ Breakpoints
 - ♦ Register display
 - ♦ Memory display
- Source code formatter ("pretty print")
- KCPSM3-to-pBlazIDE import function/syntax conversion
- HTML output, including color highlighting

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](#).



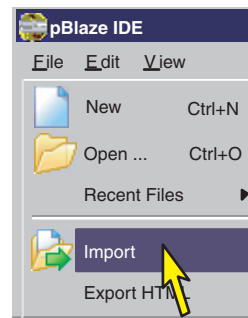
UG129_c10_02_051504

Figure 9-2: Configuring pBlazIDE to Support the PicoBlaze Microcontroller

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.



UG129_c10_03_051504

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

KCPSM Source Code	Code Imported/Converted into pBlaz IDE
<pre> CONSTANT myconstant, A5 NAMEREG s0, count16_lsb NAMEREG s1, count16_msb ADDRESS 000 main: ; initialize 16-bit counter, enable interrupts LOAD count16_lsb, myconstant ENABLE INTERRUPT loop: ; continuously increment 16-bit counter CALL increment_count JUMP loop end_main: increment_count: ; add 1 to LSB of 16-bit counter ADD count16_lsb, 01 ; only add one to MSB if carry generated by LSB ADDCY count16_msb, 00 RETURN isr: ; decrement 16-bit counter by one on interrupt ; subtract 1 from LSB of 16-bit counter SUB count16_lsb, 01 ; only subtract one from MSB if borrow ; generated by LSB SUBCY count16_msb, 00 RETURNI ENABLE ; interrupt vector is always in last memory location ADDRESS 3FF ; jump to interrupt service routing (ISR) JUMP isr </pre>	<pre> myconstant EQU \$A5 count16_lsb EQU s0 count16_msb EQU s1 ORG 0 main: ; initialize 16-bit counter, enable interrupts LOAD count16_lsb, myconstant EINT loop: ; continuously increment 16-bit counter CALL increment_count JUMP loop end_main: increment_count: ; add 1 to LSB of 16-bit counter ADD count16_lsb, 1 ; only add one to MSB if carry generated by LSB ADDC count16_msb, 0 RET isr: ; decrement 16-bit counter by one on interrupt ; subtract 1 from LSB of 16-bit counter SUB count16_lsb, 1 ; only subtract one from MSB if borrow ; generated by LSB SUBC count16_msb, 0 RETI ENABLE ; interrupt vector is always in last memory location ORG \$3FF ; jump to interrupt service routing (ISR) JUMP isr </pre>

UG129_c10_04_052004

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

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

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

Directives

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

Table 9-3: Directives

Function	KCPSM3 Directive	PBlazIDE Directive
Locating Code	ADDRESS 3FF	ORG \$3FF
Aliasing Register Names	NAMEREG s5, myregname	myregname EQU s5
Declaring Constants	CONSTANT myconstant, 80	myconstant EQU \$80
Naming the program ROM file	Named using the same base filename as the assembler source file	VHDL "template.vhd", "target.vhd", "entity_name"

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.

```

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

```

processor: kcpsm3
  port map(
    address => address_signal,
    instruction => instruction_signal,
    port_id => port_id_signal,
    write_strobe => write_strobe_signal,
    out_port => out_port_signal,
    read_strobe => read_strobe_signal,
    in_port => in_port_signal,
    interrupt => interrupt_signal,
    interrupt_ack => interrupt_ack_signal,
    reset => reset_signal,
    clk => clk_signal
  );

```

Figure 10-2: VHDL Component Instantiation of the 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`.

```

component prog_rom
port (
  address      : in  std_logic_vector( 9 downto 0);
  instruction  : out std_logic_vector(17 downto 0);
  clk         : in  std_logic
);
end component;

```

Figure 10-3: VHDL Component Declaration of Program ROM

```

program: prog_rom
  port map(
    address => address_signal,
    instruction => instruction_signal,
    clk => clk_signal
  );

```

Figure 10-4: VHDL Component Instantiation of Program ROM

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**

<http://toolbox.xilinx.com/docsan/xilinx10/books/docs/xst/xst.pdf>

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.

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 11-1: Assembler Directives to Locate Code

KCPSM3	pBlazIDE
ADDRESS 3FF	ORG \$3FF

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 11-2: Assembler Directives to Name or Alias Registers

KCPSM3	pBlazIDE
NAMEREG s5, myregname	myregname EQU s5

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_regname, new_regname) 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
<code>CONSTANT myconstant, 80</code>	<code>myconstant EQU \$80</code>

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
```

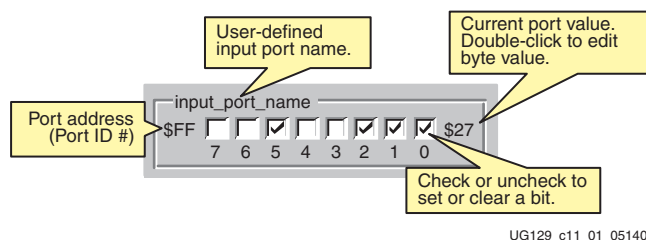
Figure 11-2: Example of pBlazIDE DSIN Directive

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.



UG129_c11_01_051404

Figure 11-4: The pBlazIDE DSIN Directive Defines an Input Port

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.

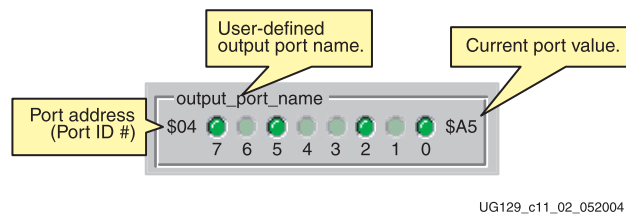


Figure 11-6: The pBlazIDE DSOUT Directive Defines an Output Port

The DSOUT directive is also useful to create stimulus files later read using DSIN directives in another pBlazIDE application program. For example, to create a stimulus input file containing incrementing data values, create a quick pBlazIDE program that increments a value and writes the value to an output port declared using a DSOUT directive, complete with file specification. Once the program completes, this resulting file can be read by another pBlazIDE program during instruction set simulation using the DSIN directive.

Input/Output Ports

The DSIO directive defines the name and the port address (or port identification number) for an output port. However, the DSIO directive differs from the DSOUT directive in that the PicoBlaze microcontroller can also read DSIO output values. The DSIO directive models an output port that connects to both the PicoBlaze microcontroller's IN_PORT and OUT_PORT ports and has the same port address for input and output operations. An optional field specifies a text file that records the result of any output operations to this during instruction set simulation. Figure 11-7 provides an example.

```
; 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.

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.

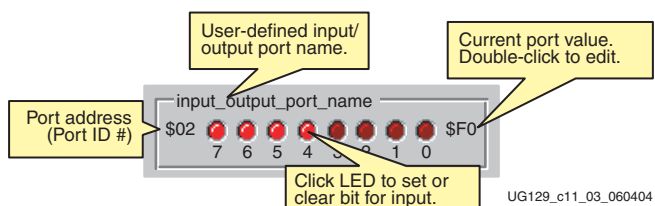


Figure 11-8: The pBlazIDE DSIO Directive Defines an Output Port That Can Be Read Back

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

Verification Tool	Strengths	Weaknesses
pBlazIDE	<ul style="list-style-type: none"> • 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! 	<ul style="list-style-type: none"> • No modeling of custom logic attached to the PicoBlaze microcontroller
ModelSim	<ul style="list-style-type: none"> • Holistic simulation of PicoBlaze microcontroller with associated FPGA logic • VHDL and Verilog logic and timing simulation • Cycle and timing accurate with FPGA hardware 	<ul style="list-style-type: none"> • Requires simulator setup and stimulus files • Digital simulator, not an ideal Instruction Set Simulation environment

Table 12-1: PicoBlaze Code Simulation Options

Verification Tool	Strengths	Weaknesses
Xilinx System Generator	<ul style="list-style-type: none"> Full PicoBlaze system-level simulation with the System Generator environment Cycle-accurate Instruction Set Simulation (ISS) Single-step Breakpoints Register and memory viewer 	<ul style="list-style-type: none"> Primarily only useful is already using Xilinx System Generator
In-system on FPGA	<ul style="list-style-type: none"> Fast, real-time performance Ideal for complex interactions Integrated with peripherals, displays, UARTs, etc. 	<ul style="list-style-type: none"> Poor visibility of register contents

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.mediatrix.com/pBlazIDE.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.

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.

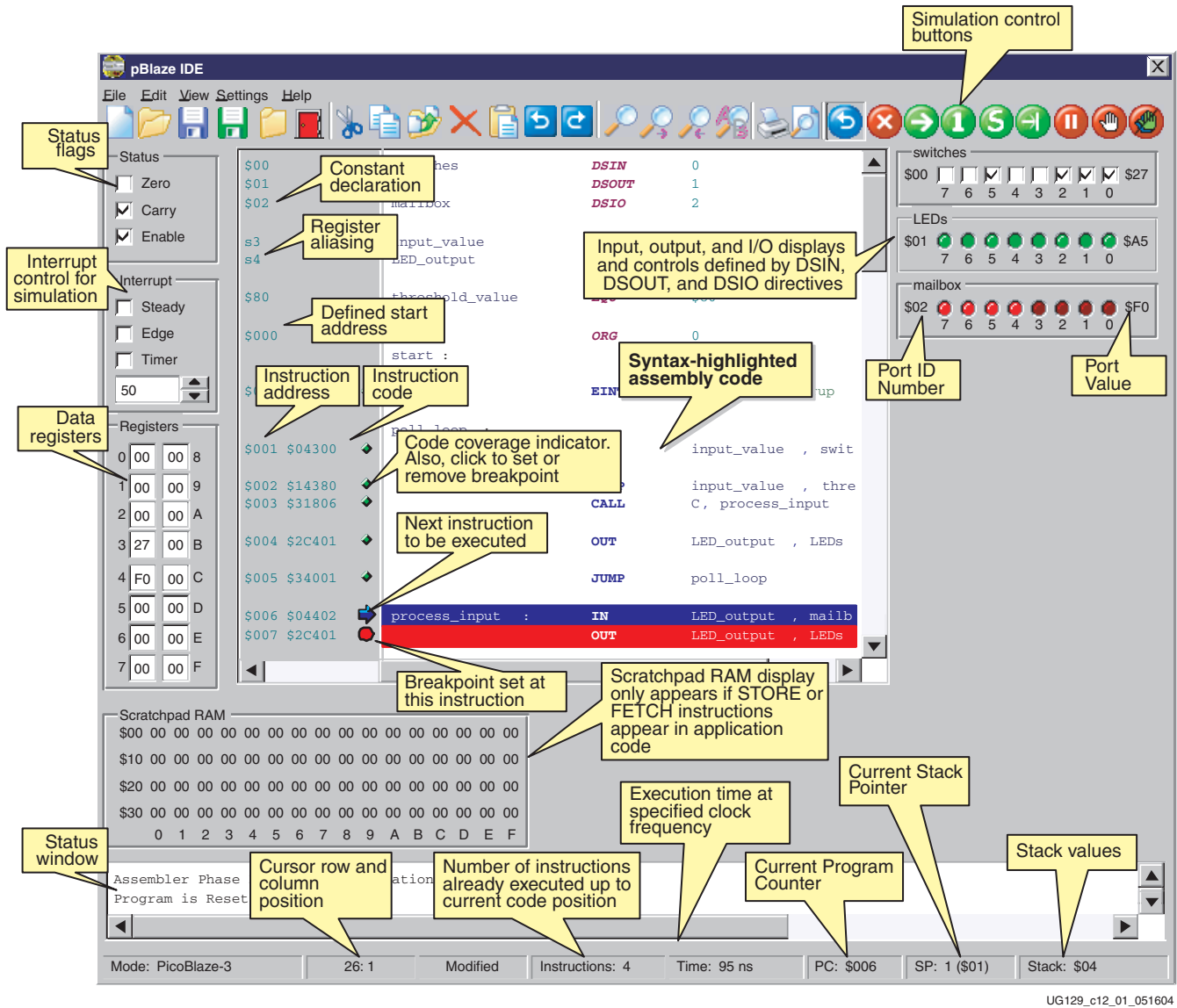


Figure 12-1: The pBlazIDE Instruction Set Simulator (ISS)

Simulator Control Buttons

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

Table 12-2: pBlazIDE Simulator Control Buttons











Button	Function
	Assemble the open document. If no errors are encountered, the simulator is invoked and the other simulation control buttons are enabled.
	Leave simulator and return to editor. All the simulation control buttons are disabled.

Table 12-2: pBlazIDE Simulator Control Buttons (*Continued*)

Button	Function
Reset 	Reset the simulator. Reset the Program Counter (PC) and Stack Pointer (SP). Register and RAM values are not reset.
Run 	Run the program. The program continues running until an active breakpoint is encountered or if the Reset or Pause button is pressed.
Single Step 	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.
Step Over 	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.
Run to Cursor 	Run the program until the program advances to the current cursor location.
Pause 	Pause a running simulation and display the current state of the PicoBlaze microcontroller. Continue the simulation using any of the green action buttons.
Toggle Breakpoint 	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.
Remove All Breakpoints 	Clear all active breakpoints.

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. Use 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 pBlazeIDE Integrated Development Environment for PicoBlaze
<http://www.mediatronix.com/pBlazeIDE.htm>
3. *Xilinx System Generator User Guide: “Designing PicoBlaze Microcontroller Applications”*
http://www.xilinx.com/support/sw_manuals/sysgen_ug.pdf
4. MicroBlaze 32-bit Soft Processor Core
<http://www.xilinx.com/microblaze>
5. UG331: *Spartan-3 Generation FPGA User Guide*: Chapter 8, “Using Dedicated Multiplexers”
http://www.xilinx.com/support/documentation/user_guides/ug331.pdf
6. *XST User Guide*: Chapter 9, “Mixed Language Support”
<http://toolbox.xilinx.com/docsan/xilinx10/books/docs/xst/xst.pdf>

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.

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

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 (\leftarrow) 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.

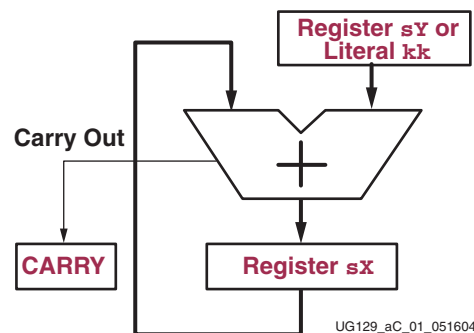


Figure C-1: ADD Operation

Example

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

```
ADD sX, sY; Add register.    sX = sX + sY.
ADD sX, kk; Add immediate.  sX = sX + kk.
```

Description

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

Pseudocode

```

sX ← (sX + Operand) mod 256; always an 8-bit result

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

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

PC ← PC + 1

```

Registers/Flags Altered

Registers: sX, PC

Flags: CARRY, ZERO

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

The ADDCY 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.

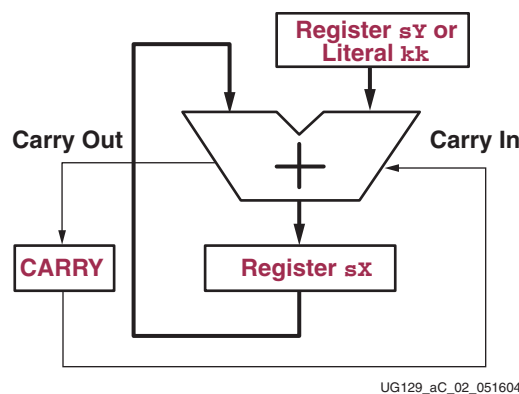


Figure C-2: ADDCY Instruction

Example

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

```

ADDCY sX, sY; Add register.    sX = sX + sY + CARRY
ADDCY sX, kk; Add immediate.  sX = sX + kk + CARRY

```

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

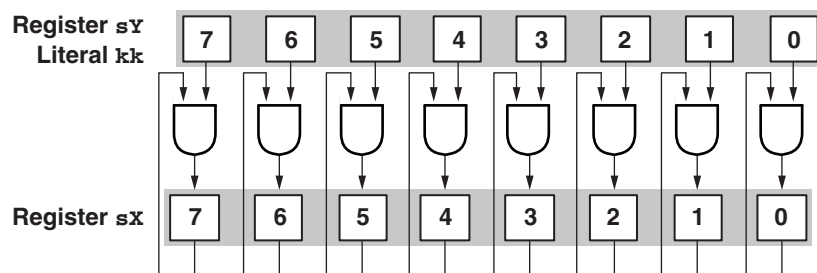
Flags: CARRY, ZERO

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.



UG129_aC_06_051604

Figure C-3: AND Operation

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

```

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

```

Pseudocode

```

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

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

```

CALL      MYSUB; Unconditionally call MYSUB subroutine
CALL C,   MYSUB; If CARRY flag set, call MYSUB subroutine
CALL NC,  MYSUB; If CARRY flag not set, call MYSUB subroutine
CALL Z,   MYSUB; If ZERO flag set, call MYSUB subroutine
CALL NZ,  MYSUB; If ZERO flag not set, call MYSUB subroutine

```

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**

Condition	Description
<none>	Always true. Call subroutine unconditionally.
C	CARRY = 1. Call subroutine if CARRY flag is set.
NC	CARRY = 0. Call subroutine if CARRY flag is cleared.
Z	ZERO = 1. Call subroutine if ZERO flag is set.
NZ	ZERO = 0. Call subroutine if ZERO flag is cleared.

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

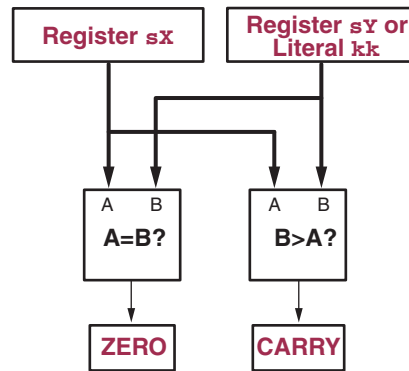
Flags: Not affected

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.



UG129_aC_05_051604

Figure C-4: COMPARE 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

```
INTERRUPT_ENABLE  $\leftarrow$  0
```

```
PC  $\leftarrow$  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

```
INTERRUPT_ENABLE  $\leftarrow$  1
```

```
PC  $\leftarrow$  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 of Operand, bits 5 to bit 0. Consequently, a FETCH operation from address FF is equivalent to a FETCH operation from address 3F.

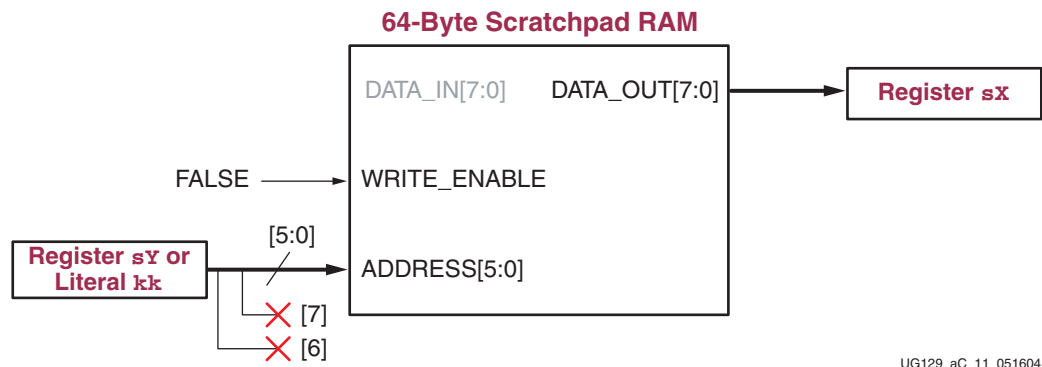


Figure C-5: FETCH Operation

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.

KCPSM3 Instruction	PBlazIDE Instruction
FETCH sX, (sY)	FETCH sX, sY

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

```
INPUT sX, sY ; Read the value on IN_PORT into register sX, set PORT_ID
              ; to the contents of sY
INPUT sX, kk ; Read the value on IN_PORT into register sX, set PORT_ID
              ; to the immediate constant kk
```

Pseudocode

```
PORT_ID ← Operand
```

```
sX ← IN_PORT
```

```
PC ← 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

```

; 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.

JUMP [Condition,] Address — Jump to Specified Address, Possibly with Conditions

The JUMP instruction modifies the normal program execution sequence by jumping to a specified program address. Each JUMP 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 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

```
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

Condition	Description
<none>	Always true. Jump unconditionally.
C	CARRY = 1. Jump if CARRY flag is set.
NC	CARRY = 0. Jump if CARRY flag is cleared.
Z	ZERO = 1. Jump if ZERO flag is set.
NZ	ZERO = 0. Jump if ZERO flag is cleared.

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 with Operand

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
```

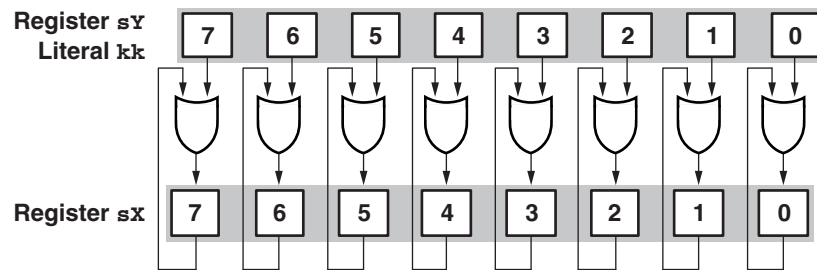
Registers/Flags Altered

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.



UG129_aC_07_051604

Figure C-6: OR Operation

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.

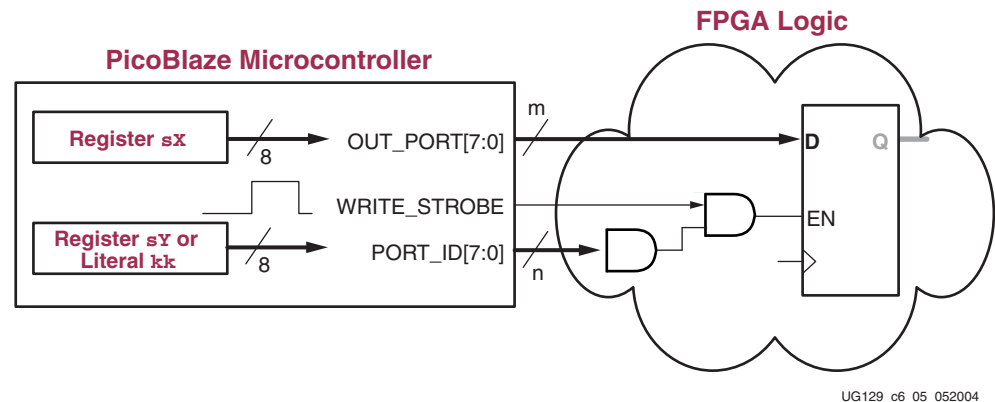


Figure C-7: OUTPUT Operation and FPGA Interface Logic

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.

RESET Event

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

Resource	RESET Event Effect
General-purpose Registers	Unaffected.
Program Counter	0
ZERO Flag	0
CARRY Flag	0
INTERRUPT_ENABLE Flag	0
Scratchpad RAM	Unaffected.
Program Store	Unaffected.
CALL/RETURN Stack	Stack Pointer reset.

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

```

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

Condition	Description
<none>	Always true. Return from called subroutine unconditionally.
C	CARRY = 1. Return from called subroutine if CARRY flag is set.
NC	CARRY = 0. Return from called subroutine if CARRY flag is cleared.
Z	ZERO = 1. Return from called subroutine if ZERO flag is set.
NZ	ZERO = 0. Return from called subroutine if ZERO flag is cleared.

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.

PBlazIDE Equivalent: RET, RET C, RET NC, RET Z, RET NZ

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

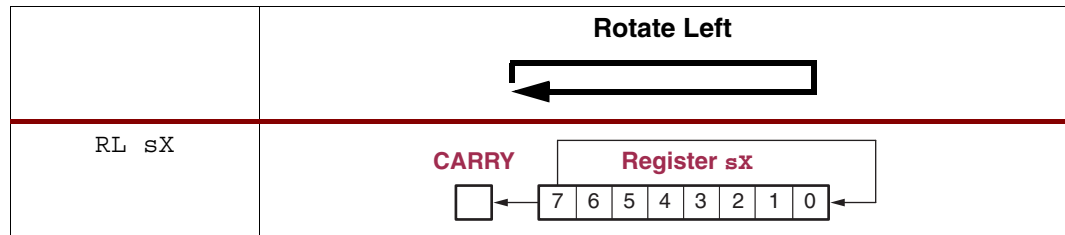
Do not use the RETURNI instruction to return from a subroutine CALL. Instead, use the RETURN instruction.

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



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

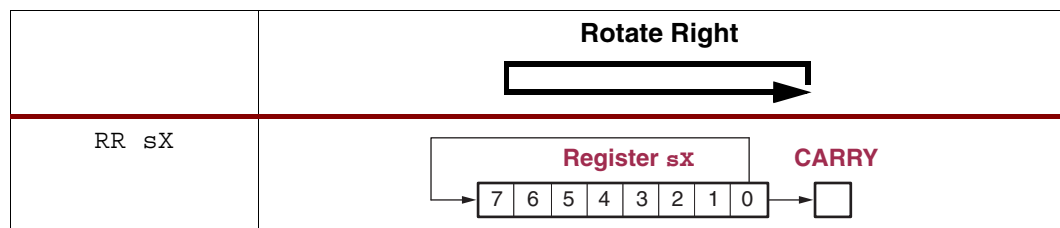
Registers: sX, PC

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



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


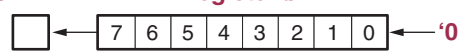



Registers: sX, PC

Flags: CARRY, ZERO

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 0.

Table C-7: Shift Left Operations

	<div> <div>Shift Left</div>  </div>
SL0 sX	<div>Shift Left with '0' fill.</div> <div> <div>CARRY</div> <div>Register sX</div>  </div>
SL1 sX	<div>Shift Left with '1' fill.</div> <div> <div>CARRY</div> <div>Register sX</div>  </div>
SLX sX	<div>Shift Left, eXtend bit 0.</div> <div> <div>CARRY</div> <div>Register sX</div>  </div>
SLA sX	<div>Shift Left through All bits, including CARRY.</div> <div> <div>CARRY</div> <div>Register sX</div>  </div>

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

Examples

```
SL0 sX; Shift left. 0 shifts into LSB, MSB shifts into CARRY.
SL1 sX; Shift left. 1 shifts into LSB, MSB shifts into CARRY.
SLX sX; Shift left. LSB shifts into LSB, MSB shifts into CARRY.
SLA sX; Shift left. CARRY shifts into LSB, MSB shifts into CARRY.
```

Pseudocode

```
case (INSTRUCTION)
  when "SL0"
    LSB ← 0
  when "SL1"
    LSB ← 1
  when "SLX"
    LSB ← sX(7)
  when "SLA"
    LSB ← CARRY
end case

CARRY ← sX[7]

sX ← {sX[6:0], LSB}

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

PC ← PC + 1
```

Registers/Flags Altered

Registers: sX, PC

Flags: CARRY, ZERO

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.

Table C-8: Shift Right Operations

	Shift Right →
SR0 sX	Shift Right with '0' fill. <div> <p>Register sX</p> <p>'0' → [7 6 5 4 3 2 1 0] → CARRY</p> </div>
SR1 sX	Shift Right with '1' fill. <div> <p>Register sX</p> <p>'1' → [7 6 5 4 3 2 1 0] → CARRY</p> </div>
SRX sX	Shift Right, sign eXtend. <div> <p>Register sX</p> <p>[7 6 5 4 3 2 1 0] → CARRY</p> </div>
SRA sX	Shift Right through All bits, including CARRY. <div> <p>Register sX</p> <p>[7 6 5 4 3 2 1 0] → CARRY</p> </div>

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

```
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 ← 1
else
  ZERO ← 0
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.

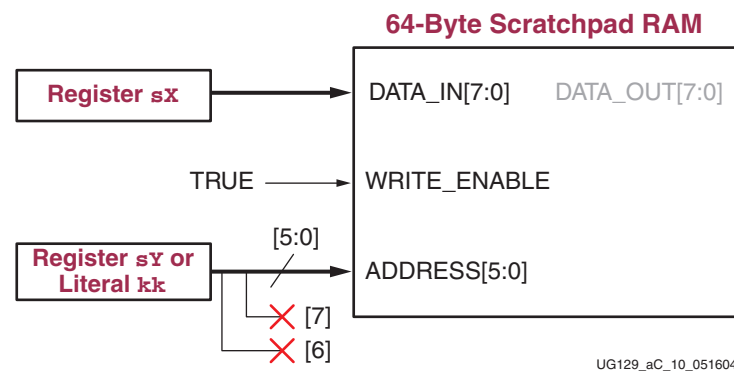


Figure C-8: STORE Operation

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

```
Scratchpad_RAM[Operand[5:0]] ← sX
```

```
PC ← 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.

KCPSM3 Instruction	PBlazIDE Instruction
STORE sX, (sY)	STORE sX, sY

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.

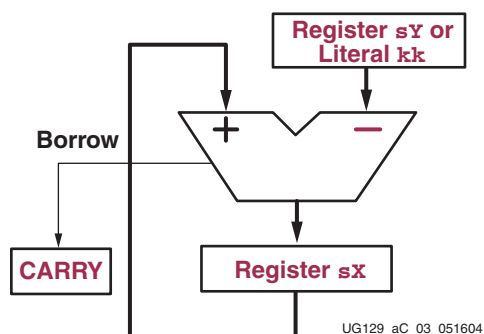


Figure C-9: SUB Instruction

Examples

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

```
SUB sX, sY; Subtract register.    sX = sX - sY.
SUB sX, kk; Subtract immediate.  sX = sX - kk.
```

Description

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

Pseudocode

```

sX ← (sX - Operand) mod 256; always an 8-bit result

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

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

PC ← PC + 1

```

Registers/Flags Altered

Registers: sX, PC

Flags: CARRY, ZERO

SUBCY sX, 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.

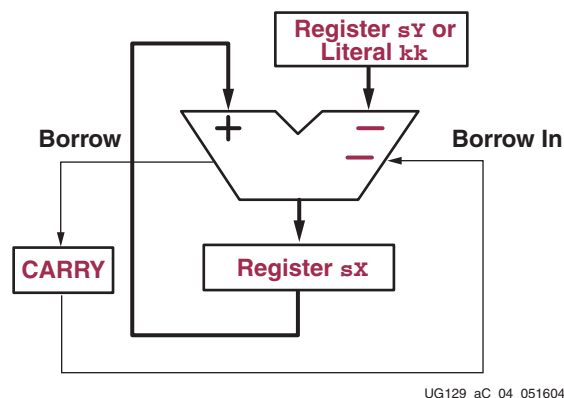


Figure C-10: SUBCY Instruction

Examples

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

```

SUBCY sX, sY; Subtract register.    sX = sX - sY - CARRY
SUBCY sX, kk; Subtract immediate.  sX = sX - kk - CARRY

```

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

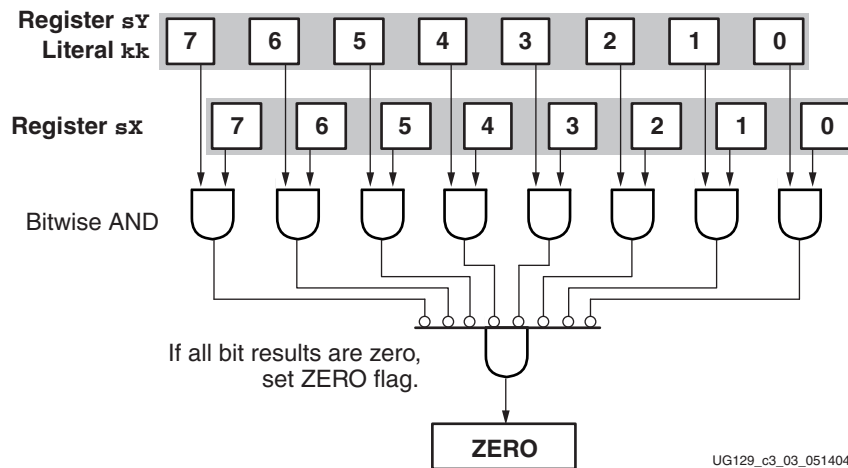
Flags: CARRY, ZERO

Notes

pBlazIDE Equivalent: SUBC

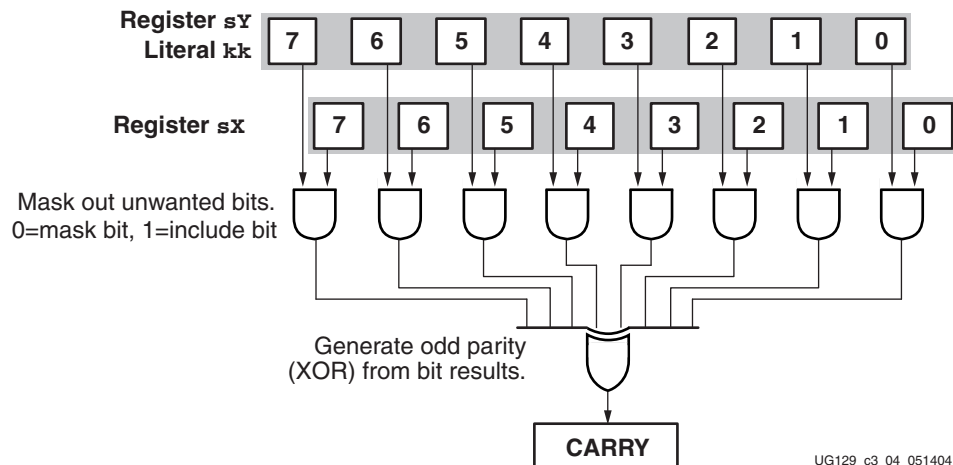
TEST sX, Operand — Test Bit Location in Register sX, Generate Odd Parity

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.



UG129_c3_03_051404

Figure C-11: ZERO Flag Logic for TEST Instruction



UG129_c3_04_051404

Figure C-12: CARRY Flag Logic for TEST Instruction

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

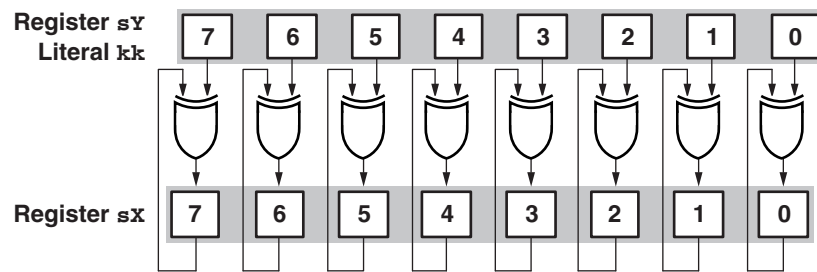
Registers: PC

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.



UG129_aC_08_051604

Figure C-13: XOR Operation

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

Instruction Codes

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

Table D-1: PicoBlaze Instruction Codes

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	x	x	x	x	k	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
ADDCY sX, sY	0	1	1	0	1	1	x	x	x	x	y	y	y	y	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
AND sX, sY	0	0	1	0	1	1	x	x	x	x	y	y	y	y	0	0	0	0
CALL	1	1	0	0	0	0	0	0	a	a	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
DISABLE INTERRUPT	1	1	1	1	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	1
FETCH sX, ss	0	0	0	1	1	0	x	x	x	x	0	0	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
INPUT sX, (sY)	0	0	0	1	0	1	x	x	x	x	y	y	y	y	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	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 (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	0	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	0	0	0	0
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	0	0	0	0
OUTPUT sX, (sY)	1	0	1	1	0	1	x	x	x	x	y	y	y	y	0	0	0	0
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	0
RETURN C	1	0	1	0	1	1	1	0	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	0
RETURN NZ	1	0	1	0	1	1	0	1	0	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	0
RETURNI DISABLE	1	1	1	0	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	1
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	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	1	1	1	1
SRA sX	1	0	0	0	0	0	x	x	x	x	0	0	0	0	1	0	0	0
SRX sX	1	0	0	0	0	0	x	x	x	x	0	0	0	0	1	0	1	0
STORE sX, ss	1	0	1	1	1	0	x	x	x	x	0	0	s	s	s	s	s	s
STORE sX, (sY)	1	0	1	1	1	1	x	x	x	x	y	y	y	y	0	0	0	0
SUB sX, kk	0	1	1	1	0	0	x	x	x	x	k	k	k	k	k	k	k	k
SUB sX, sY	0	1	1	1	0	1	x	x	x	x	y	y	y	y	0	0	0	0
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	0	0	0	0
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	0	0	0	0

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
XOR sX, kk	0	0	1	1	1	0	x	x	x	x	k	k	k	k	k	k	k	k
XOR sX, sY	0	0	1	1	1	1	x	x	x	x	y	y	y	y	0	0	0	0

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

Reg.	Description
s0	
s1	
s2	
s3	
s4	
s5	
s6	
s7	
s8	
s9	
sA	
sB	
sC	
sD	
sE	
sF	

Scratchpad RAM

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