ELEC6027 - VLSI Design Project : Programmers Guide

Team R4

28th April, 2014

Todo list

Contents

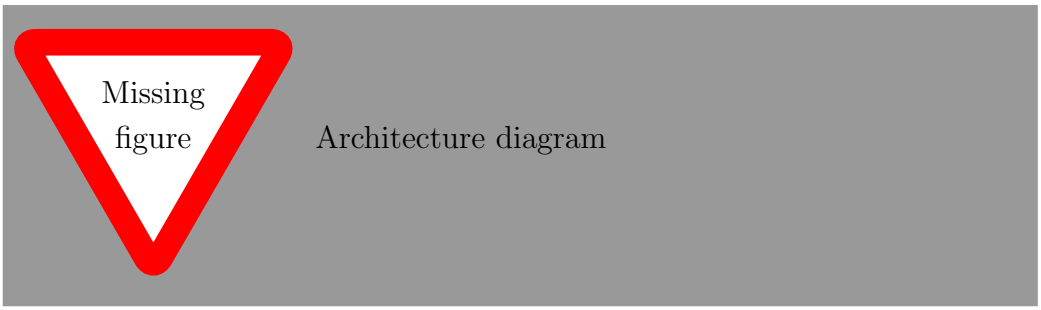


Figure 1: The Architecture diagram of the SAMURAI processor.

1 Introduction

This is the Programmers Guide for the processor designed by Team R4 in the VLSI Design Project, ELEC6027.

The processor is called SAMAURAI - **S**ixteen bit **A**rm and **M**ips **U**nified **R**isc **A**rchitecture with **I**nterrupts. It is a sixteen bit general purpose Von Neumann processor. SAMURAI implements a custom Instruction Set.

This guide documents the architecture and instruction set. In addition, four example programs are given along with instructions of the use of the Assembler. Finally, the simulation environment is explained, giving examples of how to run a program.

1.1 Architecture

Figure 1 shows the datapath architecture of the SAMURAI processor. The controller has been omitted along with all control signals. The exception is the status register is shown for data flow as this utilises the System Bus. Instruction decoding is also not shown for clarity. All registers, buses and multiplexors are 16 bits in length unless otherwise stated.

1.2 Register Description

The processor has twelve registers in total, all are 16 bits wide. These is a program counter, instruction register, link register, ALU output register and 8 general purpose registers. Each register is described below, along with any conventions.

General Purpose Registers The register block consists of eight General Purpose Registers (GPRs). There is no dummy register. By convention, Register 7 is used as the stack pointer. It is used by stack and interrupt instructions such as push, pop, store and load flags and return from interrupt.

Link Register The Link Register is used to store the return address of the caller function. However, it is not a part of the General Purpose register file. The link register is used by the branch with link and return from subroutine instructions. In these, the program counter is stored to or set by the link register. The link register can also be pushed or popped to/from the stack.

Program Counter The program counter is used to access the current instruction. It can be set by the result of an ALU operation, the link register, a value on the stack or a predefined constant used for interrupts. Branch instructions are the main modifier of the program counter. By default, all instructions increment the Program Counter by one to progress the operation of the program. This is not an addressable register and it's functionality is utilised by the control unit only.

Instruction Register The instruction register contains the currently executed instruction. This can only be set from the main memory by use of the Program Counter as the address to main memory. It is not addressable and it's function is utilised by the control unit.

AluOut The AluOut register is used to hold a value on the output of the Alu. It is used by memory access instructions and is not addressable.

2 Instruction Set

The complete instruction set architecture includes a number of instructions for performing calculations on data, memory access, transfer of control within a program and interrupt handling.

All instructions implemented by this architecture fall into one of 6 groups, categorized as follows:

- Data Manipulation - Arithmetic, Logical, Shifting
- Byte Immediate - Arithmetic, Byte Load
- Data Transfer - Memory Access
- Control Transfer - (Un)conditional Branching
- Stack Operations - Push, Pop
- Interrupts - Enabling, Status Storage, Returning

There is only one addressing mode associated with each instruction, generally following these groupings:

- Data Manipulation - Register-Register, Register-Immediate
- Byte Immediate - Register-Immediate
- Data Transfer - Base Plus Offset
- Control Transfer - PC Relative, Register-Indirect, Base Plus Offset
- Stack Operations - Register-Indirect Preincrement/Postdecrement
- Interrupts - Register-Indirect Preincrement/Postdecrement

2.1 General Instruction Formatting

	Instruction Type	Sub-Type	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
A1	**Data Manipulation**	**Register**	Opcode					Rd			Ra			Rb			X	X
A2		**Immediate**						Rd			Ra			imm4/5				
B	**Byte Immediate**		Opcode					Rd			imm8							
C	**Data Transfer**		0	LS	0	0	0	Rd			Ra			imm5				
D1	**Control Transfer**	**Others**	1	1	1	1	0	Cond.			imm8							
D2		**Jump**									Ra			imm5				
E	**Stack Operations**		0	U	0	0	1	L	X	X	Ra			0	0	0	0	1
F	**Interrupts**		1	1	0	0	1	ICond.			1	1	1	X	X	X	X	X

Instruction Field Definitions

Opcode: Operation code as defined for each instruction

Rd: Destination Register

Ra: Source register 1

Rb: Source register 2

imm$N$: Immediate value of length N

Cond.: Branching condition code as defined for branch instructions

ICond.: Interrupt instruction code as defined for interrupt instructions

LS: 0=Load Data, 1=Store Data

U: 1=PUSH, 0=POP

L: 1=Use Link Register, 0=Use GPR

Pseudocode Notation

Symbol	Meaning
$\leftarrow$	Assignment
Result[x]	Bit x of result
Ra[$x : y$]	Bit range from x to y of register Ra
$<$	Numerically less than
$>$	Numerically greater than
$<<$	Logical shift left
$>>$	Logical shift right
$>>>$	Arithmetic shift right
Mem[*val*]	Data at memory location with address *val*
$\{x, y\}$	Contatenation of x and y to form a 16-bit value
!	Bitwise Negation

Use of the word UNPREDICTABLE indicates that the resultant flag value after operation execution will not be indicative of the ALU result. Instead its value will correspond to the result of an undefined arithmetic operation and as such should not be used.

2.2 ADD — Add Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	Rd			Ra			Rb			X	X

Syntax

ADD Rd, Ra, Rb eg. ADD R5, R3, R2

Operation

Rd $\leftarrow$ Ra + Rb

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and Rb>0 and Result<0) or

(Ra<0 and Rb<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Ra] is added to the 16-bit word in GPR[Rb] and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.3 ADDI — Add Immediate

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	Rd			Ra			imm5				

Syntax

ADDI Rd, Ra, #imm5 eg. ADDI R5, R3, #7

Operation

Rd $\leftarrow$ Ra + #imm5

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and #imm5>0 and Result<0) or

(Ra<0 and #imm5<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

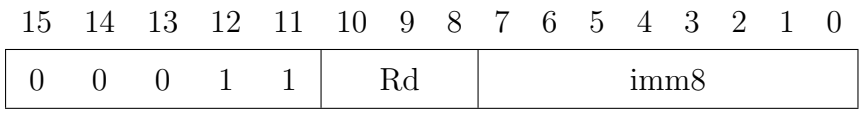
Description

The 16-bit word in GPR[Ra] is added to the sign-extended 5-bit value given in the instruction and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.4 ADDIB Add Immediate Byte

Format



Syntax

ADDIB Rd, #imm8 eg. ADDIB R5, #93

Operation

Rd $\leftarrow$ Rd + #imm8

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Rd>0 and #imm8>0 and Result<0) or

(Rd<0 and #imm8<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Rd] is added to the sign-extended 8-bit value given in the instruction and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.5 ADC Add Word With Carry

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	Rd			Ra			Rb			X	X

Syntax

ADC Rd, Ra, Rb eg. ADC R5, R3, R2

Operation

Rd $\leftarrow$ Ra + Rb + C

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and (Rb+CFlag)>0 and Result<0) or

(Ra<0 and (Rb+CFlag)<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Ra] is added to the 16-bit word in GPR[Rb] with the added carry in set according to the Carry flag from previous operation, and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.6 ADCI Add Immediate With Carry

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	Rd			Ra			imm5				

Syntax

ADCI Rd, Ra, #imm5 eg. ADCI R5, R4, #7

Operation

Rd $\leftarrow$ Ra + #imm5 + C

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and (#imm5+CFlag)>0 and Result<0) or

(Ra<0 and (#imm5+CFlag)<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Ra] is added to the sign-extended 5-bit value given in the instruction with carry in set according to the Carry flag from previous operation, and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.7 NEG Negate Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	1	0	Rd			Ra			X	X	X	X	X

Syntax

NEG Rd, Ra eg. NEG R5, R3

Operation

Rd ← 0 - Ra

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← 0

C ← 0

Description

The 16-bit word in GPR[Ra] is added to the 16-bit word in GPR[Rb] and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.8 SUB Subtract Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	Rd			Ra			Rb			X	X

Syntax

SUB Rd, Ra, Rb eg. SUB R5, R3, R2

Operation

Rd $\leftarrow$ Ra - Rb

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and Rb>0 and Result<0) or

(Ra<0 and Rb<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

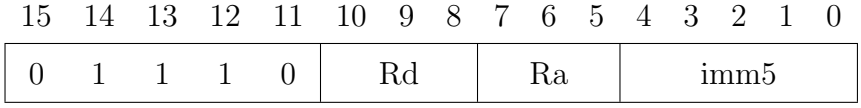
Description

The 16-bit word in GPR[Rb] is subtracted from the 16-bit word in GPR[Ra] and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.9 SUBI Subtract Immediate

Format



Syntax

SUBI Rd, Ra, #imm5 eg. SUBI R5, R3, #7

Operation

Rd ← Ra - #imm5

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← if (Ra>0 and #imm5>0 and Result<0) or

(Ra<0 and #imm5<0 and Result>0) then 1, else 0

C ← if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The sign extended 5-bit value given in the instruction is subtracted from the 16-bit word in GPR[Ra] and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.10 SUBIB Subtract Immediate Byte

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	Rd			imm8							

Syntax

SUBIB Rd, #imm8 eg. SUBIB R5, #93

Operation

Rd $\leftarrow$ Rd - #imm8

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Rd>0 and #imm8>0 and Result<0) or

(Rd<0 and #imm8<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 8-bit immediate value given in the instruction is subtracted from the 16-bit word in GPR[Rd] and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.11 SUC Subtract Word With Carry

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	0	Rd			Ra			Rb			X	X

Syntax

SUC Rd, Ra, Rb eg. SUC R5, R3, R2

Operation

Rd $\leftarrow$ Ra - Rb - C

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and (Rb-CFlag)>0 and Result<0) or

(Ra<0 and (Rb-CFlag)<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Rb] is subtracted from the 16-bit word in GPR[Rb] with the subtracted carry in set according to the Carry flag from previous operation, and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.12 SUCI Subtract Immediate With Carry

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	Rd			Ra			imm5				

Syntax

SUCI Rd, Ra, #imm5 eg. SUCI R5, R4, #7

Operation

Rd $\leftarrow$ Ra - #imm5 - C

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and (#imm5-CFlag)>0 and Result<0) or

(Ra<0 and (#imm5-CFlag)<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 5-bit immediate value in instruction is subtracted from the 16-bit word in GPR[Ra] with the subtracted carry in set according to the Carry flag from previous operation, and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.13 CMP Compare Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	1	X	X	X	Ra			Rb			X	X

Syntax

CMP Ra, Rb eg. CMP R3, R2

Operation

Ra - Rb

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and Rb>0 and Result<0) or

(Ra<0 and Rb<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

Description

The 16-bit word in GPR[Rb] is subtracted from the 16-bit word in GPR[Ra] and the status flags are updated without saving the result.

Addressing Mode: Register-Register.

2.14 CMPI Compare Immediate

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	1	1	X	X	X	Ra			imm5				

Syntax

CMPI Ra, #imm5 eg. CMPI R3, #7

Operation

Ra - #imm5

N $\leftarrow$ if (Result < 0) then 1, else 0

Z $\leftarrow$ if (Result $= 0$) then 1, else 0

V $\leftarrow$ if (Ra>0 and #imm5>0 and Result<0) or

(Ra<0 and #imm5<0 and Result>0) then 1, else 0

C $\leftarrow$ if (Result $> 2^{16} - 1$) or

(Result $< -2^{16}$) then 1, else 0

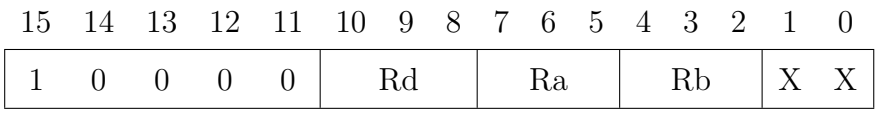
Description

The sign extended 5-bit value given in the instruction is subtracted from the 16-bit word in GPR[Ra] and the status flags are updated without saving the result.

Addressing Mode: Register-Immediate.

2.15 AND — Logical AND

Format



15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	0	Rd			Ra			Rb			X	X

Syntax

AND Rd, Ra, Rb eg. AND R5, R3, R2

Operation

Rd ← Ra `AND` Rb

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

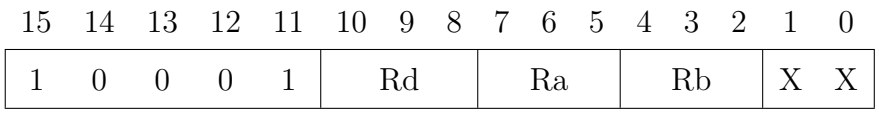
Description

The logical `AND` of the 16-bit words in GPR[Ra] and GPR[Rb] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.16 OR — Logical OR

Format



Syntax

OR Rd, Ra, Rb eg. OR R5, R3, R2

Operation

Rd ← Ra `OR` Rb

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

Description

The logical `OR` of the 16-bit words in GPR[Ra] and GPR[Rb] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.17 XOR — Logical XOR

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	1	Rd			Ra			Rb			X	X

Syntax

XOR Rd, Ra, Rb — eg. XOR R5, R3, R2

Operation

Rd ← Ra `XOR` Rb

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

Description

The logical `XOR` of the 16-bit words in GPR[Ra] and GPR[Rb] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.18 NOT — Logical NOT

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	0	Rd			Ra			X	X	X	X	X

Syntax

NOT Rd, Ra eg. NOT R5, R3

Operation

Rd ← `NOT` Ra

N ← if (Result < 0) then 1, else 0

Z ← if (Result $= 0$) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

Description

The logical `NOT` of the 16-bit word in GPR[Ra] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.19 NAND — Logical NAND

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	1	0	Rd			Ra			Rb			X	X

Syntax

NAND Rd, Ra, Rb — eg. NAND R5, R3, R2

Operation

Rd ← Ra `NAND` Rb

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

Description

The logical `NAND` of the 16-bit words in GPR[Ra] and GPR[Rb] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.20 NOR — Logical NOR

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	1	1	Rd			Ra			Rb			X	X

Syntax

NOR Rd, Ra, Rb eg. NOR R5, R3, R2

Operation

Rd ← Ra `NOR` Rb

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

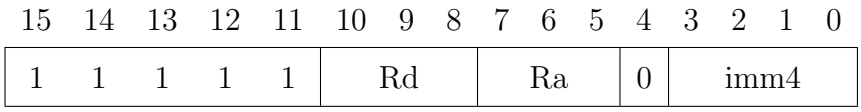
Description

The logical `NOR` of the 16-bit words in GPR[Ra] and GPR[Rb] is performed and the result is placed into GPR[Rd].

Addressing Mode: Register-Register.

2.21 LSL Logical Shift Left

Format



Syntax

LSL Rd, Ra, #imm4 eg. LSL R5, R3, #7

Operation

Rd ← Ra << #imm4

N ← if (Result < 0) then 1, else 0

Z ← if (Result = 0) then 1, else 0

V ← UNPREDICTABLE

C ← UNPREDICTABLE

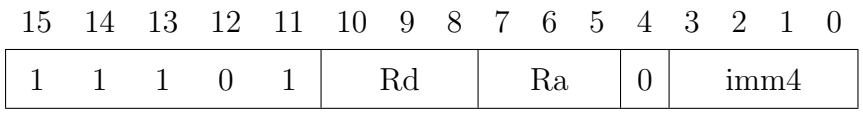
Description

The 16-bit word in GPR[Ra] is shifted left by the 4-bit amount specified in the instruction, shifting in zeros, and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.22 LSR Logical Shift Right

Format



Syntax

LSR Rd, Ra, #imm4 eg. LSR R5, R3, #7

Operation

Rd $\leftarrow$ Ra >> #imm4

N $\leftarrow$ if (Result $<$ 0) then 1, else 0

Z $\leftarrow$ if (Result $=$ 0) then 1, else 0

V $\leftarrow$ UNPREDICTABLE

C $\leftarrow$ UNPREDICTABLE

Description

The 16-bit word in GPR[Ra] is shifted right by the 4-bit amount specified in the instruction, shifting in zeros, and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.23 ASR Arithmetic Shift Right

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	0	0	Rd			Ra			0	imm4			

Syntax

ASR Rd, Ra, #imm4 eg. ASR R5, R3, #7

Operation

Rd $\leftarrow$ Ra >>> #imm4

N $\leftarrow$ if (Result $<$ 0) then 1, else 0

Z $\leftarrow$ if (Result $=$ 0) then 1, else 0

V $\leftarrow$ UNPREDICTABLE

C $\leftarrow$ UNPREDICTABLE

Description

The 16-bit word in GPR[Ra] is shifted right by the 4-bit amount specified in the instruction, shifting in the sign bit of Ra, and the result is placed into GPR[Rd].

Addressing Mode: Register-Immediate.

2.24 LDW Load Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	Rd			Ra			imm5				

Syntax

LDW Rd, [Ra, #imm5] eg. LDW R5, [R3, #7]

Operation

Rd ← Mem[Ra + #imm5]

N ← N

Z ← Z

V ← V

C ← C

Description

Data is loaded from memory at the resultant address from addition of GPR[Ra] and the 5-bit immediate value specified in the instruction, and the result is placed into GPR[Rd].

Addressing Mode: Base Plus Offset.

2.25 STW Store Word

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	Rd			Ra			imm5				

Syntax

STW Rd, [Ra, #imm5] eg. STW R5, [R3, #7]

Operation

Mem[Ra + #imm5] ← Rd

N ← N

Z ← Z

V ← V

C ← C

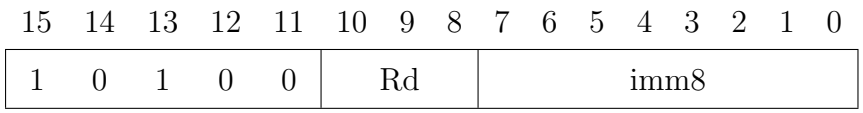
Description

Data in GPR[Rd] is stored to memory at the resultant address from addition of GPR[Ra] and the 5-bit immediate value specified in the instruction.

Addressing Mode: Base Plus Offset.

2.26 LUI Load Upper Immediate

Format



Syntax

LUI Rd #imm8 eg. LUI R5, #93

Operation

Rd ← {#imm8, 0}

N ← N

Z ← Z

V ← V

C ← C

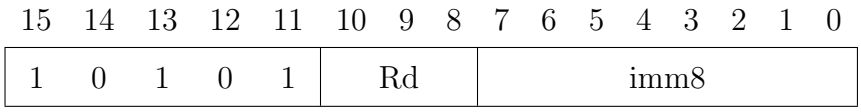
Description

The 8-bit immediate value provided in the instruction is loaded into the top half in GPR[Rd], setting the bottom half to zero.

Addressing Mode: Register-Immediate.

2.27 LLI Load Lower Immediate

Format



Syntax

LLI Rd #imm8 eg. LLI R5, #93

Operation

Rd ← {Rd[15:8], #imm8}

N ← N

Z ← Z

V ← V

C ← C

Description

The 8-bit immediate value provided in the instruction is loaded into the bottom half in GPR[Rd], leaving the top half unchanged.

Addressing Mode: Register-Immediate.

2.28 BR Branch Always

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1	0	0	0	0	imm8							

Syntax

BR LABEL eg. BR .loop

Operation

PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

Description

Unconditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.29 BNE Branch If Not Equal

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1	0	1	1	0	imm8							

Syntax

BNE LABEL eg. BNE .loop

Operation

if (z=0) PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

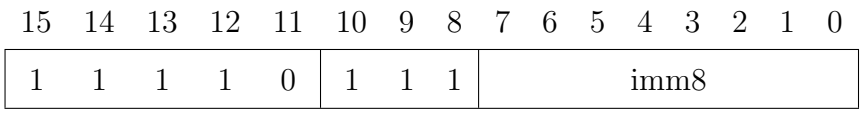
Description

Conditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction if zero status flag (Z) equals zero. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.30 BE Branch If Equal

Format



Syntax

BE LABEL eg. BE .loop

Operation

if (z=1) PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

Description

Conditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction if zero status flag (Z) equals one. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.31 BLT Branch If Less Than

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1	0	1	0	0	imm8							

Syntax

BLT LABEL eg. BLT .loop

Operation

if (n&!v OR !n&v) PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

Description

Conditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction if negative status flag and overflow status flag are not equivalent. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.32 BGE Branch If Greater Than Or Equal

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1	0	1	0	1	imm8							

Syntax

BGE LABEL eg. BGE .loop

Operation

if (n&v OR !n&!v) PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

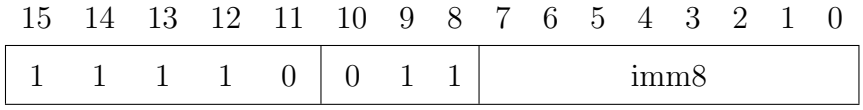
Description

Conditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction if negative status flag and overflow status flag are equivalent. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.33 BWL Branch With Link

Format



Syntax

BWL LABEL eg. BWL .loop

Operation

LR ← PC + 1; PC ← PC + #imm8

N ← N

Z ← Z

V ← V

C ← C

Description

Save the current program counter (PC) value plus one to the link register. Then unconditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction. LABEL can be both a symbolic name or a numeric value, and is capable of jumping forwards or backwards.

Addressing Mode: PC Relative.

2.34 RET — Return

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	1	1	0	0	1	0	imm8							

Syntax

RET eg. RET

Operation

PC ← LR

N ← N

Z ← Z

V ← V

C ← C

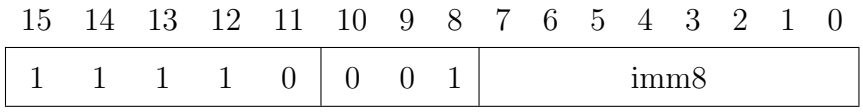
Description

Unconditionally branch to the address stored in the link register (LR).

Addressing Mode: Register-Indirect.

2.35 JMP Jump

Format



Syntax

JMP Ra, #imm5 eg. JMP R3, #7

Operation

PC ← Ra + #imm5

N ← N

Z ← Z

V ← V

C ← C

Description

Unconditionally jump to the resultant address from the addition of GPR[Ra] and the 5-bit immediate value specified in the instruction.

Addressing Mode: Base Plus Offset.

2.36 PUSH Push From Stack

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	L	X	X	Ra			0	0	0	0	1

Syntax

PUSH Ra eg. PUSH R3
PUSH LR eg. PUSH LR

Operation

Mem[R7] ← reg; R7 ← R7 - 1

N ← N

Z ← Z

V ← V

C ← C

Description

'reg' corresponds to either a GPR or the link register, the contents of which are stored to the stack using the address stored in the stack pointer (R7). Then Decrement the stack pointer by one.

Addressing Modes: Register-Indirect, Postdecrement.

2.37 POP — Pop From Stack

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	L	X	X	Ra			0	0	0	0	1

Syntax

POP Ra — eg. POP R3
POP LR — eg. POP LR

Operation

R7 ← R7 + 1; Mem[R7] ← reg;

N ← N

Z ← Z

V ← V

C ← C

Description

Increment the stack pointer by one. Then 'reg' corresponds to either a GPR or the link register, the contents of which are retrieved from the stack using the address stored in the stack pointer (R7).

Addressing Modes: Register-Indirect, Preincrement.

2.38 RETI Return From Interrupt

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	0	1	0	0	0	1	1	1	X	X	X	X	X

Syntax

RETI eg. RETI

Operation

PC ← Mem[R7]

N ← N

Z ← Z

V ← V

C ← C

Description

Restore program counter to its value before interrupt occured, which is stored on the stack, pointed to be the stack pointer (R7). This must be the last instruction in an interrupt service routine.

Addressing Mode: Register-Indirect.

2.39 ENAI Enable Interrupts

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	0	1	0	0	1	1	1	1	X	X	X	X	X

Syntax

ENAI eg. ENAI

Operation

Set Interrupt Enable Flag

N ← N

Z ← Z

V ← V

C ← C

Description

Turn on interrupts by setting interrupt enable flag to true (1).

2.40 DISI Disable Interrupts

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	0	1	0	1	0	1	1	1	X	X	X	X	X

Syntax

DISI eg. DISI

Operation

Reset Interrupt Enable Flag

N $\leftarrow$ N

Z $\leftarrow$ Z

V $\leftarrow$ V

C $\leftarrow$ C

Description

Turn off interrupts by setting interrupt enable flag to false (0).

2.41 STF Store Status Flags

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	0	1	0	1	1	1	1	1	X	X	X	X	X

Syntax

STF eg. STF

Operation

Mem[R7] ← {12-bit 0, Z, C, V, N}; R7 ← R7 - 1;

N ← N

Z ← Z

V ← V

C ← C

Description

Store contents of status flags to stack using address held in stack pointer (R7). Then decrement the stack pointer (R7) by one.

Addressing Modes: Register-Indirect, Postdecrement.

2.42 LDF — Load Status Flags

Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	1	0	0	1	1	0	0	1	1	1	X	X	X	X	X

Syntax

LDF eg. LDF

Operation

R7 ← R7 + 1

N ← Mem[R7][0]

Z ← Mem[R7][3]

V ← Mem[R7][1]

C ← Mem[R7][2]

Description

Increment the stack pointer (R7) by one. Then load content of status flags with lower 4 bits of value retrieved from stack using address held in stack pointer (R7).

Addressing Modes: Register-Indirect, Preincrement.

3 Programming Tips

Lorem Ipsum...

Programmg Tips section needs starting and completing

Outline of what to include (in no particular order):

1. Stack pointer usage
2. ISR usage - disabled automatically, first instruction should be STF. Final two LDF and RETI.
3. Sub routine calls and stack frames
4. General branching (use of CMP)
5. Any other tips

4 Assembler

The current instruction set architecture includes an assembler for converting assembly language into hexadecimal. This chapter outlines the required formatting and available features of this assembler.

4.1 Instruction Formatting

Each instruction must be formatted using the following syntax. Here "[...]" indicates an optional field:

```
[.LABELNAME] MNEMONIC, OPERANDS, ..., :[COMMENTS]
```

For example:

```
.loop ADDI, R5, R3, #5 :Add 5 to R3
```

Comments may be added by preceding them with either : or ;

Accepted general purpose register values are: R0, R1, R2, R3, R4, R5, R6, R7, SP. These can be upper or lower case and SP is equivalently evaluated to R7.

Branch instructions take a symbolic reference to the destination. Each type of branch supports moving up to 127 lines forward, or 128 lines backwards. But if a branch is over this limitation, the assembler will automatically create additional instructions to enable greater distances. Each additional branch added will cause two more lines of code to be added to the outputted file.

All label names must begin with a '.' while `.ISR`/`.isr` and `.define` are special cases used for the interrupt service routine and variable definitions respectively.

Instruction-less or comments only lines are allowed within the assembly file.

Special Case Label

The .ISR/.isr label is reserved for the interrupt service routine and may be located anywhere within the file but must finish with a 'RETI' instruction. Branches may occur within the ISR, but are not allowed into this service routine with the exception of a return from a separate subroutine.

4.2 Assembler Directives

Symbolic label names are supported for branch-type instructions. Following the previous syntax definition for '.LABELNAME', they can be used instead of numeric branching provided they branch no further than the maximum distance allowed for the instruction used. Definitions are supported by the assembler. They are used to assign meaningful names to the GPRs to aid with programming. Definitions can occur at any point within the file and create a mapping from that point onwards. Different names can be assigned to the same register, but only one is valid at a time.

The accepted syntax for definitions is:

```
.define NAME REGISTER
```

4.3 Running The Assembler

The assembler is a python executable and is run by typing "./assemble.py". Alternatively, the assembler can be placed in a folder on the users path and executed by running "assemble.py". It supports Python versions 2.4.3 to 2.7.3. A help prompt is given by the script if the usage is not correct, or given a `-h` or `--help` argument.

By default, the script will output the assembled hex to a file with the same name, but with a '.hex' extension in the same directory. The user can specify a different file to use by using a `-o filename.hex` or `--output=filename.hex` argument to the script. The output file can also be a relative or absolute path to a different directory.

The full usage for the script is seen in listing 1. This includes the basic rules for writing the assembly language and a version log.

Listing 1: Assembler help prompt

```
1 Usage: assemble.py [-o outfile] input
```

```
2
3 ---Team R4 Assembler Help---
4
5 -------Version: 1 (CMPI addition onwards)
6                 2 (Changed to final ISA, added special case I's
      and error checking
7                 3 (Ajr changes - Hex output added, bug fix)
8                 4 (Added SP symbol)
9                 5 (NOP support added, help added)
10                6 (Interrupt support added [ENAI, DISI, RETI])
11                7 (Checks for duplicate Labels)
12                8 (Support for any ISR location & automated
      startup code entry)
13                9 (Support for .define)
14               10 (Changed usage)
15     11 (ISR setup shortened, Numeric branching support removed)
16     12 (Branches automatically extended if out of 8-bit range)
17       Current is most recent iteration
18 Input Syntax: ./assemble filename
19 Commenting uses : or ;
20 Labels start with '.': SPECIAL .ISR/.isr -> Interrupt Service
      Routine)
21                        SPECIAL .define -> define new name for
      General Purpose Register, .define NAME R0-R7/SP
22 Instruction Syntax: .[LABELNAME] MNEUMONIC, OPERANDS, ..., :[
      COMMENTS]
23 Registers: R0, R1, R2, R3, R4, R5, R6, R7==SP
24 Branching: Only Symbolic Supported
25
26 Notes:
27        Input files are assumed to end with a .asm extension
28        Immediate value sizes are checked
29        Instruction-less lines allowed
30        .ISR may be located anywhere in file
31        .define may be located anywhere, definition valid from
      location in file onwards, may replace existing definitions
32
33
34 Options:
35   --version             show program's version number and exit
36   -h, --help            show this help message and exit
37   -o FILE, --output=FILE
38                         output file for the assembled output
```

4.4 Error Messages

Code	Description
ERROR1	Instruction mneumonic is not recognized
ERROR2	Register code within instruction is not recognized
ERROR3	Branch condition code is not recognised
ERROR4	Attempting to branch to undefined location
ERROR5	Instruction mneumonic is not recognized
ERROR6	Attempting to shift by more than 16 or perform a negative shift
ERROR7	Magnitude of immediate value for ADDI, ADCI, SUBI, SUCI, LDW or STW is too large
ERROR8	Magnitude of immediate value for CMPI or JMP is too large
ERROR9	Magnitude of immediate value for ADDIB, SUBIB, LUI or LLI is too large
ERROR10	Attempting to jump more than 127 forward or 128 backwards
ERROR11	Duplicate symbolic link names
ERROR12	Illegal branch to ISR
ERROR13	Multiple ISRs in file
ERROR14	Invalid formatting for .define directive

5 Programs

Every example program in this section uses R7 as a stack pointer which is initialised to the by the program to 0x07D0.The simulation environment contains an area of an area of memory with 2048 locations and memory mapped deices. There are 16 switches at location 0x0800, 16 LEDs at location 0x0801 and a serial io device which can be read from location 0xA000 and has a control register at location 0xA001.

5.1 Multiply

The code for the multiply program is held in Appendix A.1 listing 8. A sixteen bit number is read from input switches, split in to lower and upper bytes which are then multiplied. The resulting sixteen bit word is written to the LEDs before reaching a terminating loop. Equation (1) formally describes the algorithm disregarding limitations.

$$A = M \times Q = \sum_{i=0}^{\infty} 2^i M_i Q \ \ where \ \ M_i \in \{0, 1\} \tag{1}$$

The subroutine operation is described in listing 2, using C. If the result is greater than or equal to 2^{16} the subroutine will fail and return zero. The lowest bit of the multiplier controls the accumulator and the overflow check. The multiplier is shifted right and the quotient is shifted left at every iteration. An unconditional branch is used to keep the algorithm in a while loop. The state of the multiplier is compared at every iteration against zero when the algorithm is finished. As size of the multiplier controls the number of iterations a comparison is made on entry to use the smallest operand.

Listing 2: Multiply Subroutine

```
1  uint16_t multi(uint16_t op1, op2){
2      uint16_t A,M,Q;
3      A = 0;
4      if(op1 < op2){                  // Make M small, less loops
5          M = op1; Q = op2;
6      }else{
7          M = op2; Q = op1;
8      }
9      while(1){                       // No loop counter
10         if(M & 0x0001){             // LSb
```

```
11              A = A + Q;
12              if(A > 0xFFFF){         // Using carry flag
13                  return 0;           // Overflow - fail
14              }
15          }
16          M = M >> 1;
17          if(0 == M){
18              return A;               // Finished - pass
19          }
20          if(Q & 0x8000){
21              return 0;               // Q >= 2^16 - fail
22          }
23          Q = Q << 1;
24      }
25  }
```

5.2 Factorial

The code for the factorial program is held in Appendix A.2 listing 9. It is possible to calculate the factorial of any integer value between 0 and 8 inclusive. The subroutine is called which in turn calls the multiply subroutine discussed in section 5.1. The factorial subroutine does no parameter checking but the multiply code does so if overflow does occur zero is propagated and returned; zero is not a possible factorial. The result is calculated recursively as described using C in listing 3. Large values can cause stack overflow the main body of code makes sure inputs, read from the switches, are sufficiently small.

Listing 3: Recursive Factorial Subroutine

```
1  uint16_t fact(uint16_t x){
2      if(x == 0){
3          return 1;                   // 0! = 1
4      }
5      return multi(x,fact(x-1));      // Recurrsive
6  }
```

5.3 Random

The code for the random program is held in Appendix A.3 listing 10. A random series of numbers is achieved by simulating the 16 bit linear feedback

shift register in Figure 2. This produces a new number every 16 sixteen clock cycles so in this case a simulation subroutine is called 16 times. A seed taken from switches and passed to the first subroutine call via the stack is altered and passed to the next subroutine call. No more stack operations are performed. A load from the stack pointer is used write a new random number to LEDs. All contained within an unconditional branch but a loop counter is used control write and reset.

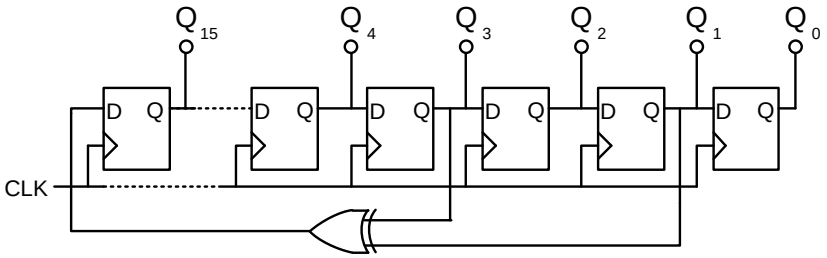


Figure 2: 16 Bit Linear Feedback Shift Register.

A two input XOR gate is simulated using the XOR operation along with shifting to compare bits in different locations. Bits 2 and 4 are used as inputs so a logical shift left by two is used to align them at the bit 4 position. Masking the output value is used feedback to the top bit. This is described using C in listing 4.

Listing 4: Linear Feedback Shift Register Subroutine

```
uint16_t rand(uint16_t last){
    uint16_t next,test;
    next = last >> 1;                   // The shift
    test = last << 2;                   // Compare different bits
    test = test ^ last;
    if(test & 0x0008){                  // Feedback to top
        return (next | 0x8000);
    }
    return next;
}
```

5.4 Interrupt

The code for the interrupt program is held in Appendix A.4 listing 11. This is the most complex example and makes use of both the multiply and factorial

subroutines in sections 5.1 and 5.2 respectively. The interrupt services the serial device by writing data to a 4 byte circular buffer. A main program check to see if data is in the buffer then and if so calculates the factorial writing the result to the LEDs. The buffer is purposefully small to test overflow.

Listing 5: Serial Device Interrupt Service Request

```
#define TOP      0x0206
#define BOTTOM   0x0202
#define WRITE    0x0201
#define READ     0x0200
#define SERIAL   0xA000

isr(){
    uint16_t data,readPtri,writePtr;
    asm("DISI");                    // critical op
    data = read(SERIAL);
    asm("ENAI");                    // nested ints
    readPtr = read(READ);
    writePtr = read(WRITE);
    if(((readPtr-1) == writePtr)     ||
        (readPtr == BOTTOM)          ||
        (writePtr == (TOP-1))        ){
        asm("RETI");                // full, don't write
    }
    if(readPtr == BOTTOM)
    write(readPtr,data);            // write to buffer
    writePtr++;
    if(writePtr == TOP){
        writePtr = BOTTOM;
    }else{
        writePtr++;
    }
    write(WRITE,writePtr);
    asm("RETI")
}

void main(){
    uint16_t readPtr,writePtri,data;
    do{
        readPtr = read(READ);
        writePtr = read(WRITE);
    }while(readPtr == writePtr)
    data = read(readPtr)
```

```
38
39          fact();
40  }
```

6 Simulation

6.1 Running the simulations

A register window could also be done for this section too

A python script, sim.py, was written to automatically invoke the assembler and simulator. The passed program is only assembled if the file exists with an extension of `.asm`. This allows for raw hex to be passed to the simulator where necessary. If a `.hex` file is passed, and a `.asm` file exists of the same name, the assembler will be invoked. The sim.py script is designed to be put on the user's path, allowing for the invocation of the assembler and simulator from anywhere.

The usage for the script is:

```
sim.py [-t type] [-m module.sv / -p program.asm ] [ -s
  switchvalue ] [ -gdS ] [+define+extra_definitions]
```

All simulation types are supported. As well as full system simulations, the sim.py script also allows for other testbenches to be run. All stimulus files are maintained in a directory and the testbenches can be run on verilog or magic modules. Where a Magic design is to be simulated, the script automatically extracts the netlist. This is done to prevent the Magic design and netlist being inconsistent.

The sim.py script provides a help prompt when run with `-h` or `--help` arguments. The help prompt is also displayed when incorrect arguments are supplied. The full help prompt is show in listing **??**.

By default, the graphical user interface is not invoked. This can be done with the `-g` or `--gui` tags. A debug option, `-d`, exists when the user wants to get the majority of the simulation command, but modify it slightly.

The program and module options should never be defined at the same time. One of them, however, should be. The program option is assembled, if necessary, and defined in the simulation command. The module option checks for the testbench file (identified by ¡module¿_stim.sv) within the verification folder. The testbench is then used as the top level module.

The type of simulation can be any of the folders in the verilog directory, for example *behavioural*, *mixed* or *extracted*. A special type, *magic* can be used. When this is done so, the magic folder, `/design/fcde/magic/design`, is checked for the module given. Type *magic* and a program is equivalent to

an extracted type simulation and is treated as such. The type is also given as a definition to the simulator, allowing reuse of test benches.

The value of the switches can be easily defined by using the `-s` tag. The value given after this option is then passed to the simulator as a definition. If other definitions are required (for example, the serial data file), they can be defined, in full, in the trailing arguments. All trailing arguments are appended to the simulation command, allowing for the user to customise the invocation beyond the scope of the script.

A scan path simulation can also be run. This is done by running `./sim.py -S` and allows the same use described above for invoking the GUI. If the `-S` option is defined, any program or module also given is ignored. The scan path test pulses a signal on the SDI line, and verifies a pulse is seen on the output. The clock cycles, and therefore the number of registers, are counted and reported upon success of the simulation.

Listing 6: Help prompt for the sim.py script.

```
Usage: sim.py [-t type] [-m module.sv / -p program.asm ] [ -s
    switchvalue ] [ -gdS ] [+define+extra_definitions]

trailing arguments are given to the simulator directly

Options:
  --version             show program's version number and exit
  -h, --help            show this help message and exit
  -m MODULE, --module=MODULE
                        module to simulate - should not be
    defined if program
                        is
  -t TYPE, --type=TYPE  Type of simulation to run, e.g.
    behavioural (default),
                        mixed, extracted, magic
  -p PROGRAM, --prog=PROGRAM
                        program to run should not be defined if
    module is. Hex
                        or ASM can be passed. ASM files will be
    assembled
                        before running the simulator.
  -g, --gui             Run the simulation with a GUI
  -s SWITCHES, --switches=SWITCHES
                        Value of switches to pass to the
    simulation
  -d                    Make, but don't execute, the command
  -S, --scanpath        Run the scan path simulation
```

6.2 Serial Data

The serial data file used is located in the programs directory. This is a hex file with white space separated values of the form "time data". The data is then sent at the time to the processor by the serial module. An example serial data hex file is shown in listing 7.

Listing 7: Example serial data file

```
// Hex file to specify serial data input
//
//
  248   7
  48F   6
  6D6   5
  91D   4
  B64   7
  DAB   5
  36B1    3
  6D61    2
```

6.3 Run Time

The number of clock cycles for each program to fully run is shown in table 1. Factorial run time is given for an input of 8 and is the worst case. Interrupt is dependant on the serial data input and the time is given for the serial data file mentioned above.

6.4 Simulation

A dissembler is also implemented in System Verilog to aid debugging. It is an ASCII formatted array implemented at the top level of the simulation. It is capable of reading the instruction register with in the design, and reconstructing the assembly language of the instruction and is supported in behavioural, mixed and extracted simulations. It will show the opcode, register addresses and immediate values. It is automatically included by the TCL script. The TCL script also opens a waveform window and adds important signals.

Table 1: Clock cycles required for each program to run

Make these more accurate when AJR has finished playing around

Program	Clock Cycles
Multiply	900
Factorial	6000
Random	
Interrupt	30000

Put a screen shot of the waveform window?

A Code Listings

All code listed in this section is passed to the assembler *as is* and has been verfied using the final design of the processor.

A.1 Multiply

Listing 8: multiply.asm

```
1         ADDIB R0,#0
2         ADDIB R0,#0
3         ADDIB R0,#0
4         ADDIB R0,#0
5         ADDIB R0,#0
6         ADDIB R0,#0
7         ADDIB R0,#0
8         ADDIB R0,#0
9         ADDIB R0,#0
10        ADDIB R0,#0
11        ADDIB R0,#0
12        ADDIB R0,#0
13        ADDIB R0,#0
14        ADDIB R0,#0
15        ADDIB R0,#0
16        ADDIB R0,#0
17        ADDIB R0,#0
18        ADDIB R0,#0
19        LUI     SP, #7        ; Init SP
20        LLI     SP, #208
21        LUI     R3, #8        ; SWs addr
22        LLI     R3, #0
23        LDW     R0,[R3,#0]    ; READ SWs
24        LUI     R1, #0
25        LLI     R1, #255      ; 0x00FF in R1
26        AND     R1,R0,R1      ; Lower byte SWs in R1
27        LSR     R0,R0,#8      ; Upper byte SWs in R0
28        PUSH    R0            ; Op1
29        PUSH    R1            ; Op2
30        SUB     R2,R2,R2      ; Zero required
31        PUSH    R2            ; Place holder is zero
32        BWL     .multi        ; Run Subroutine
33        POP     R1            ; Result
34        ADDIB   SP,#2         ; Duummy pop
35        ADDIB   R3,#1         ; Address of LEDS
```

```
36          STW     R1,[R3,#0]   ; Result on LEDS
37  .end    BR      .end         ; Finish loop
38  .multi  PUSH    R0
39          PUSH    R1
40          PUSH    R2
41          PUSH    R3
42          PUSH    R4
43          PUSH    R5
44          PUSH    R6
45          LDW     R0,[SP,#8]   ; R0 - Multiplier
46          LDW     R1,[SP,#9]   ; R1 - Quotient
47          CMP     R0,R1
48          BLT     .nSw         ; Branch if M < Q
49          ADDI    R2,R1,#0     ; Make M the smallest
50          ADDI    R1,R0,#0
51          ADDI    R0,R2,#0
52  .nSw    SUB     R2,R2,R2     ; R2 - Accumulator
53          ADDI    R3,R2,#1     ; R3 - 0x0001
54          LUI     R4,#128      ; R4 - 0x8000
55          LLI     R4,#0
56  .mloop  AND     R6,R0,R3     ; R6 - Cmp var
57          CMPI    R6,#1
58          BNE     .nAcc
59          SUB     R3,R3,R3
60          ADD     R2,R2,R1     ; A = A + Q
61          ADCI    R3,R3,#1
62          CMPI    R3,#2
63          BE      .fail        ; OV
64  .nAcc   LSR     R0,R0,#1     ; M = M >> 1
65          CMPI    R0,#0
66          BE      .done
67          AND     R5,R4,R1
68          CMPI    R5,#0
69          BNE     .fail
70          LSL     R1,R1,#1     ; Q = Q << 1
71          BR      .mloop
72  .done   STW     R2,[SP,#7]   ; Res on stack frame
73          POP     R6
74          POP     R5
75          POP     R4
76          POP     R3
77          POP     R2
78          POP     R1
79          POP     R0
80          RET
```

```
81 .fail   SUB    R2,R2,R2    ; OV - ret 0
82         BR     .done
```

A.2 Factorial

Listing 9: factorial.asm

```
1          ADDIB  R0,#0
2          ADDIB  R0,#0
3          ADDIB  R0,#0
4          ADDIB  R0,#0
5          ADDIB  R0,#0
6          ADDIB  R0,#0
7          ADDIB  R0,#0
8          ADDIB  R0,#0
9          ADDIB  R0,#0
10         ADDIB  R0,#0
11         ADDIB  R0,#0
12         ADDIB  R0,#0
13         ADDIB  R0,#0
14         ADDIB  R0,#0
15         ADDIB  R0,#0
16         ADDIB  R0,#0
17         ADDIB  R0,#0
18         ADDIB  R0,#0
19         LUI    R7, #7
20         LLI    R7, #208
21         LUI    R0, #8       ; Address in R0
22         LLI    R0, #0
23         LDW    R1,[R0,#0]   ; Read switches into R1
24         PUSH   R1           ; Pass para
25         BWL    .fact        ; Run Subroutine
26         POP    R3           ; Para overwritten with result
27         ADDIB  R0,#1
28         STW    R3,[R0,#0]   ; Result on LEDS
29 .end    BR     .end         ;  finish loop
30 .fact   PUSH   R0
31         PUSH   R1
32         PUSH   LR
33         LDW    R1,[SP,#3]   ; Get para
34         ADDIB  R1,#0
35         BE     .retOne        ; 0! = 1
36         SUBI   R0,R1,#1
37         PUSH   R0           ; Pass para
```

```
38          BWL     .fact           ; The output remains on the stack
39          PUSH    R1              ; Pass para
40          SUBIB   SP,#1           ; Placeholder
41          BWL     .multi
42          POP     R1              ; Get res
43          ADDIB   SP,#2           ; pop x 2
44          STW     R1,[SP,#3]
45          POP     LR
46          POP     R1
47          POP     R0
48          RET
49  .retOne ADDIB   R1,#1           ; Avoid jump checking
50          STW     R1,[SP,#3]
51          POP     LR
52          POP     R1
53          POP     R0
54          RET
55  .multi  PUSH    R0
56          PUSH    R1
57          PUSH    R2
58          PUSH    R3
59          PUSH    R4
60          PUSH    R5
61          PUSH    R6
62          LDW     R0,[SP,#8]      ; R0 - Multiplier
63          LDW     R1,[SP,#9]      ; R1 - Quotient
64          CMP     R0,R1
65          BLT     .nSw            ; Branch if M < Q
66          ADDI    R2,R1,#0        ; Make M the smallest
67          ADDI    R1,R0,#0
68          ADDI    R0,R2,#0
69  .nSw    SUB     R2,R2,R2        ; R2 - Accumulator
70          ADDI    R3,R2,#1        ; R3 - 0x0001
71          LUI     R4,#128         ; R4 - 0x8000
72          LLI     R4,#0
73  .mloop  AND     R6,R0,R3        ; R6 - Cmp var
74          CMPI    R6,#1
75          BNE     .nAcc
76          SUB     R3,R3,R3
77          ADD     R2,R2,R1        ; A = A + Q
78          ADCI    R3,R3,#1
79          CMPI    R3,#2
80          BE      .fail           ; OV
81  .nAcc   LSR     R0,R0,#1        ; M = M >> 1
82          CMPI    R0,#0
```

```
83              BE      .done
84              AND     R5,R4,R1
85              CMPI    R5,#0
86              BNE     .fail
87              LSL     R1,R1,#1        ; Q = Q << 1
88              BR      .mloop
89  .done       STW     R2,[SP,#7]      ; Res on stack frame
90              POP     R6
91              POP     R5
92              POP     R4
93              POP     R3
94              POP     R2
95              POP     R1
96              POP     R0
97              RET
98  .fail       SUB     R2,R2,R2        ; OV - ret 0
99              BR      .done
```

A.3 Random

Listing 10: random.asm

```
1               ADDIB   R0,#0
2   ADDIB       R0,#0
3   ADDIB       R0,#0
4   ADDIB       R0,#0
5   ADDIB       R0,#0
6   ADDIB       R0,#0
7   ADDIB       R0,#0
8   ADDIB       R0,#0
9   ADDIB       R0,#0
10  ADDIB       R0,#0
11  ADDIB       R0,#0
12  ADDIB       R0,#0
13  ADDIB       R0,#0
14  ADDIB       R0,#0
15  ADDIB       R0,#0
16  ADDIB       R0,#0
17  ADDIB       R0,#0
18  ADDIB       R0,#0
19  ADDIB       R0,#0
20              LUI     SP,#7           ; Init SP
21              LLI     SP,#208
22              LUI     R0,#8           ; SW Address in R0
```

```
23          LLI     R0,#0
24          LDW     R1,[R0,#0]  ; Read switches into R1
25          ADDIB   R0,#1       ; Address of LEDS in R0
26          PUSH    R1
27  .reset  SUB     R4,R4,R4    ; Reset Loop counter
28  .loop   BWL     .rand
29          CMPI    R4,#15
30          BE      .write
31          ADDIB   R4,#1       ; INC loop counter
32          BR      .loop
33  .write  LDW     R1,[SP,#0]  ; No pop as re-run
34          STW     R1,[R0,#0]  ; Result on LEDS
35          BR      .reset
36  .rand   PUSH    R0          ; LFSR Sim
37          PUSH    R1          ; Protect regs
38          PUSH    R2
39          LDW     R0,[SP,#3]  ; Last reg value
40          LSL     R1,R0,#2    ; Shift Bit 4 <- 2
41          XOR     R1,R0,R1    ; xor Gate
42          LSR     R0,R0,#1    ; Shifted reg
43          LUI     R2,#0
44          LLI     R2,#8
45          AND     R1,R2,R1    ; Mask off Bit 4
46          CMPI    R1,#0
47          BNE     .done
48          LUI     R1,#128
49          LLI     R1,#0
50          OR      R0,R0,R1    ; or with 0x8000
51  .done   STW     R0,[SP,#3]
52          POP     R2
53          POP     R1
54          POP     R0
55          RET
```

A.4 Interrupt

Listing 11: interrupt.asm

```
1           ADDIB R0,#0
2           ADDIB R0,#0
3           ADDIB R0,#0
4           ADDIB R0,#0
5           ADDIB R0,#0
6           ADDIB R0,#0
```

```
7           ADDIB R0,#0
8           ADDIB R0,#0
9           ADDIB R0,#0
10          ADDIB R0,#0
11          ADDIB R0,#0
12          ADDIB R0,#0
13          ADDIB R0,#0
14          ADDIB R0,#0
15          ADDIB R0,#0
16          ADDIB R0,#0
17          ADDIB R0,#0
18          ADDIB R0,#0
19          DISI                ; Reset is off anyway
20          LUI     R7, #7
21          LLI     R7, #208
22          LUI     R0, #2      ; R0 is read ptr    0x0200
23          LLI     R0, #0
24          ADDI    R1,R0,#2    ; 0x0202
25          STW     R1,[R0,#0]  ; Read ptr set to   0x0202
26          STW     R1,[R0,#1]  ; Write ptr set to  0x0202
27          LUI     R0,#160     ; Address of Serial control reg
28          LLI     R0,#1
29          LUI     R1,#0
30          LLI     R1,#1       ; Data to enable ints
31          STW     R1,[R0,#0]  ; Store 0x001 @ 0xA001
32          ENAI
33          BR      .main
34  .isr    STF                 ; Keep flags, disable auto
35          PUSH    R0          ; Save only this for now
36          LUI     R0,#160
37          LLI     R0,#0
38          LDW     R0,[R0,#0]  ; R1 contains read serial data
39          ENAI                ; Don't miss event
40          PUSH    R1
41          PUSH    R2
42          PUSH    R3
43          PUSH    R4
44          LUI     R1,#2
45          LLI     R1,#0
46          LDW     R2,[R1,#0]  ; R2 contains read ptr
47          ADDI    R3,R1,#1
48          LDW     R4,[R3,#0]  ; R4 contain the write ptr
49          SUBIB   R2,#1       ; Get out if W == R - 1
50          CMP     R4,R2
51          BE      .isrOut
```

```
52              ADDIB   R2,#1
53              LUI     R1,#2
54              LLI     R1,#2
55              CMP     R2,R1
56              BNE     .write
57              ADDIB   R1,#3
58              CMP     R4,R1
59              BE      .isrOut
60  .write      STW     R0,[R4,#0]   ; Write to buffer
61              ADDIB   R4,#1
62              LUI     R1,#2
63              LLI     R1,#6
64              CMP     R1,R4
65              BNE     .wrapW
66              SUBIB   R4,#4
67  .wrapW      STW     R4,[R3,#0]   ; Inc write ptr
68  .isrOut     POP     R4
69              POP     R3
70              POP     R2
71              POP     R1
72              POP     R0
73              LDF
74              RETI
75  .main       LUI     R0, #2       ; Read ptr address in R0
76              LLI     R0, #0
77              LDW     R2,[R0,#0]   ; Read ptr in R2
78              LDW     R3,[R0,#1]   ; Write ptr in R3
79              CMP     R2,R3
80              BE      .main        ; Jump back if the same
81              LDW     R3,[R2,#0]   ; Load data out of buffer
82              ADDIB   R2,#1        ; Inc read ptr
83              SUB     R0,R0,R0
84              LUI     R0,#2
85              LLI     R0,#6
86              SUB     R0,R0,R2
87              BNE     .wrapR
88              SUBIB   R2,#4
89  .wrapR      LUI     R0, #2       ; Read ptr address in R0
90              LLI     R0, #0
91              STW     R2,[R0,#0]   ; Store new read pointer
92              SUB     R4,R4,R4
93              LLI     R4,#15
94              AND     R3,R4,R3
95              CMPI    R3,#8
96              BE      .do
```

```
97          LLI     R4,#7
98          AND     R3,R3,R4
99  .do     PUSH    R3
100         BWL     .fact
101         POP     R3
102         LUI     R4,#8
103         LLI     R4,#1       ; Address of LEDs
104         STW     R3,[R4,#0]  ; Put factorial on LEDs
105         BR      .main           ; look again
106 .fact   PUSH    R0
107         PUSH    R1
108         PUSH    LR
109         LDW     R1,[SP,#3]  ; Get para
110         ADDIB   R1,#0
111         BE      .retOne         ; 0! = 1
112         SUBI    R0,R1,#1
113         PUSH    R0          ; Pass para
114         BWL     .fact       ; The output remains on the stack
115         PUSH    R1          ; Pass para
116         SUBIB   SP,#1       ; Placeholder
117         BWL     .multi
118         POP     R1          ; Get res
119         ADDIB   SP,#2       ; pop x 2
120         STW     R1,[SP,#3]
121         POP     LR
122         POP     R1
123         POP     R0
124         RET
125 .retOne ADDIB   R1,#1       ; Avoid jump checking
126         STW     R1,[SP,#3]
127         POP     LR
128         POP     R1
129         POP     R0
130         RET
131 .multi  PUSH    R0
132         PUSH    R1
133         PUSH    R2
134         PUSH    R3
135         PUSH    R4
136         PUSH    R5
137         PUSH    R6
138         LDW     R0,[SP,#8]  ; R0 - Multiplier
139         LDW     R1,[SP,#9]  ; R1 - Quotient
140         CMP     R0,R1
141         BLT     .nSw        ; Branch if M < Q
```

```
142             ADDI    R2,R1,#0        ; Make M the smallest
143             ADDI    R1,R0,#0
144             ADDI    R0,R2,#0
145 .nSw         SUB     R2,R2,R2        ; R2 - Accumulator
146             ADDI    R3,R2,#1        ; R3 - 0x0001
147             LUI     R4,#128         ; R4 - 0x8000
148             LLI     R4,#0
149 .mloop       AND     R6,R0,R3        ; R6 - Cmp var
150             CMPI    R6,#1
151             BNE     .nAcc
152             SUB     R3,R3,R3
153             ADD     R2,R2,R1        ; A = A + Q
154             ADCI    R3,R3,#1
155             CMPI    R3,#2
156             BE      .fail           ; OV
157 .nAcc       LSR     R0,R0,#1        ; M = M >> 1
158             CMPI    R0,#0
159             BE      .done
160             AND     R5,R4,R1
161             CMPI    R5,#0
162             BNE     .fail
163             LSL     R1,R1,#1        ; Q = Q << 1
164             BR      .mloop
165 .done       STW     R2,[SP,#7]      ; Res on stack frame
166             POP     R6
167             POP     R5
168             POP     R4
169             POP     R3
170             POP     R2
171             POP     R1
172             POP     R0
173             RET
174 .fail       SUB     R2,R2,R2        ; OV - ret 0
175             BR      .done
```