

ELEC6027 - VLSI Design Project Programmers Guide

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*Todo list

■ Programmng Tips section needs starting and completing	55
■ Standardise all references to instructions	55
■ repetition here with next section	56
■ If the asm supports errors about the required instructions, mention this here	57
■ give minimum pulse time for the nIRQ to be held to guarentee entering the ISR	57
■ check ISR references. Make the first in full and acronym then on . .	57
■ A register window could also be done for this section too	69
■ Put a screen shot of the waveform window?	71
■ Make these more accurate when AJR has finished playing around .	72

Contents

1	Introduction	7
1.1	Architecture	7
1.2	Register Description	7
2	Instruction Set	11
2.1	General Instruction Formatting	12
2.2	ADD	14
2.3	ADDI	15
2.4	ADDIB	16
2.5	ADC	17
2.6	ADCI	18
2.7	NEG	19
2.8	SUB	20
2.9	SUBI	21
2.10	SUBIB	22
2.11	SUC	23
2.12	SUCI	24
2.13	CMP	25
2.14	CMPI	26
2.15	AND	27
2.16	OR	28
2.17	XOR	29
2.18	NOT	30
2.19	NAND	31
2.20	NOR	32
2.21	LSL	33
2.22	LSR	34
2.23	ASR	35
2.24	LDW	36
2.25	STW	37
2.26	LUI	38
2.27	LLI	39
2.28	BR	40
2.29	BNE	41
2.30	BE	42

2.31	BLT	43
2.32	BGE	44
2.33	BWL	45
2.34	RET	46
2.35	JMP	47
2.36	PUSH	48
2.37	POP	49
2.38	RETI	50
2.39	ENAI	51
2.40	DISI	52
2.41	STF	53
2.42	LDF	54
3	Programming Tips	55
3.1	Branching	55
3.2	Stack Pointer Usage	55
3.3	Sub routine calling convention	55
3.4	Interrupt Service Routines	55
4	Assembler	59
4.1	Instruction Formatting	59
4.2	Assembler Directives	60
4.3	Running The Assembler	60
4.4	Error Messages	62
5	Programs	63
5.1	Multiply	63
5.2	Factorial	64
5.3	Random	64
5.4	Interrupt	65
6	Simulation	69
6.1	Running the simulations	69
6.2	Serial Data	71
6.3	Run Time	71
6.4	Simulation	71

A	Code Listings	73
A.1	Multiply	73
A.2	Factorial	75
A.3	Random	77
A.4	Interrupt	78

SAMURAI: Programmers Guide

1 Introduction

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

The processor is called SAMURAI - **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 SAMURAI 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.

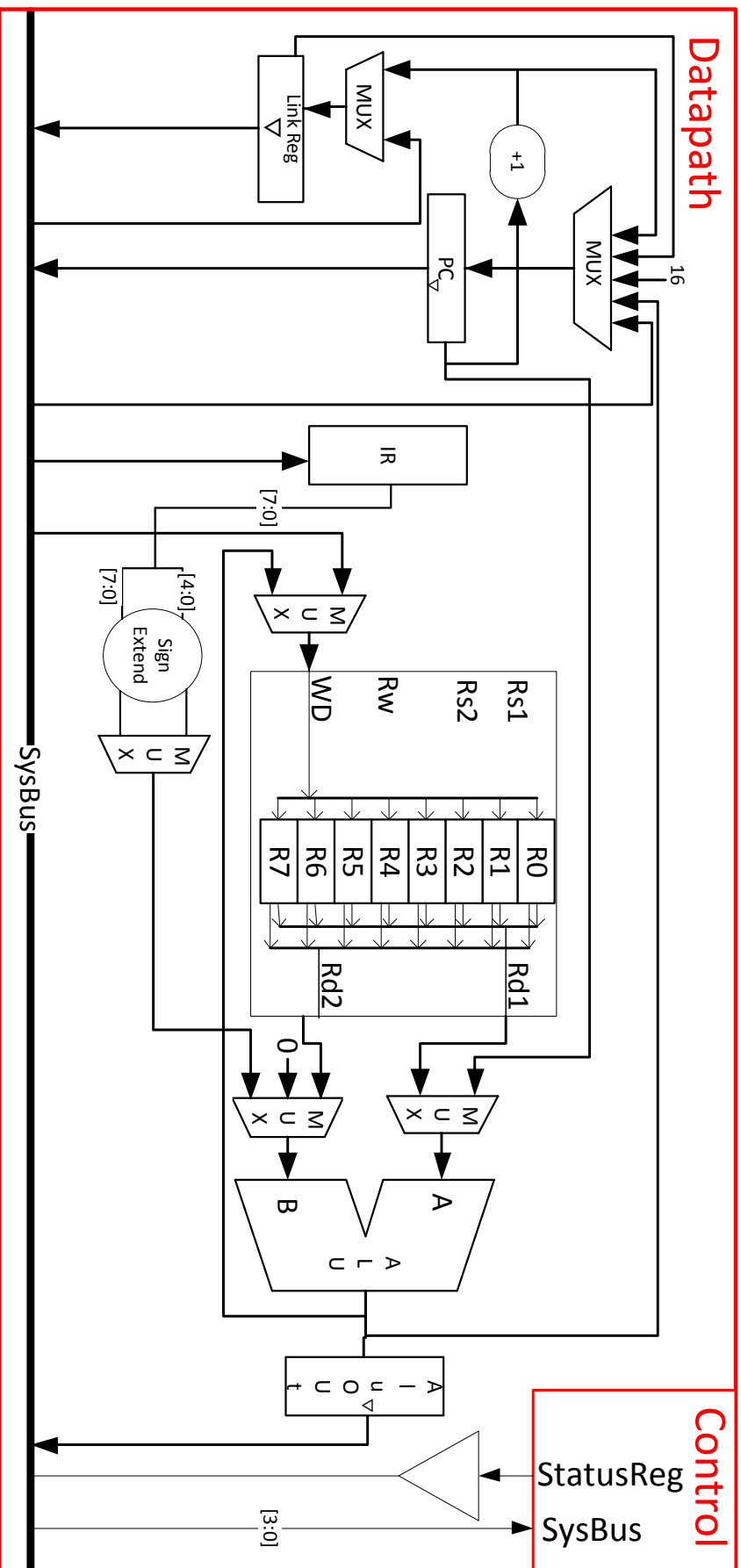


Figure 1: The Architecture diagram of the SAMURAI processor.

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	
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

$Rd \leftarrow Ra + Rb$

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

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

$V \leftarrow \text{if (Ra} > 0 \text{ and Rb} > 0 \text{ and Result} < 0) \text{ or}$
 $(\text{Ra} < 0 \text{ and Rb} < 0 \text{ and Result} > 0) \text{ then } 1, \text{ else } 0$

$C \leftarrow \text{if (Result} > 2^{16} - 1) \text{ or}$
 $(\text{Result} < -2^{16}) \text{ then } 1, \text{ else } 0$

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

$Rd \leftarrow Ra + \#imm5$

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

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

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

$(Ra < 0 \text{ and } \#imm5 < 0 \text{ and } \text{Result} > 0) \text{ then } 1, \text{ else } 0$

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

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

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

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

Syntax

ADDIB Rd, #imm8

eg. ADDIB R5, #93

Operation

$Rd \leftarrow Rd + \#imm8$

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

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

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

$(Rd < 0 \text{ and } \#imm8 < 0 \text{ and } Result > 0) \text{ then } 1, \text{ else } 0$

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

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

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

$Rd \leftarrow Ra + Rb + C$

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

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

$V \leftarrow \text{if } (Ra > 0 \text{ and } (Rb + CFlag) > 0 \text{ and } \text{Result} < 0) \text{ or}$
 $(Ra < 0 \text{ and } (Rb + CFlag) < 0 \text{ and } \text{Result} > 0) \text{ then } 1, \text{ else } 0$

$C \leftarrow \text{if } (\text{Result} > 2^{16} - 1) \text{ or}$
 $(\text{Result} < -2^{16}) \text{ then } 1, \text{ else } 0$

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

$Rd \leftarrow Ra + \#imm5 + C$

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

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

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

$(Ra < 0 \text{ and } (\#imm5 + CFlag) < 0 \text{ and } Result > 0) \text{ then } 1, \text{ else } 0$

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

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

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

$Rd \leftarrow 0 - Ra$

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

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

$V \leftarrow 0$

$C \leftarrow 0$

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

$Rd \leftarrow Ra - Rb$

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

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

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

$(Ra < 0 \text{ and Rb} < 0 \text{ and Result} > 0) \text{ then } 1, \text{ else } 0$

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

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

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

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

Syntax

SUBI Rd, Ra, #imm5

eg. SUBI R5, R3, #7

Operation

$Rd \leftarrow Ra - \#imm5$

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

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

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

$(Ra < 0 \text{ and } \#imm5 < 0 \text{ and } \text{Result} > 0) \text{ then } 1, \text{ else } 0$

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

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

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

 $Rd \leftarrow Rd - \#imm8$ $N \leftarrow \text{if } (Result < 0) \text{ then } 1, \text{ else } 0$ $Z \leftarrow \text{if } (Result = 0) \text{ then } 1, \text{ else } 0$ $V \leftarrow \text{if } (Rd > 0 \text{ and } \#imm8 > 0 \text{ and } Result < 0) \text{ or}$ $(Rd < 0 \text{ and } \#imm8 < 0 \text{ and } Result > 0) \text{ then } 1, \text{ else } 0$ $C \leftarrow \text{if } (Result > 2^{16} - 1) \text{ or}$ $(Result < -2^{16}) \text{ then } 1, \text{ else } 0$

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

$Rd \leftarrow Ra - Rb - C$

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

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

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

$(Ra < 0 \text{ and } (Rb - CFlag) < 0 \text{ and } \text{Result} > 0) \text{ then } 1, \text{ else } 0$

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

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

Description

The 16-bit word in GPR[Rb] 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-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 $Rd \leftarrow Ra - \#imm5 - C$ $N \leftarrow \text{if } (Result < 0) \text{ then } 1, \text{ else } 0$ $Z \leftarrow \text{if } (Result = 0) \text{ then } 1, \text{ else } 0$ $V \leftarrow \text{if } (Ra > 0 \text{ and } (\#imm5 - CFlag) > 0 \text{ and } Result < 0) \text{ or}$ $(Ra < 0 \text{ and } (\#imm5 - CFlag) < 0 \text{ and } Result > 0) \text{ then } 1, \text{ else } 0$ $C \leftarrow \text{if } (Result > 2^{16} - 1) \text{ or}$ $(Result < -2^{16}) \text{ then } 1, \text{ else } 0$ **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

$Ra - Rb$

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

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

$V \leftarrow \text{if } (Ra > 0 \text{ and } Rb > 0 \text{ and } \text{Result} < 0) \text{ or}$
 $(Ra < 0 \text{ and } Rb < 0 \text{ and } \text{Result} > 0) \text{ then } 1, \text{ else } 0$

$C \leftarrow \text{if } (\text{Result} > 2^{16} - 1) \text{ or}$
 $(\text{Result} < -2^{16}) \text{ then } 1, \text{ else } 0$

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

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

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

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

$(\text{Ra} < 0 \text{ and } \#imm5 < 0 \text{ and Result} > 0) \text{ then } 1, \text{ else } 0$

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

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

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

$Rd \leftarrow Ra \text{ AND } Rb$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

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

Syntax

OR Rd, Ra, Rb

eg. OR R5, R3, R2

Operation

$Rd \leftarrow Ra \text{ OR } Rb$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow Ra \text{ XOR } Rb$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow \text{NOT } Ra$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow Ra \text{ NAND } Rb$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow Ra \text{ NOR } Rb$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

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

Syntax

LSL Rd, Ra, #imm4

eg. LSL R5, R3, #7

Operation

$Rd \leftarrow Ra \ll \#imm4$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

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

Syntax

LSR Rd, Ra, #imm4

eg. LSR R5, R3, #7

Operation

$Rd \leftarrow Ra \gg \#imm4$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow Ra \ggg \#imm4$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

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

$Rd \leftarrow \text{Mem}[Ra + \#imm5]$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

$\text{Mem}[\text{Ra} + \#imm5] \leftarrow \text{Rd}$

$\text{N} \leftarrow \text{N}$

$\text{Z} \leftarrow \text{Z}$

$\text{V} \leftarrow \text{V}$

$\text{C} \leftarrow \text{C}$

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

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

Syntax

LUI Rd #imm8

eg. LUI R5, #93

Operation

$Rd \leftarrow \{\#imm8, 0\}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

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

Syntax

LLI Rd #imm8

eg. LLI R5, #93

Operation

$Rd \leftarrow \{Rd[15:8], \#imm8\}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

$PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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) $PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

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

Syntax

BE LABEL

eg. BE .loop

Operation

if (z=1) $PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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) $PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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) $PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

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

Syntax

BWL LABEL

eg. BWL .loop

Operation

$LR \leftarrow PC + 1$; $PC \leftarrow PC + \#imm8$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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 \leftarrow LR

N \leftarrow N

Z \leftarrow Z

V \leftarrow V

C \leftarrow C

Description

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

Addressing Mode: Register-Indirect.

2.35 JMP

Jump

Format

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

Syntax

JMP Ra, #imm5

eg. JMP R3, #7

Operation

$PC \leftarrow Ra + \#imm5$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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 $\text{Mem}[\text{R7}] \leftarrow \text{reg}; \text{R7} \leftarrow \text{R7} - 1$ $\text{N} \leftarrow \text{N}$ $\text{Z} \leftarrow \text{Z}$ $\text{V} \leftarrow \text{V}$ $\text{C} \leftarrow \text{C}$ **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

$R7 \leftarrow R7 + 1$; $\text{Mem}[R7] \leftarrow \text{reg}$;

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

$PC \leftarrow \text{Mem}[R7]$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

Description

Restore program counter to its value before interrupt occurred, 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

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

$$\text{Mem}[\text{R7}] \leftarrow \{12\text{-bit } 0, Z, C, V, N\}; \text{R7} \leftarrow \text{R7} - 1;$$

$$N \leftarrow N$$

$$Z \leftarrow Z$$

$$V \leftarrow V$$

$$C \leftarrow C$$

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

$R7 \leftarrow R7 + 1$

$N \leftarrow \text{Mem}[R7][0]$

$Z \leftarrow \text{Mem}[R7][3]$

$V \leftarrow \text{Mem}[R7][1]$

$C \leftarrow \text{Mem}[R7][2]$

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

Programmg Tips section needs starting and completing

This section gives hints and tips about programming for the SAMURAI processor.

3.1 Branching

Explanation of the branches available.

use of CMP and CMPI

a little bit of code

3.2 Stack Pointer Usage

3.3 Sub routine calling convention

3.4 Interrupt Service Routines

Standardise all references to instructions

On reset, interrupts are disabled on the SAMURAI processor. Two instructions are used to enable and disable interrupts, ENAI, DISI. These set or clear an internal flag with in the control unit. It is not accessible to the user for reading or branching on it's value. The use of interrupts requires the use of R7 as the stack pointer. The stack pointer should be set up before interrupts are enabled in the program.

The nIRQ signal to the SAMURAI processor is an active low, level triggered signal. If the interrupt occurs during an instruction, the instruction is completed before the Interrupt Service Routine is entered. Before the ISR is started, the Program Counter value is stored to the stack. Also, interrupts are automatically disabled once an interrupt is triggered to prevent the processor being continually interrupted. Interrupts must be re-enabled before the ISR is completed by the ENAI instruction. The first instruction in the ISR **must be** the store flags instruction (STF). The final two instructions in the ISR **must be** load flags (LDF) and return from interrupt (RETI). The user is responsible for saving all the registers and restoring them before returning.

Nested interrupts are supported on the SAMURAI if required. The initial interrupt must first be cleared. Interrupts can then be re-enabled. If a new interrupt occurs, the ISR is run. Once the second ISR is completed, the program flow is returned to where it was before hand and the first ISR run is then complete.

The ISR can also conduct a function call. However, this is not recommended as the ISR should be short in length.

The general outline for the ISR is:

1. Store Flags
2. Push registers to stack
3. Clear interrupt source
4. Enable interrupts
5. Process data
6. Restore registers
7. Load Flags
8. Return from Interrupt

repetition here with next section

The ISR is implemented by using the “.isr” or “.ISR” label. It can be placed anywhere in the code and be any length. A general outline in assembly language is shown in listing 1. This structure should be followed for the ISR.

Listing 1: Example outline for the Interrupt Service Routine

```
1 LUI      R7, #7          ;set up stack pointer
2 LLI      R7, #208
3 ENAI                      ;enable the interrupts
4 BR .main                ;go to main
5 .isr      STF            ;store flags
6     PUSH R0              ;free some registers to use
7     PUSH R1
8     PUSH R2
9     ;clear interrupt source
10    ENAI                ;enable interrupts
11    ;process data if necessary
```



```
12     POP R2    ;restore the registers in reverse order
13     POP R1
14     POP R0
15     LDF ;load the flags
16     RETI     ;end of the ISR
```

If the asm supports errors about the required instructions, mention this here

give minimum pulse time for the nIRQ to be held to guarantee entering the ISR

check ISR references. Make the first in full and acronym then on

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 2. This includes the basic rules for writing the assembly language and a version log.

Listing 2: 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 mnemonic 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 mnemonic 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 9. 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.

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

The subroutine operation is described in listing 3, 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 3: 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 10. 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 4. Large values can cause stack overflow the main body of code makes sure inputs, read from the switches, are sufficiently small.

Listing 4: 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));  // Recursive
6  }

```

5.3 Random

The code for the random program is held in Appendix A.3 listing 11. 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.

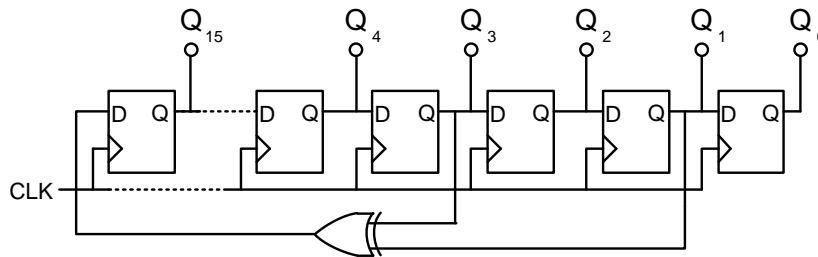


Figure 2: 16 Bit Linear Feedback Shift Register.

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 5.

Listing 5: Linear Feedback Shift Register Subroutine

```

1 uint16_t rand(uint16_t last){
2     uint16_t next, test;
3     next = last >> 1;           // The shift
4     test = last << 2;           // Compare different bits
5     test = test ^ last;
6     if(test & 0x0008){          // Feedback to top
7         return (next | 0x8000);
8     }
9     return next;
10 }
```

5.4 Interrupt

The code for the interrupt program is held in Appendix A.4 listing 12. 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 6: Serial Device Interrupt Service Request

```

1 #define TOP      0x0206
2 #define BOTTOM   0x0202
3 #define WRITE    0x0201
4 #define READ     0x0200
5 #define SERIAL   0xA000
6
7 isr() {
8     uint16_t data, readPtr, writePtr;
9     asm("DISI");           // critical op
10    data = read(SERIAL);
11    asm("ENAI");           // nested ints
12    readPtr = read(READ);
13    writePtr = read(WRITE);
14    if(((readPtr-1) == writePtr) ||
15        (readPtr == BOTTOM) ||
16        (writePtr == (TOP-1))) {
17        asm("RETI");       // full, don't write
18    }
19    if(readPtr == BOTTOM)
20        write(readPtr, data); // write to buffer
21    writePtr++;
22    if(writePtr == TOP) {
23        writePtr = BOTTOM;
24    } else {
25        writePtr++;
26    }
27    write(WRITE, writePtr);
28    asm("RETI")
29 }
30
31 void main() {
32     uint16_t readPtr, writePtr, data;
33     do {
34         readPtr = read(READ);
35         writePtr = read(WRITE);
36     } while(readPtr == writePtr)
37     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 shown 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 `jmodule_i_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 7: Help prompt for the `sim.py` script.

```

1 Usage: sim.py [-t type] [-m module.sv / -p program.asm ] [ -s
   switchvalue ] [ -gdS ] [+define+extra_definitions]
2
3 trailing arguments are given to the simulator directly
4
5 Options:
6   --version                show program's version number and exit
7   -h, --help              show this help message and exit
8   -m MODULE, --module=MODULE
9                           module to simulate - should not be
   defined if program
10                           is
11   -t TYPE, --type=TYPE    Type of simulation to run, e.g.
   behavioural (default),
12                           mixed, extracted, magic
13   -p PROGRAM, --prog=PROGRAM
14                           program to run should not be defined if
   module is. Hex
15                           or ASM can be passed. ASM files will be
   assembled
16                           before running the simulator.
17   -g, --gui              Run the simulation with a GUI
18   -s SWITCHES, --switches=SWITCHES
19                           Value of switches to pass to the
   simulation
20   -d                      Make, but don't execute, the command
21   -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 8.

Listing 8: Example serial data file

```

1 // Hex file to specify serial data input
2 //
3 //
4 248 7
5 48F 6
6 6D6 5
7 91D 4
8 B64 7
9 DAB 5
10 36B1 3
11 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 verified using the final design of the processor.

A.1 Multiply

Listing 9: 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       ; Dummy 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 10: 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 11: 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 12: 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

```