

# ELEC6027 - VLSI Design Project Programmers Guide

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# SAMURAI: Programmers Guide

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# 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.

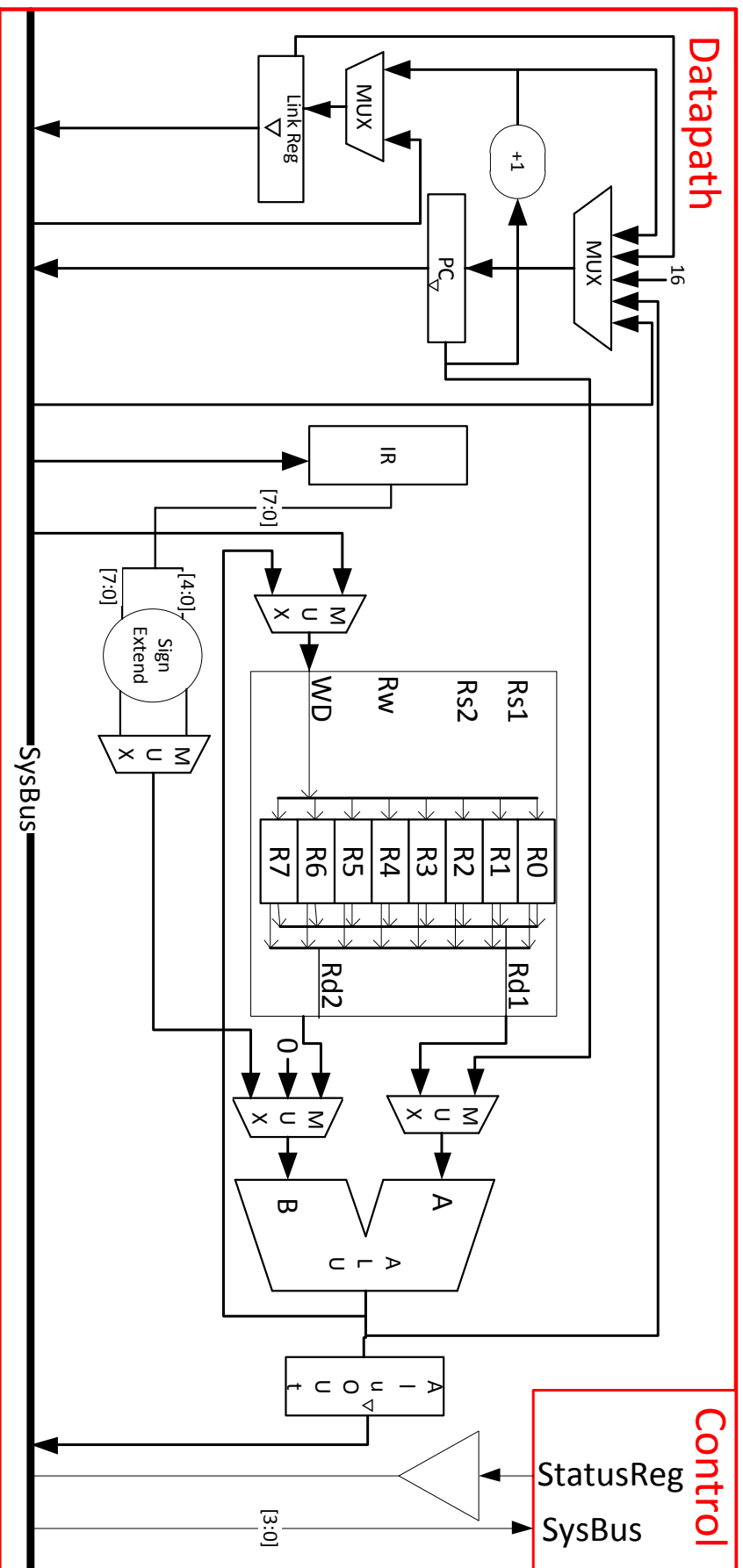


Figure 1: The Architecture diagram of the SAMURAI processor.



**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, categorised 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 $val$
{ $x, y$ }	Concatenation 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

$Rd \leftarrow Ra + imm5$

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

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

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

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

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

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

### 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. The result is then 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. The result is then 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

$Rd \leftarrow 0 - Ra$

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

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

$V \leftarrow 0$

$C \leftarrow 0$

### Description

The 16-bit word in GPR[Ra] is subtracted from zero 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

$Rd \leftarrow Ra - Rb$

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

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

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

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

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

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

### Description

The 16-bit word in GPR[Rb] is subtracted from the 16-bit word in GPR[Ra] and the 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

$Rd \leftarrow Ra - \text{imm5}$

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

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

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

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

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

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

### Description

The sign extended 5-bit value given in the instruction is subtracted from the 16-bit word in GPR[Ra] and the 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. The result is then 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** $Rd \leftarrow Ra - \text{imm5} - C$  $N \leftarrow \text{if } (\text{Result} < 0) \text{ then } 1, \text{ else } 0$  $Z \leftarrow \text{if } (\text{Result} = 0) \text{ then } 1, \text{ else } 0$ 

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

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

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

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

The 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. The result is then 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

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

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

### 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

$Rd \leftarrow Ra \gg \text{imm4}$

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

### 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. The result is then 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** $Rd \leftarrow \text{Mem}[Ra + \text{imm5}]$  $N \leftarrow N$  $Z \leftarrow Z$  $V \leftarrow V$  $C \leftarrow C$ **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. The result is then 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

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

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

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

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

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

### 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 of GPR[Rd], setting the bottom half to zero. The result is then stored in GPR[Rd].

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 of GPR[Rd], leaving the top half unchanged. The result is then stored in GPR[Rd].

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

$PC \leftarrow PC + \text{imm8}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### Description

Unconditionally branch to the resultant address from addition of PC and the 8-bit immediate value specified in the instruction. LABEL is a symbolic name for the destination 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)  $PC \leftarrow PC + \text{imm8}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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 is a symbolic name for the destination 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)  $PC \leftarrow PC + \text{imm8}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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 is a symbolic name for the destination 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)  $PC \leftarrow PC + \text{imm8}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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 is a symbolic name for the destination 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 is a symbolic name for the destination 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 is a symbolic name for the destination 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). This then Decrements 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

This instruction increments 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 by the stack pointer (R7).

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

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

### 3.1 Branching

The SAMURAI processor supports four conditional branches. There are **BE**, **BNE**, **BLT** and **BGE**. All conditional branches have an eight bit signed immediate field which is added to the program counter. Labels are supported by the assembler to aid programming (see section 4).

All arithmetic operations update the flags based on the result of the operation. Logic operations update the negative and zero flags. As well as these, the **CMP** and **CMPI** instructions update the flags, but the result is not stored.

Conditional branches should be conducted by first doing a logic or arithmetic operation, followed by the relevant branch instruction. Listing 1 shows assembly for a simple *if-then-else* clause. First, some definitions are made to make the code more readable. These are discussed further in section 4. A compare is done between the *a* value and an immediate 1. If these two numbers are not equal, the program flows takes the jump and loads a 0 into *b*. Else, the program falls through and a 1 is loaded to the *b* register. The program then takes an unconditional jump to the end of the clause. This is a simple implementation and can be extended to large case statements.

Listing 1: Example code for an *if-then-else* operation.

```

1 ;if 'a' == 1 then b = 1 else b = 0
2 .define a R0
3 .define b R1
4 CMPI a 1 ; store flags for operation (a - 1)
5 BNE .else ; branch is a != 1
6 LUI b 0 ; else fall through
7 LLI b 1 ; load b with 1
8 JMP .end
9 .else LUI b 0 ; LUI sets lower byte to 0
10 .end ...

```

Listing 2 is an example of how to implement a for loop. Again, definitions are made give the code more meaning. Then the *i* variable is initialised to 0 before the loop. Since only greater than or equal, and less than branches are

supported, the condition is non-trivial. This is done by using a temporary register which is set to  $i + 1$ . A compare is done between the temporary register and an immediate 11. This is as  $i \leq 10$  is the same as  $(i + 1) < 11$ . A **BGE** is done to escape the loop. If this isn't taken, the contents of the loop is executed.  $i$  is then incremented and the program jumps to the start of the loop.

Listing 2: Example code for a *for* loop.

```

1 ;for ( i = 0; i <= 10; i ++)
2 ; a = a + i;
3 .define i R0
4 .define a R1
5 .define temp R2
6 LUI i 0 ;initialise i to 0
7 .loop ADDI temp i 1 ;need to add one to i so the branch is a
   greater than
8 CMPI temp 11 ;check condition
9 BGE .end ;if not(temp >= 11) -> i < 10
10 ADD a a i ;do the operation of a += i
11 ADDIB i 1 ;increment i
12 JMP .loop ; return to the top of the loop
13 .end ...

```

### 3.2 Stack Pointer Usage

The SAMURAI processor uses a full descending stack, example usage is held in listing ???. This means from the initial value the stack pointer is incremented before data is written to memory. It is recommended that stack pointer is initialised to  $x$  where  $x - 1$  is the top address in main memory. A **PUSH** increments then writes and a **POP** reads then decrements. Relative loads from the stack pointer are possible and discussed at length in section 3.3.

Listing 3: Example code for **SP** usage.

```

1 LUI SP,#7
2 LLI SP,#208           ; Set SP to 0x07D0
3 PUSH R0               ; R0 written to address 0x07CF
4 PUSH R1               ; R1 written to address 0x07CE
5 LDW R0,[SP,#0]        ; R0 = Mem[0x07CE] (R1 initially)
6 LDW R1,[SP,#1]        ; R1 = Mem[0x07CF] (R0 initially)
7 POP R1                ; SP moves to 0x07CF
8 POP R0                ; SP moves to 0x07D0

```



### 3.3 Sub routine calling convention

Use of a stack frame to pass variables to and from subroutines is recommended when writing assembly for SAMURAI. This improves code reuse and debugging. Example calls for both linked and unlinked subroutines are contained in listing 4. The stack is explained using figure 2 which shows the state during the main matter of each subroutine.

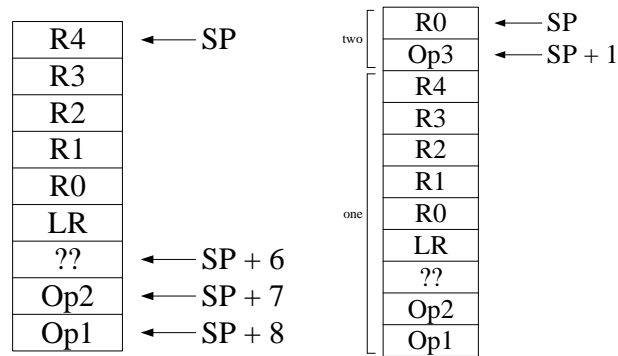
Subroutine *one* requires two input parameters and returns a single result. The caller pushes two register values to the stack and a third dummy value is created by decrementing the stack pointer. A **BWL** instruction is used to enter the subroutine. The callee now has to save the registers it wishes to work with by storing them on the stack. This subroutine calls another subroutine therefore the first operation should be a **PUSH LR** which places the link register on the stack. Five register values are saved then the two input parameters are loaded relative to the stack pointer. On exit the result is stored at the dummy memory location. Once all register values are restored it is crucial the link register is also restored before the **RET** command is used to return the program to the caller. The caller does one **POP** followed by two dummy pops to return the stack to its initial state.

Subroutine *two* is called from inside subroutine *one* but because it is a leaf call then the link register does not have to be copied to the stack. The input parameter is bidirectional and on exit the result is written to the same place from which it was read.

Listing 4: Example code for calling subroutines.

1		<b>PUSH</b>	R0	; Op1	STEM CALLER
2		<b>PUSH</b>	R1	; Op2	
3		<b>SUBIB</b>	SP,#1	; Dummy push	
4		<b>BWL</b>	.one	; Run Subroutine	
5		<b>POP</b>	R0	; Result	
6		<b>ADDIB</b>	SP,#2	; Dummy pop x 2	
7		...			
8	.one	<b>PUSH</b>	LR	; Save LR	CALLEE/CALLER
9		<b>PUSH</b>	R0		
10		<b>PUSH</b>	R1	; Save caller regs	
11		<b>PUSH</b>	R2		
12		<b>PUSH</b>	R3		
13		<b>PUSH</b>	R4		
14		<b>LDW</b>	R3,[SP,#7]	; R3 - Op2	
15		<b>LDW</b>	R4,[SP,#8]	; R4 - Op1	
16		...			

17		PUSH	R3		
18		BWL	.two	; Nested subroutine	
19		POP	R3	; Pass and return	
20		...			
21		STW	R2,[SP,#6]	; Output on frame	
22		POP	R4		
23		POP	R3		
24		POP	R2		
25		POP	R1		
26		POP	R0		
27		POP	LR		
28		RET			
29	.two	PUSH	R0	; No LR save	LEAF CALLEE
30		LDW	R0,[SP,#1]		
31		...			
32		STW	R0,[SP,#1]		
33		POP	R0		
34		RET			



(a) Stack state during *one* main matter. (b) Stack state during *two* main matter.

Figure 2: Stack growth.

### 3.4 Interrupt Service Routines

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 (ISR) is entered. The peripheral should hold the *nIRQ* signal low until it has been cleared by the processor.

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

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 5. This structure should be followed for the ISR.

Listing 5: 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
```

## 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 ISR 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. There is no restriction on size of the service routine. Branches may occur within the ISR, but are not allowed into this service routine with the exception of a return from a separate subroutine. For ISR set-up code to be added successfully, there must be at least one unused register within the first 11 lines of the program file, excluding `.define` statements and the ISR.

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

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

```

```
38 | -h, --help          show this help message and exit
39 | -o FILE, --output=FILE
40 |                   output file for the assembled output
```



## 4.4 Error Messages

This is a list of all the error messages produced by the assembler. Each time an error is thrown, the error number, a brief description and the line it occurred on is displayed before exiting. A 'f' corresponds to a line number in the assembly file, and a 'p' corresponds to the pre-processed code list displayed on screen. Figure 3 shows an example screen shot of an error message.

A screenshot of a terminal window with a dark background and green text. The text shows a command prompt where a file named 'testprog.asm' is being processed by a script called 'assemble.py'. The output shows the file being converted and then syntax being interpreted. An error is then reported: 'ERROR1: Unrecognised Mnemonic lineNo: f37 -> ADDX\_R6 R6 5'.

```
hind<~/VLSI/GIT/Design/InstructionSet/Assembler>$ ./assemble.py testprog
-----Converting File testprog.asm-----

-----Interpreting Syntax-----
ERROR1: Unrecognised Mnemonic lineNo: f37 -> ADDX_R6 R6 5
```

Figure 3: Error1 Example Screen Shot

Code	Description
ERROR1	Instruction mnemonic is not recognised
ERROR2	Register code within instruction is not recognised
ERROR3	Branch condition code is not recognised
ERROR4	Attempting to branch to undefined location
ERROR5	Instruction mnemonic is not recognised
ERROR6	Attempting to shift by more than 16 or perform a negative shift
ERROR7	Magnitude of immediate value for ADDI, ADCI, SUBI, SUCI, LDW, STW, CMPI or JMP is too large
ERROR8	Magnitude of immediate value for ADDIB, SUBIB, LUI or LLI is too large
ERROR9	Attempting to jump more than 127 forward or 128 backwards
ERROR10	Duplicate symbolic link names
ERROR11	Illegal branch to ISR
ERROR12	Multiple ISRs in file
ERROR13	Invalid formatting for .define directive
ERROR14	Could not find empty register in first 10 lines for automated ISR setup
ERROR15	Instruction does not have enough operands

## 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 I/O 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 13. 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 7, 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 7: 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 14. 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 8. Large values can cause stack overflow the main body of code makes sure inputs, read from the switches, are sufficiently small.

Listing 8: 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 15. A random series of numbers is achieved by simulating the 16 bit linear feedback

shift register in Figure 4. 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.

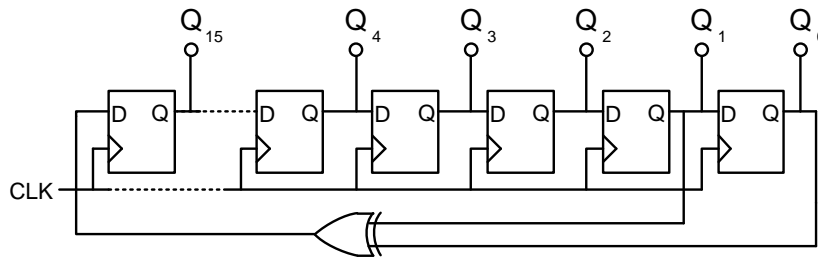


Figure 4: 16 Bit Linear Feedback Shift Register.

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 9.

Listing 9: 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 16. 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 10: 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 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 11.

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 11: 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

```

Table 1: Clock cycles required for each program to run

Program	Clock Cycles
Multiply	1,100
Factorial	5,700
Random	2,500
Interrupt	30,000

## 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*”. Both values are given as hexadecimal numbers. 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 12.

Listing 12: 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. Random is the time taken to compute a new value of the pseudo-random sequence. 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.

## 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 13: multiply.asm

```

1      LUI      SP, #7          ; Init SP
2      LLI      SP, #208
3      LUI      R3, #8          ; SWs addr
4      LLI      R3, #0
5      LDW      R0, [R3, #0]    ; READ SWs
6      LUI      R1, #0
7      LLI      R1, #255        ; 0x00FF in R1
8      AND      R1, R0, R1      ; Lower byte SWs in R1
9      LSR      R0, R0, #8      ; Upper byte SWs in R0
10     PUSH     R0              ; Op1
11     PUSH     R1              ; Op2
12     SUB      R2, R2, R2      ; Zero required
13     PUSH     R2              ; Place holder is zero
14     BWL      .multi         ; Run Subroutine
15     POP      R1              ; Result
16     ADDIB    SP, #2          ; Dummy pop
17     ADDIB    R3, #1          ; Address of LEDS
18     STW      R1, [R3, #0]    ; Result on LEDS
19 .end      BR      .end      ; Finish loop
20 .multi    PUSH     R0
21           PUSH     R1
22           PUSH     R2
23           PUSH     R3
24           PUSH     R4
25           PUSH     R5
26           PUSH     R6
27     LDW      R0, [SP, #8]    ; R0 - Multiplier
28     LDW      R1, [SP, #9]    ; R1 - Quotient
29     CMP      R0, R1
30     BLT      .nSw           ; Branch if M < Q
31     ADDI     R2, R1, #0      ; Make M the smallest
32     ADDI     R1, R0, #0
33     ADDI     R0, R2, #0
34 .nSw      SUB      R2, R2, R2 ; R2 - Accumulator
35     ADDI     R3, R2, #1      ; R3 - 0x0001

```

```

36      LUI      R4,#128      ; R4 = 0x8000
37      LLI      R4,#0
38  .mloop  AND     R6,R0,R3    ; R6 = Cmp var
39      CMPI     R6,#1
40      BNE      .nAcc
41      SUB      R3,R3,R3
42      ADD      R2,R2,R1      ; A = A + Q
43      ADCI     R3,R3,#1
44      CMPI     R3,#2
45      BE       .fail        ; OV
46  .nAcc   LSR     R0,R0,#1    ; M = M >> 1
47      CMPI     R0,#0
48      BE       .done
49      AND      R5,R4,R1
50      CMPI     R5,#0
51      BNE      .fail
52      LSL      R1,R1,#1      ; Q = Q << 1
53      BR       .mloop
54  .done   STW     R2,[SP,#7]   ; Res on stack frame
55      POP      R6
56      POP      R5
57      POP      R4
58      POP      R3
59      POP      R2
60      POP      R1
61      POP      R0
62      RET
63  .fail   SUB     R2,R2,R2     ; OV = ret 0
64      BR       .done

```

## A.2 Factorial

Listing 14: factorial.asm

```

1      LUI      R7, #7
2      LLI      R7, #208
3      LUI      R0, #8        ; Address in R0
4      LLI      R0, #0
5      LDW      R1,[R0,#0]    ; Read switches into R1
6      PUSH     R1            ; Pass para
7      BWL      .fact        ; Run Subroutine
8      POP      R3            ; Para overwritten with result
9      ADDIB    R0,#1
10     STW      R3,[R0,#0]    ; Result on LEDS

```

```

11 .end      BR      .end      ; finish loop
12 .fact    PUSH    R0
13          PUSH    R1
14          PUSH    LR
15          LDW     R1,[SP,#3] ; Get para
16          ADDIB   R1,#0
17          BE      .retOne    ; 0! = 1
18          SUBI    R0,R1,#1
19          PUSH    R0      ; Pass para
20          BWL     .fact    ; The output remains on the stack
21          PUSH    R1      ; Pass para
22          SUBIB   SP,#1    ; Placeholder
23          BWL     .multi
24          POP     R1      ; Get res
25          ADDIB   SP,#2    ; pop x 2
26          STW     R1,[SP,#3]
27          POP     LR
28          POP     R1
29          POP     R0
30          RET
31 .retOne   ADDIB   R1,#1    ; Avoid jump checking
32          STW     R1,[SP,#3]
33          POP     LR
34          POP     R1
35          POP     R0
36          RET
37 .multi    PUSH    R0
38          PUSH    R1
39          PUSH    R2
40          PUSH    R3
41          PUSH    R4
42          PUSH    R5
43          PUSH    R6
44          LDW     R0,[SP,#8] ; R0 – Multiplier
45          LDW     R1,[SP,#9] ; R1 – Quotient
46          CMP     R0,R1
47          BLT     .nSw      ; Branch if M < Q
48          ADDI    R2,R1,#0  ; Make M the smallest
49          ADDI    R1,R0,#0
50          ADDI    R0,R2,#0
51 .nSw      SUB     R2,R2,R2  ; R2 – Accumulator
52          ADDI    R3,R2,#1  ; R3 – 0x0001
53          LUI     R4,#128   ; R4 – 0x8000
54          LLI     R4,#0
55 .mloop    AND     R6,R0,R3 ; R6 – Cmp var

```

```

56      CMPI      R6,#1
57      BNE      .nAcc
58      SUB      R3,R3,R3
59      ADD      R2,R2,R1      ; A = A + Q
60      ADCI     R3,R3,#1
61      CMPI     R3,#2
62      BE       .fail      ; OV
63 .nAcc  LSR      R0,R0,#1      ; M = M >> 1
64      CMPI     R0,#0
65      BE       .done
66      AND      R5,R4,R1
67      CMPI     R5,#0
68      BNE     .fail
69      LSL      R1,R1,#1      ; Q = Q << 1
70      BR       .mloop
71 .done  STW      R2,[SP,#7]    ; Res on stack frame
72      POP      R6
73      POP      R5
74      POP      R4
75      POP      R3
76      POP      R2
77      POP      R1
78      POP      R0
79      RET
80 .fail  SUB      R2,R2,R2      ; OV - ret 0
81      BR       .done

```

### A.3 Random

Listing 15: random.asm

```

1      LUI      SP,#7          ; Init SP
2      LLI      SP,#208
3      LUI      R0,#8          ; SW Address in R0
4      LLI      R0,#0
5      LDW      R1,[R0,#0]     ; Read switches into R1
6      ADDIB    R0,#1          ; Address of LEDS in R0
7      PUSH     R1
8 .reset SUB      R4,R4,R4      ; Reset Loop counter
9 .loop  BWL      .rand
10      CMPI     R4,#15
11      BE       .write
12      ADDIB    R4,#1          ; INC loop counter
13      BR       .loop

```



```

14 .write LDW      R1,[SP,#0] ; No pop as re-run
15       STW      R1,[R0,#0] ; Result on LEDS
16       BR       .reset
17 .rand  PUSH     R0          ; LFSR Sim
18       PUSH     R1          ; Protect regs
19       PUSH     R2
20       LDW      R0,[SP,#3] ; Last reg value
21       LSR      R0,R0,#1    ; Shifted reg
22       XOR      R1,R0,R1    ; xor 0 and 1
23       LUI      R2,#0
24       LLI      R2,#1
25       AND      R1,R2,R1    ; Mask off Bit 0
26       CMPI     R1,#0
27       BE       .done
28       LSL      R1,R2,#15
29       OR       R0,R0,R1    ; or with 0x8000
30 .done  STW      R0,[SP,#3]
31       POP      R2
32       POP      R1
33       POP      R0
34       RET

```

## A.4 Interrupt

Listing 16: interrupt.asm

```

1       DISI      ; Reset is off anyway
2       LUI       R7, #7
3       LLI       R7, #208
4       LUI       R0, #2      ; R0 is read ptr    0x0200
5       LLI       R0, #0
6       ADDI      R1,R0,#2    ; 0x0202
7       STW       R1,[R0,#0] ; Read ptr set to    0x0202
8       STW       R1,[R0,#1] ; Write ptr set to 0x0202
9       LUI       R0,#160    ; Address of Serial control reg
10      LLI       R0,#1
11      LUI       R1,#0
12      LLI       R1,#1      ; Data to enable ints
13      STW       R1,[R0,#0] ; Store 0x001 @ 0xA001
14      ENAI
15 .main  LUI       R0, #2      ; Read ptr address in R0
16      LLI       R0, #0
17      LDW       R2,[R0,#0] ; Read ptr in R2
18      LDW       R3,[R0,#1] ; Write ptr in R3

```

```

19      CMP      R2,R3
20      BE       .main          ; Jump back if the same
21      LDW      R3,[R2,#0]     ; Load data out of buffer
22      ADDIB    R2,#1          ; Inc read ptr
23      SUB      R0,R0,R0
24      LUI      R0,#2
25      LLI      R0,#6
26      SUB      R0,R0,R2
27      BNE      .wrapR
28      SUBIB    R2,#4
29 .wrapR      LUI      R0, #2          ; Read ptr address in R0
30              LLI      R0, #0
31              STW      R2,[R0,#0]    ; Store new read pointer
32              SUB      R4,R4,R4
33              LLI      R4,#15
34              AND      R3,R4,R3
35              CMPI     R3,#8
36              BE       .do
37              LLI      R4,#7
38              AND      R3,R3,R4
39 .do          PUSH     R3
40              BWL      .fact
41              POP      R3
42              LUI      R4,#8
43              LLI      R4,#1          ; Address of LEDs
44              STW      R3,[R4,#0]    ; Put factorial on LEDs
45              BR       .main          ; look again
46 .fact        PUSH     R0
47              PUSH     R1
48              PUSH     LR
49              LDW      R1,[SP,#3]    ; Get para
50              ADDIB    R1,#0
51              BE       .retOne        ; 0! = 1
52              SUBI     R0,R1,#1
53              PUSH     R0          ; Pass para
54              BWL      .fact          ; The output remains on the stack
55              PUSH     R1          ; Pass para
56              SUBIB    SP,#1          ; Placeholder
57              BWL      .multi
58              POP      R1          ; Get res
59              ADDIB    SP,#2          ; pop x 2
60              STW      R1,[SP,#3]
61              POP      LR
62              POP      R1
63              POP      R0

```

```

64      RET
65 .retOne ADDIB    R1,#1      ; Avoid jump checking
66      STW      R1,[SP,#3]
67      POP      LR
68      POP      R1
69      POP      R0
70      RET
71 .multi  PUSH     R0
72      PUSH     R1
73      PUSH     R2
74      PUSH     R3
75      PUSH     R4
76      PUSH     R5
77      PUSH     R6
78      LDW      R0,[SP,#8]    ; R0 - Multiplier
79      LDW      R1,[SP,#9]    ; R1 - Quotient
80      CMP      R0,R1
81      BLT      .nSw          ; Branch if M < Q
82      ADDI     R2,R1,#0      ; Make M the smallest
83      ADDI     R1,R0,#0
84      ADDI     R0,R2,#0
85 .nSw    SUB     R2,R2,R2     ; R2 - Accumulator
86      ADDI     R3,R2,#1      ; R3 - 0x0001
87      LUI      R4,#128      ; R4 - 0x8000
88      LLI      R4,#0
89 .mloop  AND     R6,R0,R3     ; R6 - Cmp var
90      CMPI     R6,#1
91      BNE      .nAcc
92      SUB      R3,R3,R3
93      ADD      R2,R2,R1      ; A = A + Q
94      ADCI     R3,R3,#1
95      CMPI     R3,#2
96      BE       .fail        ; OV
97 .nAcc   LSR     R0,R0,#1     ; M = M >> 1
98      CMPI     R0,#0
99      BE       .done
100     AND      R5,R4,R1
101     CMPI     R5,#0
102     BNE      .fail
103     LSL      R1,R1,#1      ; Q = Q << 1
104     BR       .mloop
105 .done   STW     R2,[SP,#7]   ; Res on stack frame
106     POP      R6
107     POP      R5
108     POP      R4

```

```

109      POP      R3
110      POP      R2
111      POP      R1
112      POP      R0
113      RET
114 .fail  SUB      R2,R2,R2      ; OV - ret 0
115      BR       .done
116 .isr   STF      ; Keep flags , disable auto
117      PUSH     R0             ; Save only this for now
118      LUI      R0,#160
119      LLI      R0,#0
120      LDW      R0,[R0,#0]     ; R1 contains read serial data
121      ENAI      ; Don't miss event
122      PUSH     R1
123      PUSH     R2
124      PUSH     R3
125      PUSH     R4
126      LUI      R1,#2
127      LLI      R1,#0
128      LDW      R2,[R1,#0]     ; R2 contains read ptr
129      ADDI     R3,R1,#1
130      LDW      R4,[R3,#0]     ; R4 contain the write ptr
131      SUBIB    R2,#1          ; Get out if W == R - 1
132      CMP      R4,R2
133      BE       .isrOut
134      ADDIB    R2,#1
135      LUI      R1,#2
136      LLI      R1,#2
137      CMP      R2,R1
138      BNE      .write
139      ADDIB    R1,#3
140      CMP      R4,R1
141      BE       .isrOut
142 .write STW      R0,[R4,#0]     ; Write to buffer
143      ADDIB    R4,#1
144      LUI      R1,#2
145      LLI      R1,#6
146      CMP      R1,R4
147      BNE      .wrapW
148      SUBIB    R4,#4
149 .wrapW STW      R4,[R3,#0]     ; Inc write ptr
150 .isrOut POP      R4
151      POP      R3
152      POP      R2
153      POP      R1

```

154	POP	R0
155	LDF	
156	RETI	



## B Declaration of Work

Table 2 shows the break down of the work for this programming guide. Where multiple team members contributed to a section, approximate work percentages are given.

Table 2: Work Breakdown for the Programmers Guide

Chapter	User
Introduction	hl13g10
Register Description	arr1g13 (50%), hl13g10 (50%)
Instruction Set	mw20g10
Programming Tips	ajr2g10 (50%), hl13g10 (50%)
Assembler	mw20g10 (75%), hl13g10 (50%)
Programs	ajr2g10
Simulation	hl13g10
Code Listings	ajr2g10