

# ELEC6027 - VLSI Design Project : Programmers Guide

Team R4

25<sup>th</sup> April, 2014

## Todo list

■ HSL - this doesn't sound right. Maybe "transfer of program flow". Not sure on the use of the word "control" but i know it is the technical term . . . . .	6
■ HSL - this is a bit too short. Surely there is more to say about it? .	6
■ HSL - I remember Iain saying something about the instruction for- mats being called A1 / A2. I don't see a problem personally as I can't remember exactly what he said! MRW - Said they should be diff instead of just A since there is no addressing mode field, numbered A1/A2 or redoing lettering is fine . . . . .	7
■ surely this should be in the register description section . . . . .	54
■ surely this we can just use the XOR instruction . . . . .	56
■ Maybe change to IEEE symbols if we have time . . . . .	57
■ A register window could also be done for this section too . . . . .	58
■ Sim.py needs a fair bit of change. If we have time, this could be altered to use Iains dir structure. This section highlights how to use his script and our assembler. . . . .	58
■ Make these more accurate when AJR has finished playing around .	60
■ how to run scan path sim too . . . . .	60
■ need to mention extracting? i wouldn't say so as it should already be done and that can't really change. . . . .	60
■ and TCL? . . . . .	60
■ check that the dissembler works in all the simulations (it doesn't...) .	60

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# **1 Introduction**

Lorem Ipsum. . .

# **2 Architecture**

Lorem Ipsum. . .

# **3 Register Description**

Lorem Ipsum. . .

## 4 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

HSL - this doesn't sound right. Maybe "transfer of program flow". Not sure on the use of the word "control" but i know it is the technical term

HSL - this is a bit too short. Surely there is more to say about it?

## 4.1 General Instruction Formatting

HSL - I remember Iain saying something about the instruction formats being called A1 / A2. I don't see a problem personally as I can't remember exactly what he said! MRW - Said they should be diff instead of just A since there is no addressing mode field, numbered A1/A2 or redoing lettering is fine

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

### Instruction Field Definitions

Opcode: Operation code as defined for each instruction

Rd: Destination Register

Ra: Source register 1

Rb: Source register 2

immX: Immediate value of length X

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
$\leftarrow, \rightarrow$	Assignment
Result[ $x$ ]	Bit $x$ of result
Ra[ $x : y$ ]	Bit range from $x$ to $y$ of register Ra
$+Ra$	Positive value in Register Ra
$-Ra$	Negative value in Register Ra
$<$	Numerically greater than
$>$	Numerically less 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
$(cond)?$	Operation performed if $cond$ evaluates to true
$!$	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.

## 4.2 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

$Rd \leftarrow Ra + Rb$

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

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

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

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

### Description

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

Addressing Mode: Register-Register.

### 4.3 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

$Rd \leftarrow Ra + \#imm5$

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

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

$V \leftarrow \text{if } (+Ra \text{ and } +\#imm5 \text{ and } -\text{Result}) \text{ or}$

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

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

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

#### 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.

## 4.4 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

$Rd \leftarrow Rd + \#imm8$

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

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

$V \leftarrow \text{if } (+Rd \text{ and } +\#imm8 \text{ and } -\text{Result}) \text{ or } (-Rd \text{ and } -\#imm8 \text{ and } +\text{Result}) \text{ then } 1, \text{ else } 0$

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

### Description

The 16-bit word in GPR[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.

## 4.5 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

$Rd \leftarrow Ra + Rb + C$

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

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

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

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

### Description

The 16-bit word in GPR[Ra] is added to the 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.

## 4.6 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

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

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

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

$V \leftarrow \text{if } (+Ra \text{ and } +(\#imm5+CFlag) \text{ and } -Result) \text{ or}$   
 $(-Ra \text{ and } -(\#imm5+CFlag) \text{ and } +Result) \text{ then } 1, \text{ else } 0$

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

### 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.

## 4.7 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			Rb		X	X	

### Syntax

NEG Rd, Ra

eg. NEG R5, R3

### Operation

$Rd \leftarrow 0 - Ra$

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

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

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

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

### Description

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

Addressing Mode: Register-Register.

## 4.8 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

$Rd \leftarrow Ra - Rb$

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

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

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

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

### 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.



## 4.9 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

$Rd \leftarrow Ra - \#imm5$

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

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

$V \leftarrow \text{if } (+Ra \text{ and } +\#imm5 \text{ and } -\text{Result}) \text{ or}$   
 $(-Ra \text{ and } -\#imm5 \text{ and } +\text{Result}) \text{ then } 1, \text{ else } 0$

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

### 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.

## 4.10 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

$Rd \leftarrow Rd - \#imm8$

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

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

$V \leftarrow \text{if } (+Rd \text{ and } +\#imm8 \text{ and } -\text{Result}) \text{ or}$   
 $(-Rd \text{ and } -\#imm8 \text{ and } +\text{Result}) \text{ then } 1, \text{ else } 0$

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

### Description

The 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.

## 4.11 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

$Rd \leftarrow Ra - Rb - C$

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

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

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

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

### Description

The 16-bit word in GPR[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.

## 4.12 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

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

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

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

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

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

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

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

### 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.

## 4.13 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					Rd			Ra			Rb		X X		

### Syntax

CMP Ra, Rb

eg. CMP R3, R2

### Operation

Ra - Rb

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

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

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

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

### 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.

## 4.14 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	Rd			Ra			imm5				

### Syntax

CMPI Ra, #imm5

eg. CMPI R3, #7

### Operation

Ra - #imm5

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

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

$V \leftarrow \text{if } (+\text{Ra and } +\text{\#imm5 and } -\text{Result}) \text{ or}$

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

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

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

### Description

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

Addressing Mode: Register-Immediate.

## 4.15 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

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

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

### Description

The logical 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.

## 4.16 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.



## 4.17 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

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

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

### Description

The logical 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.

## 4.18 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			Rb		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.

## 4.19 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

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

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

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

$V \leftarrow \text{UNPREDICTABLE}$

$C \leftarrow \text{UNPREDICTABLE}$

### Description

The logical 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.

## 4.20 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.

## 4.21 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.

## 4.22 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.

## 4.23 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.

## 4.24 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.



## 4.25 STW

## Store Word

### Format

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

### Syntax

STW Rd, [Ra, #imm5]

eg. STW R5, [R3, #7]

### Operation

Mem [Ra + #imm5]  $\leftarrow$  Rd

N  $\leftarrow$  N

Z  $\leftarrow$  Z

V  $\leftarrow$  V

C  $\leftarrow$  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.

## 4.26 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.

## 4.27 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.

## 4.28 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.

## 4.29 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

$PC \leftarrow PC + \#imm8$  (z==0)?

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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.

## 4.30 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

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

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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.

## 4.31 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

$PC \leftarrow PC + \#imm8 \text{ (n\&!v OR !n\&v)?}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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.

## 4.32 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

$PC \leftarrow PC + \#imm8 \text{ (n\&v OR !n\&!v)?}$

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

### 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.



### 4.33 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.

## 4.34 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.

## 4.35 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.

## 4.36 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 RL

eg. PUSH RL

### Operation

Mem [R7]  $\leftarrow$  reg; R7  $\leftarrow$  R7 - 1

N  $\leftarrow$  N

Z  $\leftarrow$  Z

V  $\leftarrow$  V

C  $\leftarrow$  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.

## 4.37 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 RL

eg. POP RL

### 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.

## 4.38 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.

## 4.39 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).

## 4.40 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).



## 4.41 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.

## 4.42 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.

## 5 Programming Tips

Lorem Ipsum...

## 6 Assembler

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

### 6.1 Instruction Formatting

Each instruction must be formatted using the following syntax, here “[...]” indicates an optional field:

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

eg. `.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 can take either a symbolic or numeric value. Where a numeric must be relative and between -32 and 31 for a JMP instruction, or between -128 and 127 for any other branch type. If the branch exceeds the accepted range, the assembler will flag an error message.

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 and be no longer than 126 lines of code. Branches may occur within the ISR, but are not allowed into this subroutine with the exception of a return from a separate subroutine.

## 6.2 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
```

## 6.3 Running The Assembler

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

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

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

Listing 1: Assembler help prompt

```

1 $> assemble.py
2 Usage: assemble.py [-o outfile] input
3
4 —Team R4 Assembler Help—
5 ———Version:
6   1 (CMPI addition onwards)
7   2 (Changed to final ISA, added special case I's and error
8     checking)
9   3 (Ajr changes – Hex output added, bug fix)
10  4 (Added SP symbol)
11  5 (NOP support added, help added) UNTESTED
12  6 (Interrupt support added [ENAI, DISI, RETI])
13  7 (Checks for duplicate Labels)
14  8 (Support for any ISR location & automated startup code entry)
15  9 (Support for .define)
16 10 (Changed usage)
17   Current is most recent iteration
18   Commenting uses : or ;
19   Labels start with '.': SPECIAL .ISR/.isr -> Interrupt Service
20     Routine)
21     SPECIAL .define -> define new name for
22     General Purpose Register, .define NAME R0-R7/SP
23   Instruction Syntax: .[LABELNAME] MNEUMONIC, OPERANDS, ..., :[
24     COMMENTS]
25   Registers: R0, R1, R2, R3, R4, R5, R6, R7==SP
26   Branching: Symbolic and Numeric 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
34     in file onwards, may replace existing definitions
35
36   Options:
37   -h, --help          show this help message and exit
38   -o FILE, --output=FILE
39                        output file for the assembled output

```

## 6.4 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

## 7 Programs

Every example program in this section uses R7 as a stack pointer which is initialised to the by the program to 0x07D0 using the LUI and LLI instructions. It is possible a stack is not required in which case no initialisation is needed and R7 can be used as a general purpose register.

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## 7.1 Multiply

The code for the multiply program is held in Appendix A.1 listing 7. A sixteen bit number is read from input switches and then 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.

The subroutine operation is described using C in listing 2. If the result is greater than or equal to  $2^{16}$  the subroutine will fail and return zero; The lowest bit of the multiplier control the accumulator and the overflow check. The multiplier is shifted right and the quotient is shifted left at every iteration. Equation (1) formally describes the result of algorithm. In implementation a trade off between code size and execution time is made by loop unrolling the eight stages. This creates scope for optimisation in operations contained in the loop, doesn't use a counter and requires less branch operations.

Listing 2: Shift and Add Subroutine

```
1 uint16_t multi(uint16_t mul, quo){
2     uint32_t A;
3     uint16_t M,Q,i;
4     A = 0; M = mul; Q = quo;
5     for (i=0;i<16;i++){
6         if (M && 0x0001){           // LSb
7             A = A + Q;
8             if (A > 0xFFFF){        // Larger than 16 bits?
9                 return 0;           // Fail
10            }
11        }
12        Q = Q << 1;
13        M = M >> 1;
14    }
15    return A;                        // Bottom 16 bits
16 }
```

$$A = M \times Q = \sum_{i=0}^7 2^i M_i Q \text{ where } M_i \in \{0,1\} \quad (1)$$

## 7.2 Factorial

The code for the factorial program is held in Appendix A.2 listing 8. It is possible to calculate the factorial of any integer value between 0 and 8

inclusive. The main body of code masks the value read from the input switches so only acceptable values are passed to subroutine. The factorial subroutine is called which in turn calls the multiply subroutine discussed in section 7.1. The result is calculated recursively as described using C in listing 3.

Listing 3: Recursive Factorial Subroutine

```

1 uint16_t multi(uint16_t mul, quo);           // Prototpye
2
3 uint16_t fact(uint16_t x){
4     if(x == 0){
5         return 1;                             // 0! = 1
6     }else{
7         return multi(x, fact(x-1));           // Recurrsvive
8     }
9 }

```

### 7.3 Random

The code for the random program is held in Appendix A.3 listing 9. A random series of numbers is achieved by simulating a 16 bit linear feedback shift register. 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 is passed to the first subroutine call then using BWL instructions the parameter is altered and passed to the next subroutine call. No more PUSH or POP operations are performed. A load from the stack pointer is used write a new random number to LEDs. All contained within an unconditional branch.

An 2 input XOR gate is simulated by using masking the register value the comparing against inputs 00 and 11. These would return zero so only a shift is performed. If this is not true then a shift is performed followed by an OR operation with 0x8000 therefore feeding back a value to the top of the shift register. This is described using C in listing 4.

Listing 4: Linear Feedback Shift Register Subroutine

```

1 uint16_t rand(uint16_t last){
2     uint16_t next, test;
3     next = last >> 1;                             // Shift reg
4     test = last & 0x000A;                           // Bits 4 and 1
5     if((test == 0x0000) | (test == 0x000A)){         // XOR test

```

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can  
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tion



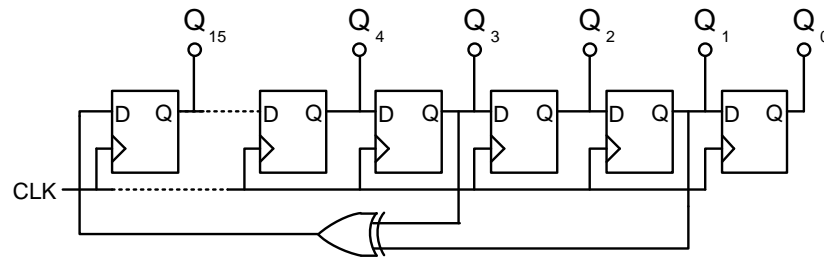


Figure 1: 16 Bit Linear Feedback Shift Register.

Maybe change to IEEE symbols if we have time

```

6         return next;
7     }
8     return next | 0x8000;           // Feedback to top
9 }

```

## 7.4 Interrupt

The code for the interrupt program is held in Appendix A.4 listing 10. This is the most complex example and makes use of both the multiply and factorial subroutines in sections 7.1 and 7.2 respectively.

Listing 5: Serial Device Interrupt Service Request

```

1  uint16_t multi(uint16_t mul, quo);           // Prototpye
2
3  uint16_t fact(uint16_t x);                   // Prototpye#
4
5  isr() {
6
7  }
8
9  void main() {
10
11
12 }

```

## 8 Simulation

### 8.1 Running the simulations

A register window could also be done for this section too

Sim.py needs a fair bit of change. If we have time, this could be altered to use Iains dir structure. This section highlights how to use his script and our assembler.

How to run for each of the behavioural, extracted and mixed

Before the simulator is invoked, the assembler should be invoked. This is discussed in section 6.3. It can be done from within the programs directory ( `/design/fcde/verilog/programs`) by running, for example `assemble.py` multiply

The script “simulate” is an executable shell script. It is run from the terminal in the directory `/design/fcde/verilog`. This supports running simulations of a full verilog model, cross simulation and a fully extracted simulation. Usage is as follows:

```
./simulate type program [definitions]
```

The ‘type’ can be one of the following: *behavioural*, *mixed*, *extracted*. ‘Program’ is a relative path to the assembled hex file, usually located in the programs folder. Extra definitions can also be included to set the switch value or serial data input.

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 6.

Listing 6: 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

Below is a complete list of commands to run all programs on all versions of the processor. 'Number' is a user defined decimal value to set the switches.

- ./assembler/assemble.py programs/multiply.asm  
./simulate behavioural programs/multiply.hex +define+switch\_value=number
- ./assembler/assemble.py programs/multiply.asm  
./simulate mixed programs/multiply.hex +define+switch\_value=number
- ./assembler/assemble.py programs/multiply.asm  
./simulate extracted programs/multiply.hex +define+switch\_value=number
- ./assembler/assemble.py programs/random.asm  
./simulate behavioural programs/random.hex +define+switch\_value=number
- ./assembler/assemble.py programs/random.asm  
./simulate mixed programs/random.hex +define+switch\_value=number
- ./assembler/assemble.py programs/random.asm  
./simulate extracted programs/random.hex +define+switch\_value=number
- ./assembler/assemble.py programs/factorial.asm  
./simulate behavioural programs/factorial.hex +define+switch\_value=number
- ./assembler/assemble.py programs/factorial.asm  
./simulate mixed programs/factorial.hex +define+switch\_value=number
- ./assembler/assemble.py programs/factorial.asm  
./simulate extracted programs/factorial.hex +define+switch\_value=number
- ./assembler/assemble.py programs/interrupt.asm  
./simulate behavioural programs/interrupt.hex programs/serial\_data.hex
- ./assembler/assemble.py programs/interrupt.asm  
./simulate mixed programs/interrupt.hex programs/serial\_data.hex

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

- ./assembler/assemble.py programs/interrupt.asm  
./simulate extracted programs/interrupt.hex programs/serial\_data.hex

how to run scan path sim too

need to mention extracting? i wouldn't say so as it should already be done and that can't really change.

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.

and TCL?

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. 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.

check that the dissembler works in all the simulations (it doesn't...)

## 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 7: multiply.asm

```
1      LUI SP, #7      ; Init SP
2      LLI SP, #208
3      LUI R0, #8      ; SWs ADDR
4      LLI R0, #0
5      LDW R0, [R0, #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     SUB R2, R2, R2   ; Zero required
11     PUSH R0          ; Op1
12     PUSH R1          ; Op2
13     PUSH R2          ; Place holder is zero
14     BWL .multi      ; Run Subroutine
15     POP R1           ; Result
16     ADDIB SP, #2     ; Dummy pop
17     LUI R4, #8
18     LLI R4, #1      ; Address of LEDS
19     STW R1, [R4, #0] ; Result on LEDS
20 .end BR .end        ; Finish loop
21 .multi PUSH R0
22     PUSH R1
23     PUSH R2
24     PUSH R3
25     PUSH R4
26     PUSH R5
27     PUSH R6
28     LDW R0, [SP, #8] ; R0 - Multiplier
29     LDW R1, [SP, #9] ; R1 - Quotient
30     SUB R2, R2, R2   ; R2 - Accumulator
31     ADDI R3, R2, #1  ; R3 - Compare 1/0
32     SUB R4, R4, R4   ; R4 - Loop counter
33 .lpMul AND R6, R0, R3 ; R6 - Cmp var
34     CMPI R6, #0
35     BE .sh
```

```

36      SUB R3,R3,R3
37      ADD R2,R2,R1      ; A = A + Q
38      ADCI R3,R3,#1
39      CMPI R3,#2
40      BE .over          ; OV
41 .sh      LUI R5,#128
42          LLI R5,#0      ; 0x8000
43          AND R5,R5,R1
44          CMPI R5,#0
45          BE .shift
46          CMPI R0,#0
47          BNE .over      ; And M != 0
48 .shift   LSL R1,R1,#1   ; Q = Q << 1
49          LSR R0,R0,#1   ; M = M >> 1
50          ADDIB R4,#1     ; i++
51          CMPI R4,#15
52          BNE .lpMul
53 .done    STW R2,[SP,#7] ; Res on stack frame
54          POP R6
55          POP R5
56          POP R4
57          POP R3
58          POP R2
59          POP R1
60          POP R0
61          RET
62 .over    SUB R2,R2,R2    ; OV – RET 0
63          BR .done

```

## A.2 Factorial

Listing 8: factorial.asm

```

1      LUI R7, #7
2      LLI R7, #208
3      LUI R0, #8        ; Address in R0
4      LLI R0, #0
5      LDW R0,[R0,#0]    ; Read switches into R0
6      LUI R1,#0          ; Calculate only 8 or less
7      LLI R1,#8
8      CMP R1,R0
9      BE .do
10     SUBIB R1,#1
11     AND R0,R0,R1

```

```

12 .do      PUSH R0          ; Pass para
13          BWL .fact       ; Run Subroutine
14          POP R0          ; Para overwritten with result
15          LUI R4, #8
16          LLI R4, #1      ; Address of LEDS
17          STW R0,[R4,#0]  ; Result on LEDS
18 .end     BR .end         ; finish loop
19 .fact    PUSH R0
20          PUSH R1
21          PUSH LR
22          LDW R1,[SP,#3]  ; Get para
23          ADDIB R1,#0
24          BE .retOne     ; 0! = 1
25          SUBI R0,R1,#1
26          PUSH R0        ; Pass para
27          BWL .fact      ; The output remains on the stack
28          PUSH R1        ; Pass para
29          SUBIB SP,#1     ; Placeholder
30          BWL .multi
31          POP R1          ; Get res
32          ADDIB SP,#2     ; POP x 2
33          STW R1,[SP,#3]
34          POP LR
35          POP R1
36          POP R0
37          RET
38 .retOne  ADDIB R1,#1     ; Avoid jump checking
39          STW R1,[SP,#3]
40          POP LR
41          POP R1
42          POP R0
43          RET
44 .multi   PUSH R0
45          PUSH R1
46          PUSH R2
47          PUSH R3
48          PUSH R4
49          PUSH R5
50          PUSH R6
51          LDW R2,[SP,#8]  ; R2 - Multiplier
52          LDW R3,[SP,#9] ; R3 - Quotient
53          SUB R4,R4,R4    ; R4 - Accumulator
54          ADDI R6,R4,#1   ; R6 - Constant 1
55          SUB R5,R5,R5    ; R5 - Constant 0
56          SUB R0,R0,R0    ; R0 - C check

```

```

57      AND R1,R2,R6      ; Stage 1, R1 – cmp
58      CMPI R1,#0        ; LSb ?
59      BE .sh1
60      ADD R4,R4,R3      ; (LSb == 1)?
61 .sh1  LSL R3,R3,#1
62      LSR R2,R2,#1
63      AND R1,R2,R6      ; Stage 2
64      CMPI R1,#0
65      BE .sh2
66      ADD R4,R4,R3
67 .sh2  LSL R3,R3,#1
68      LSR R2,R2,#1
69      AND R1,R2,R6      ; Stage 3
70      CMPI R1,#0
71      BE .sh3
72      ADD R4,R4,R3
73 .sh3  LSL R3,R3,#1
74      LSR R2,R2,#1
75      AND R1,R2,R6      ; Stage 4
76      CMPI R1,#0
77      BE .sh4
78      ADD R4,R4,R3
79 .sh4  LSL R3,R3,#1
80      LSR R2,R2,#1
81      AND R1,R2,R6      ; Stage 5
82      CMPI R1,#0
83      BE .sh5
84      ADD R4,R4,R3
85 .sh5  LSL R3,R3,#1
86      LSR R2,R2,#1
87      AND R1,R2,R6      ; Stage 6
88      CMPI R1,#0
89      BE .sh6
90      ADD R4,R4,R3
91 .sh6  LSL R3,R3,#1
92      LSR R2,R2,#1
93      AND R1,R2,R6      ; Stage 7
94      CMPI R1,#0
95      BE .sh7
96      ADD R4,R4,R3
97 .sh7  LSL R3,R3,#1
98      LSR R2,R2,#1
99      AND R1,R2,R6      ; Stage 8
100     CMPI R1,#0
101     BE .sh8

```



```

102      ADD R4,R4,R3
103 .sh8   LSL R3,R3,#1
104      LSR R2,R2,#1
105      AND R1,R2,R6      ; Stage 9
106      CMPI R1,#0
107      BE .sh9
108      ADD R4,R4,R3
109      ADCI R0,R5,#0
110      CMPI R0,#0
111      BNE .over
112 .sh9   LSL R3,R3,#1
113      LSR R2,R2,#1
114      AND R1,R2,R6      ; Stage 10
115      CMPI R1,#0
116      BE .sh10
117      ADD R4,R4,R3
118      ADCI R0,R5,#0
119      CMPI R0,#0
120      BNE .over
121 .sh10  LSL R3,R3,#1
122      LSR R2,R2,#1
123      AND R1,R2,R6      ; Stage 11
124      CMPI R1,#0
125      BE .sh11
126      ADD R4,R4,R3
127      ADCI R0,R5,#0
128      CMPI R0,#0
129      BNE .over
130 .sh11  LSL R3,R3,#1
131      LSR R2,R2,#1
132      AND R1,R2,R6      ; Stage 12
133      CMPI R1,#0
134      BE .sh12
135      ADD R4,R4,R3
136      ADCI R0,R5,#0
137      CMPI R0,#0
138      BNE .over
139 .sh12  LSL R3,R3,#1
140      LSR R2,R2,#1
141      AND R1,R2,R6      ; Stage 13
142      CMPI R1,#0
143      BE .sh13
144      ADD R4,R4,R3
145      ADCI R0,R5,#0
146      CMPI R0,#0

```

```

147     BNE .over
148 .sh13  LSL R3,R3,#1
149         LSR R2,R2,#1
150         AND R1,R2,R6      ; Stage 14
151         CMPI R1,#0
152         BE .sh14
153         ADD R4,R4,R3
154         ADCI R0,R5,#0
155         CMPI R0,#0
156     BNE .over
157 .sh14  LSL R3,R3,#1
158         LSR R2,R2,#1
159         AND R1,R2,R6      ; Stage 15
160         CMPI R1,#0
161         BE .sh15
162         ADD R4,R4,R3
163         ADCI R0,R5,#0
164         CMPI R0,#0
165     BNE .over
166 .sh15  LSL R3,R3,#1
167         LSR R2,R2,#1
168         AND R1,R2,R6      ; Stage 16
169         CMPI R1,#0
170         BE .sh16
171         ADD R4,R4,R3
172         ADCI R0,R5,#0
173         CMPI R0,#0
174     BNE .over
175 .sh16  STW R4,[SP,#7]    ; Res on stack frame
176         POP R6
177         POP R5
178         POP R4
179         POP R3
180         POP R2
181         POP R1
182         POP R0
183         RET
184 .over  SUB R4,R4,R4
185         STW R4,[SP,#7]    ; Res on stack frame
186         POP R6
187         POP R5
188         POP R4
189         POP R3
190         POP R2
191         POP R1

```

```

192     POP R0
193     RET

```

## A.3 Random

Listing 9: 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     LSL    R1,R0,#2       ; Shift Bit 4 <- 2
22     XOR    R1,R0,R1       ; XOR Gate
23     LSR    R0,R0,#1       ; Shifted reg
24     LUI    R2,#0
25     LLI    R2,#8
26     AND    R1,R2,R1       ; Mask off Bit 4
27     CMPI   R1,#0
28     BNE    .done
29     LUI    R1,#128
30     LLI    R1,#0
31     OR     R0,R0,R1       ; OR with 0x8000
32  .done  STW    R0,[SP,#3]
33     POP    R2
34     POP    R1
35     POP    R0
36     RET

```

## A.4 Interrupt

Listing 10: 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     BR .main
16 .isr DISI
17     STF                ; Keep flags
18     PUSH R0             ; Save only this for now
19     LUI R0,#160
20     LLI R0,#0
21     LDW R0,[R0,#0]      ; R1 contains read serial data
22     ENAI                ; Don't miss event
23     PUSH R1
24     PUSH R2
25     PUSH R3
26     PUSH R4
27     LUI R1,#2
28     LLI R1,#0
29     LDW R2,[R1,#0]      ; R2 contains read ptr
30     ADDI R3,R1,#1
31     LDW R4,[R3,#0]      ; R4 contain the write ptr
32     SUBIB R2,#1         ; Get out if W == R - 1
33     CMP R4,R2
34     BE .isrOut
35     ADDIB R2,#1
36     LUI R1,#2
37     LLI R1,#2
38     CMP R2,R1
39     BNE .write
40     ADDIB R1,#3
41     CMP R4,R1
42     BE .isrOut
```

```

43 .write STW R0,[R4,#0] ; Write to buffer
44 ADDIB R4,#1
45 LUI R1,#2
46 LLI R1,#6
47 CMP R1,R4
48 BNE .wrapW
49 SUBIB R4,#4
50 .wrapW STW R4,[R3,#0] ; Inc write ptr
51 .isrOut POP R4
52 POP R3
53 POP R2
54 POP R1
55 POP R0
56 LDF
57 RETI
58 .main LUI R0, #2 ; Read ptr address in R0
59 LLI R0, #0
60 LDW R2,[R0,#0] ; Read ptr in R2
61 LDW R3,[R0,#1] ; Write ptr in R3
62 CMP R2,R3
63 BE .main ; Jump back if the same
64 LDW R3,[R2,#0] ; Load data out of buffer
65 ADDIB R2,#1 ; Inc read ptr
66 SUB R0,R0,R0
67 LUI R0,#2
68 LLI R0,#6
69 SUB R0,R0,R2
70 BNE .wrapR
71 SUBIB R2,#4
72 .wrapR LUI R0, #2 ; Read ptr address in R0
73 LLI R0, #0
74 STW R2,[R0,#0] ; Store new read pointer
75 SUB R4,R4,R4
76 LLI R4,#15
77 AND R3,R4,R3
78 CMPI R3,#8
79 BE .do
80 LLI R4,#7
81 AND R3,R3,R4
82 .do PUSH R3
83 BWL .fact
84 POP R3
85 LUI R4,#8
86 LLI R4,#1 ; Address of LEDs
87 STW R3,[R4,#0] ; Put factorial on LEDs

```

```

88      BR .main          ; look again
89  .fact  PUSH R0
90        PUSH R1
91        PUSH LR
92        LDW R1,[SP,#3]  ; Get para
93        ADDIB R1,#0
94        BE .retOne     ; 0! = 1
95        SUBI R0,R1,#1
96        PUSH R0        ; Pass para
97        BWL .fact      ; The output remains on the stack
98        PUSH R1        ; Pass para
99        SUBIB SP,#1    ; Placeholder
100       BWL .multi
101       POP R1          ; Get res
102       ADDIB SP,#2    ; POP x 2
103       STW R1,[SP,#3]
104       POP LR
105       POP R1
106       POP R0
107       RET
108  .retOne ADDIB R1,#1  ; Avoid jump checking
109         STW R1,[SP,#3]
110         POP LR
111         POP R1
112         POP R0
113         RET
114  .multi  PUSH R0
115         PUSH R1
116         PUSH R2
117         PUSH R3
118         PUSH R4
119         PUSH R5
120         PUSH R6
121         LDW R2,[SP,#8] ; R2 - Multiplier
122         LDW R3,[SP,#9] ; R3 - Quotient
123         SUB R4,R4,R4   ; R4 - Accumulator
124         ADDI R6,R4,#1  ; R6 - Constant 1
125         SUB R5,R5,R5   ; R5 - Constant 0
126         SUB R0,R0,R0   ; R0 - C check
127         AND R1,R2,R6   ; Stage 1, R1 - cmp
128         CMPI R1,#0     ; LSb ?
129         BE .sh1
130         ADD R4,R4,R3   ; (LSb == 1)?
131  .sh1   LSL R3,R3,#1
132         LSR R2,R2,#1

```

```

133      AND R1,R2,R6      ; Stage 2
134      CMPI R1,#0
135      BE .sh2
136      ADD R4,R4,R3
137 .sh2  LSL R3,R3,#1
138      LSR R2,R2,#1
139      AND R1,R2,R6      ; Stage 3
140      CMPI R1,#0
141      BE .sh3
142      ADD R4,R4,R3
143 .sh3  LSL R3,R3,#1
144      LSR R2,R2,#1
145      AND R1,R2,R6      ; Stage 4
146      CMPI R1,#0
147      BE .sh4
148      ADD R4,R4,R3
149 .sh4  LSL R3,R3,#1
150      LSR R2,R2,#1
151      AND R1,R2,R6      ; Stage 5
152      CMPI R1,#0
153      BE .sh5
154      ADD R4,R4,R3
155 .sh5  LSL R3,R3,#1
156      LSR R2,R2,#1
157      AND R1,R2,R6      ; Stage 6
158      CMPI R1,#0
159      BE .sh6
160      ADD R4,R4,R3
161 .sh6  LSL R3,R3,#1
162      LSR R2,R2,#1
163      AND R1,R2,R6      ; Stage 7
164      CMPI R1,#0
165      BE .sh7
166      ADD R4,R4,R3
167 .sh7  LSL R3,R3,#1
168      LSR R2,R2,#1
169      AND R1,R2,R6      ; Stage 8
170      CMPI R1,#0
171      BE .sh8
172      ADD R4,R4,R3
173 .sh8  LSL R3,R3,#1
174      LSR R2,R2,#1
175      AND R1,R2,R6      ; Stage 9
176      CMPI R1,#0
177      BE .sh9

```

```

178      ADD R4,R4,R3
179      ADCI R0,R5,#0
180      CMPI R0,#0
181      BNE .over
182 .sh9   LSL R3,R3,#1
183      LSR R2,R2,#1
184      AND R1,R2,R6      ; Stage 10
185      CMPI R1,#0
186      BE .sh10
187      ADD R4,R4,R3
188      ADCI R0,R5,#0
189      CMPI R0,#0
190      BNE .over
191 .sh10  LSL R3,R3,#1
192      LSR R2,R2,#1
193      AND R1,R2,R6      ; Stage 11
194      CMPI R1,#0
195      BE .sh11
196      ADD R4,R4,R3
197      ADCI R0,R5,#0
198      CMPI R0,#0
199      BNE .over
200 .sh11  LSL R3,R3,#1
201      LSR R2,R2,#1
202      AND R1,R2,R6      ; Stage 12
203      CMPI R1,#0
204      BE .sh12
205      ADD R4,R4,R3
206      ADCI R0,R5,#0
207      CMPI R0,#0
208      BNE .over
209 .sh12  LSL R3,R3,#1
210      LSR R2,R2,#1
211      AND R1,R2,R6      ; Stage 13
212      CMPI R1,#0
213      BE .sh13
214      ADD R4,R4,R3
215      ADCI R0,R5,#0
216      CMPI R0,#0
217      BNE .over
218 .sh13  LSL R3,R3,#1
219      LSR R2,R2,#1
220      AND R1,R2,R6      ; Stage 14
221      CMPI R1,#0
222      BE .sh14

```



```

223      ADD R4,R4,R3
224      ADCI R0,R5,#0
225      CMPI R0,#0
226      BNE .over
227 .sh14  LSL R3,R3,#1
228      LSR R2,R2,#1
229      AND R1,R2,R6      ; Stage 15
230      CMPI R1,#0
231      BE .sh15
232      ADD R4,R4,R3
233      ADCI R0,R5,#0
234      CMPI R0,#0
235      BNE .over
236 .sh15  LSL R3,R3,#1
237      LSR R2,R2,#1
238      AND R1,R2,R6      ; Stage 16
239      CMPI R1,#0
240      BE .sh16
241      ADD R4,R4,R3
242      ADCI R0,R5,#0
243      CMPI R0,#0
244      BNE .over
245 .sh16  STW R4,[SP,#7]  ; Res on stack frame
246      POP R6
247      POP R5
248      POP R4
249      POP R3
250      POP R2
251      POP R1
252      POP R0
253      RET
254 .over  SUB R4,R4,R4
255      STW R4,[SP,#7]  ; Res on stack frame
256      POP R6
257      POP R5
258      POP R4
259      POP R3
260      POP R2
261      POP R1
262      POP R0
263      RET

```