

ELEC6027 - VLSI Design Project : Programmers Guide

Team R4

25th April, 2014

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!

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

$Rd \leftarrow Ra + Rb$

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

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

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

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

Description

The 16-bit word in GPR[Ra] is added to the 16-bit word in GPR[Rb] 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[Rd] 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 if Result < 0 then 1, else 0

Z \leftarrow if Result = 0 then 1, else 0

V \leftarrow if (+Ra and +#imm5 and -Result) or

(-Ra and -#imm5 and +Result) then 1, else 0

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

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

Description

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

Addressing Mode: Register-Immediate.

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

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

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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

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

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

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

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

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

Description

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

Addressing Modes: Register-Indirect, Postdecrement.

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

POP RL

eg. POP R3

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 by 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

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

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

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

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

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

Description

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.

surely
this
should
be in
the
reg-
ister
de-
scrip-
tion
sec-
tion

7.1 Multiply

The code for the multiply program is held in Appendix A.1 listing 6. 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 7. 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 8. 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

```

surely
this
we
can
just
use
the
XOR
in-
struc-
tion

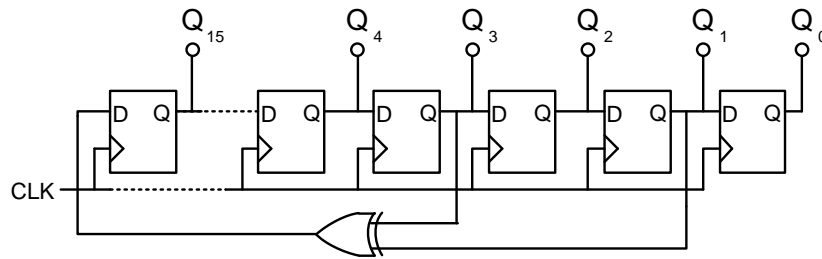


Figure 1: 16 Bit Linear Feedback Shift Register.

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 9. 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

Describe sim.py

What it does, why it is needed

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

NEED TO CHANGE SIM.PY TO RUN USING IAINS STRUCTURE

(/home/user/design/fcde...)

Clock cycles for each of the programs

Register window - need to do one. Description of also.

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 6: 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 R2,[SP,#8] ; R2 - Multiplier
29         LDW R3,[SP,#9] ; R3 - Quotient
30         SUB R4,R4,R4   ; R4 - Accumulator
31         ADDI R6,R4,#1  ; R6 - Compare 1/0
32         LUI R5,#128
33         LLI R5,#0      ; R5 - 0x8000
34         AND R1,R2,R6   ; Stage 1, R1 - cmp
35         CMPI R1,#0     ; LSb ?
36         BE .sh1
37         ADD R4,R4,R3   ; (LSb == 1)?
38 .sh1    AND R0,R5,R3
39         CMPI R0,#0
40         BNE .over1
41         LSL R3,R3,#1
42         LSR R2,R2,#1
43         AND R1,R2,R6   ; Stage 2
44         CMPI R1,#0
45         BE .sh2
46         ADD R4,R4,R3
47 .sh2    AND R0,R5,R3
48         CMPI R0,#0
49         BNE .over1
50         LSL R3,R3,#1
51         LSR R2,R2,#1
52         AND R1,R2,R6   ; Stage 3
53         CMPI R1,#0
54         BE .sh3
55         ADD R4,R4,R3
56 .sh3    AND R0,R5,R3
57         CMPI R0,#0
58         BNE .over1
59         LSL R3,R3,#1
60         LSR R2,R2,#1
61         AND R1,R2,R6   ; Stage 4
62         CMPI R1,#0
63         BE .sh4
64         ADD R4,R4,R3
65 .sh4    AND R0,R5,R3

```

```

66      CMPI R0,#0
67      BNE .over1
68      LSL R3,R3,#1
69      LSR R2,R2,#1
70      AND R1,R2,R6      ; Stage 5
71      CMPI R1,#0
72      BE .sh5
73      ADD R4,R4,R3
74 .sh5  AND R0,R5,R3
75      CMPI R0,#0
76      BNE .over1
77      LSL R3,R3,#1
78      LSR R2,R2,#1
79      AND R1,R2,R6      ; Stage 6
80      CMPI R1,#0
81      BE .sh6
82      ADD R4,R4,R3
83 .sh6  AND R0,R5,R3
84      CMPI R0,#0
85      BNE .over1
86      LSL R3,R3,#1
87      LSR R2,R2,#1
88      AND R1,R2,R6      ; Stage 7
89      CMPI R1,#0
90      BE .sh7
91      ADD R4,R4,R3
92 .sh7  AND R0,R5,R3
93      CMPI R0,#0
94      BNE .over1
95      LSL R3,R3,#1
96      LSR R2,R2,#1
97      AND R1,R2,R6      ; Stage 8
98      CMPI R1,#0
99      BE .sh8
100     ADD R4,R4,R3
101     BR .sh8
102 .over1 BR .over
103 .sh8  AND R0,R5,R3
104      CMPI R0,#0
105      BNE .over
106      LSL R3,R3,#1
107      LSR R2,R2,#1
108      AND R1,R2,R6      ; Stage 9
109      CMPI R1,#0
110     BE .sh9

```

```

111 SUB R6,R6,R6
112 ADD R4,R4,R3
113 ADCI R6,R4,#1
114 CMPI R6,#2
115 BNE .over
116 .sh9 AND R0,R5,R3
117 CMPI R0,#0
118 BNE .over
119 LSL R3,R3,#1
120 LSR R2,R2,#1
121 AND R1,R2,R6 ; Stage 10
122 CMPI R1,#0
123 BE .sh10
124 SUB R6,R6,R6
125 ADD R4,R4,R3
126 ADCI R6,R4,#1
127 CMPI R6,#2
128 BNE .over
129 .sh10 AND R0,R5,R3
130 CMPI R0,#0
131 BNE .over
132 LSL R3,R3,#1
133 LSR R2,R2,#1
134 AND R1,R2,R6 ; Stage 11
135 CMPI R1,#0
136 BE .sh11
137 SUB R6,R6,R6
138 ADD R4,R4,R3
139 ADCI R6,R4,#1
140 BNE .over
141 .sh11 AND R0,R5,R3
142 CMPI R0,#0
143 BNE .over
144 LSL R3,R3,#1
145 LSR R2,R2,#1
146 AND R1,R2,R6 ; Stage 12
147 CMPI R1,#0
148 BE .sh12
149 SUB R6,R6,R6
150 ADD R4,R4,R3
151 ADCI R6,R4,#1
152 BNE .over
153 .sh12 AND R0,R5,R3
154 CMPI R0,#0
155 BNE .over

```



```

156     LSL R3,R3,#1
157     LSR R2,R2,#1
158     AND R1,R2,R6      ; Stage 13
159     CMPI R1,#0
160     BE .sh13
161     SUB R6,R6,R6
162     ADD R4,R4,R3
163     ADCI R6,R4,#1
164     BNE .over
165 .sh13  AND R0,R5,R3
166     CMPI R0,#0
167     BNE .over
168     LSL R3,R3,#1
169     LSR R2,R2,#1
170     AND R1,R2,R6      ; Stage 14
171     CMPI R1,#0
172     BE .sh14
173     SUB R6,R6,R6
174     ADD R4,R4,R3
175     ADCI R6,R4,#1
176     BNE .over
177 .sh14  AND R0,R5,R3
178     CMPI R0,#0
179     BNE .over
180     LSL R3,R3,#1
181     LSR R2,R2,#1
182     AND R1,R2,R6      ; Stage 15
183     CMPI R1,#0
184     BE .sh15
185     SUB R6,R6,R6
186     ADD R4,R4,R3
187     ADCI R6,R4,#1
188     BNE .over
189 .sh15  AND R0,R5,R3
190     CMPI R0,#0
191     BNE .over
192     LSL R3,R3,#1
193     LSR R2,R2,#1
194     AND R1,R2,R6      ; Stage 16
195     CMPI R1,#0
196     BE .sh16
197     SUB R6,R6,R6
198     ADD R4,R4,R3
199     ADCI R6,R4,#1
200     BNE .over

```

```

201 .sh16    STW R4,[SP,#7] ; Res on stack frame
202         POP R6
203         POP R5
204         POP R4
205         POP R3
206         POP R2
207         POP R1
208         POP R0
209         RET
210 .over    SUB R4,R4,R4
211         BR .sh16

```

A.2 Factorial

Listing 7: 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 8: random.asm

```

1      LUI    R7,#7      ; Init SP
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,#8
7      LLI    R1,#1      ; CONSTANT – Address of LEDS
8      LUI    R2,#0
9      LLI    R2,#10     ; CONSTANT – 0x0008

```

```

10      LUI      R3,#128
11      LLI      R3,#0          ; CONSTANT – 0x8000
12      SUB      R4,R4,R4      ; Loop counter
13      PUSH     R0
14  .loop  BWL      .rand
15      ADDIB    R4,#1          ; INC loop counter
16      CMPI     R4,#15
17      BNE      .loop
18      LDW      R0,[SP,#0]     ; No POP as re-run
19      STW      R0,[R1,#0]     ; Result on LEDS
20      BR       .loop
21  .rand  LDW      R4,[SP,#0]     ; Linear feedback shift register sim
22      LSL      R5,R4,#2      ; Shift Bit 2 -> 4
23      XOR      R3,R4,R5      ; XOR Gate
24      LSR      R4,R4,#1      ; Shifted reg
25      AND      R3,R3,R2      ; Mask off Bit 4
26      CMPI     R3,#0
27      BNE      .done
28      OR       R4,R4,R3      ; OR with 0x8000
29  .done  STW      R4,[SP,#0]
30      RET

```

A.4 Interrupt

Listing 9: 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		