

ELEC6027 - VLSI Design Project : Programmers Guide

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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, moving data between external memory and general purpose registers, 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

4.1 General Instruction Formatting

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

Instruction Field Definitions

Opcode: Operation code as defined for each instruction

Rd: Destination Register

Ra: Source register 1

Rb: Source register 2

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[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

$PC \leftarrow PC + \#imm8$ (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

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

$N \leftarrow N$

$Z \leftarrow Z$

$V \leftarrow V$

$C \leftarrow C$

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 reads a `'asm'` file and outputs a `'hex'` file in hexadecimal format. It is run by typing `“./assemble filename”` at the command line when in the directory of both the assembler executable and the program assembly file. `“filename”` does not have to include the `.asm` file extension. The outputted file is saved to the same directory as the input file.

HSL: I'm going to add an option parser to make the UI a bit easier. This section is likely to change a fair amount

Typing `-h` or `--help` instead of the file name will bring up the help menu with version information and basic formatting support.

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.

7.1 Multiply

The code for the multiply program is held in appendix A.1 listing 5. 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 placed upon the LEDs before reaching a terminating loop.

The subroutine operation is described as C in listing 1. 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.

```
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 }
```

Listing 1: Shift and Add Subroutine

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

7.2 Factorial

The code for the factorial program is held in appendix A.2 listing 6. 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 2.

```

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));           // Recurrusive
8     }
9 }

```

Listing 2: Recursive Factorial Subroutine

7.3 Random

The code for the random program is held in appendix A.3 listing 7. 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 3.

```

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

```

```
9 | }
```

Listing 3: Linear Feedback Shift Register Subroutine

7.4 Interrupt

The code for the interrupt program is held in appendix A.4 listing 8. This is the most complex example and makes use of both the multiply and factorial subroutines in sections 7.1 and 7.2 respectively.

```
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 }
```

Listing 4: Serial Device Interrupt Service Request

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

```
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 - Constant 1
32       SUB R5,R5,R5   ; R5 - Constant 0
33       SUB R0,R0,R0   ; R0 - C check
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    LSL R3,R3,#1
39         LSR R2,R2,#1
40         AND R1,R2,R6    ; Stage 2
41         CMPI R1,#0
42         BE .sh2
43         ADD R4,R4,R3
44 .sh2    LSL R3,R3,#1
45         LSR R2,R2,#1
46         AND R1,R2,R6    ; Stage 3
47         CMPI R1,#0
48         BE .sh3
49         ADD R4,R4,R3
50 .sh3    LSL R3,R3,#1
51         LSR R2,R2,#1
52         AND R1,R2,R6    ; Stage 4
53         CMPI R1,#0
54         BE .sh4
55         ADD R4,R4,R3
56 .sh4    LSL R3,R3,#1
57         LSR R2,R2,#1
58         AND R1,R2,R6    ; Stage 5
59         CMPI R1,#0
60         BE .sh5
61         ADD R4,R4,R3
62 .sh5    LSL R3,R3,#1
63         LSR R2,R2,#1
64         AND R1,R2,R6    ; Stage 6
65         CMPI R1,#0
66         BE .sh6
67         ADD R4,R4,R3
68 .sh6    LSL R3,R3,#1
69         LSR R2,R2,#1
70         AND R1,R2,R6    ; Stage 7
71         CMPI R1,#0
72         BE .sh7
73         ADD R4,R4,R3
74 .sh7    LSL R3,R3,#1
75         LSR R2,R2,#1
76         AND R1,R2,R6    ; Stage 8
77         CMPI R1,#0
78         BE .sh8
79         ADD R4,R4,R3
80 .sh8    LSL R3,R3,#1
81         LSR R2,R2,#1
82         AND R1,R2,R6    ; Stage 9

```

```

83      CMPI R1,#0
84      BE .sh9
85      ADD R4,R4,R3
86      ADCI R0,R5,#0
87      CMPI R0,#0
88      BNE .over
89 .sh9   LSL R3,R3,#1
90       LSR R2,R2,#1
91       AND R1,R2,R6      ; Stage 10
92       CMPI R1,#0
93       BE .sh10
94       ADD R4,R4,R3
95       ADCI R0,R5,#0
96       CMPI R0,#0
97       BNE .over
98 .sh10  LSL R3,R3,#1
99       LSR R2,R2,#1
100      AND R1,R2,R6      ; Stage 11
101      CMPI R1,#0
102      BE .sh11
103      ADD R4,R4,R3
104      ADCI R0,R5,#0
105      CMPI R0,#0
106      BNE .over
107 .sh11  LSL R3,R3,#1
108       LSR R2,R2,#1
109       AND R1,R2,R6      ; Stage 12
110      CMPI R1,#0
111      BE .sh12
112      ADD R4,R4,R3
113      ADCI R0,R5,#0
114      CMPI R0,#0
115      BNE .over
116 .sh12  LSL R3,R3,#1
117       LSR R2,R2,#1
118       AND R1,R2,R6      ; Stage 13
119      CMPI R1,#0
120      BE .sh13
121      ADD R4,R4,R3
122      ADCI R0,R5,#0
123      CMPI R0,#0
124      BNE .over
125 .sh13  LSL R3,R3,#1
126       LSR R2,R2,#1
127      AND R1,R2,R6      ; Stage 14

```

```

128      CMPI R1,#0
129      BE .sh14
130      ADD R4,R4,R3
131      ADCI R0,R5,#0
132      CMPI R0,#0
133      BNE .over
134 .sh14  LSL R3,R3,#1
135        LSR R2,R2,#1
136        AND R1,R2,R6      ; Stage 15
137        CMPI R1,#0
138        BE .sh15
139        ADD R4,R4,R3
140        ADCI R0,R5,#0
141        CMPI R0,#0
142        BNE .over
143 .sh15  LSL R3,R3,#1
144        LSR R2,R2,#1
145        AND R1,R2,R6      ; Stage 16
146        CMPI R1,#0
147        BE .sh16
148        ADD R4,R4,R3
149        ADCI R0,R5,#0
150        CMPI R0,#0
151        BNE .over
152 .sh16  STW R4,[SP,#7]    ; Res on stack frame
153        POP R6
154        POP R5
155        POP R4
156        POP R3
157        POP R2
158        POP R1
159        POP R0
160        RET
161 .over  SUB R4,R4,R4
162        STW R4,[SP,#7]    ; Res on stack frame
163        POP R6
164        POP R5
165        POP R4
166        POP R3
167        POP R2
168        POP R1
169        POP R0
170        RET

```

Listing 5: multiply.asm

A.2 Factorial

```

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

```

Listing 6: factorial.asm

A.3 Random

```

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 – 0x000A
10     LUI R3,#128
11     LLI R3,#0 ; CONSTANT – 0x8000
12     PUSH R0
13 .loop BWL .rand ; 1
14     BWL .rand ; 2
15     BWL .rand ; 3
16     BWL .rand ; 4
17     BWL .rand ; 5
18     BWL .rand ; 6
19     BWL .rand ; 7
20     BWL .rand ; 8
21     BWL .rand ; 9
22     BWL .rand ; 10
23     BWL .rand ; 11
24     BWL .rand ; 12

```

```

25      BWL .rand      ; 13
26      BWL .rand      ; 14
27      BWL .rand      ; 15
28      BWL .rand      ; 16
29      LDW R0,[SP,#0]  ; No POP as re-run
30      STW R0,[R1,#0] ; Result on LEDS
31      BR .loop
32 .rand LDW R4,[SP,#0] ; Linear feedback shift register sim
33      LSR R5,R4,#1
34      AND R4,R2,R4   ; Mask bits one and three
35      BE .done       ; Both zero
36      CMP R4,R2
37      BE .done       ; Both one
38      OR R5,R5,R3
39 .done STW R5,[SP,#0]
40      RET

```

Listing 7: random.asm

A.4 Interrupt

```

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      SIW 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

```

Listing 8: interrupt.asm