WASHINGTON STATE UNIVERSITY

School of Electrical Engineering and Computer Science

Introduction to Computer Architecture, Fall 2017

Midterm #1
October 4, 2017
Duration: 55 minutes

NAME: solutions ID:

	Total Points	Earned
Problem 1	15	
Problem 2	15	
Problem 3	20	
Problem 4	15	
Problem 5	20	
Problem 6	15	

Notes:

- You may bring a double-sided letter-size cheat-sheet and a calculator to the test. No other resources are allowed! In particular, NO textbook, lecture notes, internet access, smartphone usage, etc. are allowed!
- Make sure to write your name and WSU ID down on all pages.
- Show your work for each question.
- MIPS reference data is provided!

1. **(15 points)** Assume for a given program, 60% of the executed instructions are of Class A, 25% are of Class B, and 15% are of Class C. Furthermore, assume that an instruction in Class A requires 2 cycles, an instruction in Class B requires 4 cycles, and an instruction in Class C requires 5 to complete. Compute the overall CPI for this program.

solution:

class	percentage	CPI
A	60%	2
B	25%	4
C	15%	5

$$CPI_{averge} = \sum_{i=1}^{class\#} Percentage_i \times CPI_i$$

$$CPI_{avg} = \frac{60}{100} \times 2 + \frac{25}{100} \times 4 + \frac{15}{100} \times 5$$

$$= 1.2 + 1 + 0.75 = \boxed{2.95}$$

2. **(15 Points)** Give the 16-bit 2's complement *binary* and *hexadecimal* representations of the decimal number (- 2060).

Solution :

- 2060 ⟶ negative number

2060 $\xrightarrow{\text{binary}}$ 0000 1000 0000 0100

1's complement: 1111 0111 1111 1011

\+ 1

2's complement ⟵ 1111 0111 1111 0100

2' complement = 1111 0111 1111 0100

hexadecimal = 0x F7F4

3. **(20 Points)** Consider the decimal number (-18.625). Write down binary representation of this number using the IEEE 745 single precision format. Clearly specify "Sign", "Exponent" and "Fraction" fields of the single precision representation.

Solution :

negative number ← -18.625

$\boxed{\text{sign} = 1}$

$(18)_{10} = (10010)_2$

$0.625 \times 2 = 1.25 \quad (1)$

$0.25 \times 2 = 0.50 \quad (0)$

$0.50 \times 2 = 1.0 \quad (1)$

(101)

$\Rightarrow (-1)(10010.101)$

$** \; (-1)^{\text{sign}} \times (1.\text{Fraction})_2 \times 2^{\text{Exponent} - \text{Bias}} \; **$ (Bias → 127)

$\Rightarrow (-1)^1 (1.0010101) \times 2^4 \Rightarrow$ Exponent − 127 = 4

Exponent = 131

$\boxed{\text{Exponent} = 10000011}$ 8bit

Fraction = 0010101 $\xrightarrow[\text{23 bits}]{\text{extend}}$ $\boxed{00101010000\cdots0}$

Single precision number = 1 10000011 00101010000000000000000

4 bits 3bits

4. **(15 Points)** Consider two positive numbers as follows: Multiplicand 1101 (decimal 13) and Multiplier 101 (decimal 5). Fill the table below with the value of different registers (Product, Multiplicand, and Multiplier) initially and during each clock cycle of the sequential multiplier discussed in the class.

4+3 = 7 bits for product

result

	Initial Values	Cycle 1	Cycle 2	Cycle 3	Cycle 5
Product	0000000	0001101	0001101	1000001	
Multiplicand	0001101	0011010	0110100	1101000	
Multiplier	101	10	1	0	

5. **(20 points)** Write MIPS assembly code that will execute the following C statements. Assume that the following registers are used to represent the variables "sum", "k", "list", and "len":

- base address of "list" in register $s0
- length of "list" ("len") in register $s1
- "sum" in register $s2
- "k" in register $s3.

```
sum = 0;
for (k = 0; k < len; k++)
    sum += list[k];
```

Solution :

```
                                                    or
add   $S2, $zero, $zero     # sum = 0   / li $S2, 0
add   $S3, $zero, $zero     # K = 0     / li $S3, 0

For:  slt   $t0, $S3, $S1   # if (K < len) then $t0 = 1
                              else $t0 = 0
      beq   $t0, $zero, Forend  # if ($t0 == 0) then go to Forend
                                  else continue to loop
      sll   $t1, $S3, 2     # $t1 = 4 x K
      lw    $t2, 0($t1)     # sum += list[K]
      add   $S2, $S2, $t2
      j     For             # jumps to beginning of loop
Forend:
```

6. **(15 points)** Suppose we execute the following MIPS instructions:

```
        li      $t0, 2              ---> $t0 = 2
        li      $t1, 5              ---> $t1 = 5
        slt     $t2, $t1, $t0       ---> if ($t1 < $t0) then $t2=0 else $t2=1
        beq     $t2, $zero, skip    ---> if ($t2 == 0) then go to skip
        addi    $t1, $t2, 3         not executed
skip:   li      $v0, 42             ---> $v0 = 42
```

Assume that all registers are initialized to '0' prior to execution of these instructions. In the following table, write down final value of each register after the code has executed.

Register name	**$t0**	**$t1**	**$t2**	**$v0**
Register initial value	**0**	**0**	**0**	**0**
Register final value	2	5	0	42

MIPS Reference Data Card ("Green Card") 1. Pull along perforation to separate card 2. Fold bottom side (columns 3 and 4) together

MIPS Reference Data

①

CORE INSTRUCTION SET

NAME, MNEMONIC		FORMAT	OPERATION (in Verilog)		OPCODE / FUNCT (Hex)
Add	add	R	R[rd] = R[rs] + R[rt]	(1)	0 / 20_{hex}
Add Immediate	addi	I	R[rt] = R[rs] + SignExtImm	(1,2)	8_{hex}
Add Imm. Unsigned	addiu	I	R[rt] = R[rs] + SignExtImm	(2)	9_{hex}
Add Unsigned	addu	R	R[rd] = R[rs] + R[rt]		0 / 21_{hex}
And	and	R	R[rd] = R[rs] & R[rt]		0 / 24_{hex}
And Immediate	andi	I	R[rt] = R[rs] & ZeroExtImm	(3)	c_{hex}
Branch On Equal	beq	I	if(R[rs]==R[rt]) PC=PC+4+BranchAddr	(4)	4_{hex}
Branch On Not Equal	bne	I	if(R[rs]!=R[rt]) PC=PC+4+BranchAddr	(4)	5_{hex}
Jump	j	J	PC=JumpAddr	(5)	2_{hex}
Jump And Link	jal	J	R[31]=PC+8;PC=JumpAddr	(5)	3_{hex}
Jump Register	jr	R	PC=R[rs]		0 / 08_{hex}
Load Byte Unsigned	lbu	I	R[rt]={24'b0,M[R[rs] +SignExtImm](7:0)}	(2)	24_{hex}
Load Halfword Unsigned	lhu	I	R[rt]={16'b0,M[R[rs] +SignExtImm](15:0)}	(2)	25_{hex}
Load Linked	ll	I	R[rt] = M[R[rs]+SignExtImm]	(2,7)	30_{hex}
Load Upper Imm.	lui	I	R[rt] = {imm, 16'b0}		f_{hex}
Load Word	lw	I	R[rt] = M[R[rs]+SignExtImm]	(2)	23_{hex}
Nor	nor	R	R[rd] = ~ (R[rs] | R[rt])		0 / 27_{hex}
Or	or	R	R[rd] = R[rs] | R[rt]		0 / 25_{hex}
Or Immediate	ori	I	R[rt] = R[rs] | ZeroExtImm	(3)	d_{hex}
Set Less Than	slt	R	R[rd] = (R[rs] < R[rt]) ? 1 : 0		0 / $2a_{hex}$
Set Less Than Imm.	slti	I	R[rt] = (R[rs] < SignExtImm)? 1 : 0	(2)	a_{hex}
Set Less Than Imm. Unsigned	sltiu	I	R[rt] = (R[rs] < SignExtImm) ? 1 : 0	(2,6)	b_{hex}
Set Less Than Unsig.	sltu	R	R[rd] = (R[rs] < R[rt]) ? 1 : 0	(6)	0 / $2b_{hex}$
Shift Left Logical	sll	R	R[rd] = R[rt] << shamt		0 / 00_{hex}
Shift Right Logical	srl	R	R[rd] = R[rt] >>> shamt		0 / 02_{hex}
Store Byte	sb	I	M[R[rs]+SignExtImm](7:0) = R[rt](7:0)	(2)	28_{hex}
Store Conditional	sc	I	M[R[rs]+SignExtImm] = R[rt]; R[rt] = (*atomic*) ? 1 : 0	(2,7)	38_{hex}
Store Halfword	sh	I	M[R[rs]+SignExtImm](15:0) = R[rt](15:0)	(2)	29_{hex}
Store Word	sw	I	M[R[rs]+SignExtImm] = R[rt]	(2)	$2b_{hex}$
Subtract	sub	R	R[rd] = R[rs] - R[rt]	(1)	0 / 22_{hex}
Subtract Unsigned	subu	R	R[rd] = R[rs] - R[rt]		0 / 23_{hex}

(1) May cause overflow exception
(2) SignExtImm = { 16{immediate[15]}, immediate }
(3) ZeroExtImm = { 16{1b'0}, immediate }
(4) BranchAddr = { 14{immediate[15]}, immediate, 2'b0 }
(5) JumpAddr = { PC+4[31:28], address, 2'b0 }
(6) Operands considered unsigned numbers (vs. 2's comp.)
(7) Atomic test&set pair; R[rt] = 1 if pair atomic, 0 if not atomic

BASIC INSTRUCTION FORMATS

R	opcode	rs	rt	rd	shamt	funct
	31–26	25–21	20–16	15–11	10–6	5–0
I	opcode	rs	rt	immediate		
	31–26	25–21	20–16	15–0		
J	opcode	address				
	31–26	25–0				

ARITHMETIC CORE INSTRUCTION SET

②

NAME, MNEMONIC		FORMAT	OPERATION		OPCODE / FMT /FT / FUNCT (Hex)
Branch On FP True	bc1t	FI	if(FPcond)PC=PC+4+BranchAddr	(4)	11/8/1/--
Branch On FP False	bc1f	FI	if(!FPcond)PC=PC+4+BranchAddr	(4)	11/8/0/--
Divide	div	R	Lo=R[rs]/R[rt]; Hi=R[rs]%R[rt]		0/--/--/1a
Divide Unsigned	divu	R	Lo=R[rs]/R[rt]; Hi=R[rs]%R[rt]	(6)	0/--/--/1b
FP Add Single	add.s	FR	F[fd]= F[fs] + F[ft]		11/10/--/0
FP Add Double	add.d	FR	{F[fd],F[fd+1]} = {F[fs],F[fs+1]} + {F[ft],F[ft+1]}		11/11/--/0
FP Compare Single	c.x.s*	FR	FPcond = (F[fs] *op* F[ft]) ? 1 : 0		11/10/--/*y*
FP Compare Double	c.x.d*	FR	FPcond = ({F[fs],F[fs+1]} *op* {F[ft],F[ft+1]}) ? 1 : 0		11/11/--/*y*

* (*x* is eq, lt, or le) (*op* is ==, <, or <=) (*y* is 32, 3c, or 3e)

FP Divide Single	div.s	FR	F[fd] = F[fs] / F[ft]		11/10/--/3
FP Divide Double	div.d	FR	{F[fd],F[fd+1]} = {F[fs],F[fs+1]} / {F[ft],F[ft+1]}		11/11/--/3
FP Multiply Single	mul.s	FR	F[fd] = F[fs] * F[ft]		11/10/--/2
FP Multiply Double	mul.d	FR	{F[fd],F[fd+1]} = {F[fs],F[fs+1]} * {F[ft],F[ft+1]}		11/11/--/2
FP Subtract Single	sub.s	FR	F[fd]=F[fs] - F[ft]		11/10/--/1
FP Subtract Double	sub.d	FR	{F[fd],F[fd+1]} = {F[fs],F[fs+1]} - {F[ft],F[ft+1]}		11/11/--/1
Load FP Single	lwc1	I	F[rt]=M[R[rs]+SignExtImm]	(2)	31/--/--/--
Load FP Double	ldc1	I	F[rt]=M[R[rs]+SignExtImm]; F[rt+1]=M[R[rs]+SignExtImm+4]	(2)	35/--/--/--
Move From Hi	mfhi	R	R[rd] = Hi		0 /--/--/10
Move From Lo	mflo	R	R[rd] = Lo		0 /--/--/12
Move From Control	mfc0	R	R[rd] = CR[rs]		10 /0/--/0
Multiply	mult	R	{Hi,Lo} = R[rs] * R[rt]		0/--/--/18
Multiply Unsigned	multu	R	{Hi,Lo} = R[rs] * R[rt]	(6)	0/--/--/19
Shift Right Arith.	sra	R	R[rd] = R[rt] >> shamt		0/--/--/3
Store FP Single	swc1	I	M[R[rs]+SignExtImm] = F[rt]	(2)	39/--/--/--
Store FP Double	sdc1	I	M[R[rs]+SignExtImm] = F[rt]; M[R[rs]+SignExtImm+4] = F[rt+1]	(2)	3d/--/--/--

FLOATING-POINT INSTRUCTION FORMATS

FR	opcode	fmt	ft	fs	fd	funct
	31–26	25–21	20–16	15–11	10–6	5–0
FI	opcode	fmt	ft	immediate		
	31–26	25–21	20–16	15–0		

PSEUDOINSTRUCTION SET

NAME	MNEMONIC	OPERATION
Branch Less Than	blt	if(R[rs]<R[rt]) PC = Label
Branch Greater Than	bgt	if(R[rs]>R[rt]) PC = Label
Branch Less Than or Equal	ble	if(R[rs]<=R[rt]) PC = Label
Branch Greater Than or Equal	bge	if(R[rs]>=R[rt]) PC = Label
Load Immediate	li	R[rd] = immediate
Move	move	R[rd] = R[rs]

REGISTER NAME, NUMBER, USE, CALL CONVENTION

NAME	NUMBER	USE	PRESERVED ACROSS A CALL?
$zero	0	The Constant Value 0	N.A.
$at	1	Assembler Temporary	No
$v0-$v1	2-3	Values for Function Results and Expression Evaluation	No
$a0-$a3	4-7	Arguments	No
$t0-$t7	8-15	Temporaries	No
$s0-$s7	16-23	Saved Temporaries	Yes
$t8-$t9	24-25	Temporaries	No
$k0-$k1	26-27	Reserved for OS Kernel	No
$gp	28	Global Pointer	Yes
$sp	29	Stack Pointer	Yes
$fp	30	Frame Pointer	Yes
$ra	31	Return Address	Yes

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OPCODES, BASE CONVERSION, ASCII SYMBOLS

③

MIPS opcode (31:26)	(1) MIPS funct (5:0)	(2) MIPS funct (5:0)	Binary	Decimal	Hexadecimal	ASCII Character	Decimal	Hexadecimal	ASCII Character
(1)	sll	add.*f*	00 0000	0	0	NUL	64	40	@
		sub.*f*	00 0001	1	1	SOH	65	41	A
j	srl	mul.*f*	00 0010	2	2	STX	66	42	B
jal	sra	div.*f*	00 0011	3	3	ETX	67	43	C
beq	sllv	sqrt.*f*	00 0100	4	4	EOT	68	44	D
bne		abs.*f*	00 0101	5	5	ENQ	69	45	E
blez	srlv	mov.*f*	00 0110	6	6	ACK	70	46	F
bgtz	srav	neg.*f*	00 0111	7	7	BEL	71	47	G
addi	jr		00 1000	8	8	BS	72	48	H
addiu	jalr		00 1001	9	9	HT	73	49	I
slti	movz		00 1010	10	a	LF	74	4a	J
sltiu	movn		00 1011	11	b	VT	75	4b	K
andi	syscall	round.w.*f*	00 1100	12	c	FF	76	4c	L
ori	break	trunc.w.*f*	00 1101	13	d	CR	77	4d	M
xori		ceil.w.*f*	00 1110	14	e	SO	78	4e	N
lui	sync	floor.w.*f*	00 1111	15	f	SI	79	4f	O
	mfhi		01 0000	16	10	DLE	80	50	P
(2)	mthi		01 0001	17	11	DC1	81	51	Q
	mflo	movz.*f*	01 0010	18	12	DC2	82	52	R
	mtlo	movn.*f*	01 0011	19	13	DC3	83	53	S
			01 0100	20	14	DC4	84	54	T
			01 0101	21	15	NAK	85	55	U
			01 0110	22	16	SYN	86	56	V
			01 0111	23	17	ETB	87	57	W
	mult		01 1000	24	18	CAN	88	58	X
	multu		01 1001	25	19	EM	89	59	Y
	div		01 1010	26	1a	SUB	90	5a	Z
	divu		01 1011	27	1b	ESC	91	5b	[
			01 1100	28	1c	FS	92	5c	\
			01 1101	29	1d	GS	93	5d	]
			01 1110	30	1e	RS	94	5e	^
			01 1111	31	1f	US	95	5f	_
lb	add	cvt.s.*f*	10 0000	32	20	Space	96	60	`
lh	addu	cvt.d.*f*	10 0001	33	21	!	97	61	a
lwl	sub		10 0010	34	22	"	98	62	b
lw	subu		10 0011	35	23	#	99	63	c
lbu	and	cvt.w.*f*	10 0100	36	24	$	100	64	d
lhu	or		10 0101	37	25	%	101	65	e
lwr	xor		10 0110	38	26	&	102	66	f
	nor		10 0111	39	27	'	103	67	g
sb			10 1000	40	28	(	104	68	h
sh			10 1001	41	29	)	105	69	i
swl	slt		10 1010	42	2a	*	106	6a	j
sw	sltu		10 1011	43	2b	+	107	6b	k
			10 1100	44	2c	,	108	6c	l
			10 1101	45	2d	-	109	6d	m
swr			10 1110	46	2e	.	110	6e	n
cache			10 1111	47	2f	/	111	6f	o
ll	tge	c.f.*f*	11 0000	48	30	0	112	70	p
lwc1	tgeu	c.un.*f*	11 0001	49	31	1	113	71	q
lwc2	tlt	c.eq.*f*	11 0010	50	32	2	114	72	r
pref	tltu	c.ueq.*f*	11 0011	51	33	3	115	73	s
	teq	c.olt.*f*	11 0100	52	34	4	116	74	t
ldc1		c.ult.*f*	11 0101	53	35	5	117	75	u
ldc2	tne	c.ole.*f*	11 0110	54	36	6	118	76	v
		c.ule.*f*	11 0111	55	37	7	119	77	w
sc		c.sf.*f*	11 1000	56	38	8	120	78	x
swc1		c.ngle.*f*	11 1001	57	39	9	121	79	y
swc2		c.seq.*f*	11 1010	58	3a	:	122	7a	z
		c.ngl.*f*	11 1011	59	3b	;	123	7b	{
		c.lt.*f*	11 1100	60	3c	<	124	7c	|
sdc1		c.nge.*f*	11 1101	61	3d	=	125	7d	}
sdc2		c.le.*f*	11 1110	62	3e	>	126	7e	~
		c.ngt.*f*	11 1111	63	3f	?	127	7f	DEL

(1) opcode(31:26) == 0

(2) opcode(31:26) == 17_{ten} (11_{hex}); if fmt(25:21)==16_{ten} (10_{hex}).*f* = s (single); if fmt(25:21)==17_{ten} (11_{hex}).*f* = d (double)

IEEE 754 FLOATING-POINT STANDARD

$(-1)^S \times (1 + \text{Fraction}) \times 2^{(\text{Exponent} - \text{Bias})}$

where Single Precision Bias = 127, Double Precision Bias = 1023.

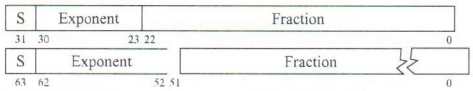
④

IEEE 754 Symbols

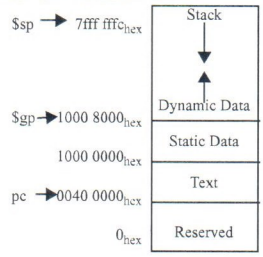
Exponent	Fraction	Object
0	0	± 0
0	≠0	± Denorm
1 to MAX - 1	anything	± Fl. Pt. Num.
MAX	0	±∞
MAX	≠0	NaN

S.P. MAX = 255, D.P. MAX = 2047

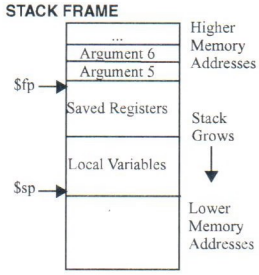
IEEE Single Precision and Double Precision Formats:



MEMORY ALLOCATION



STACK FRAME

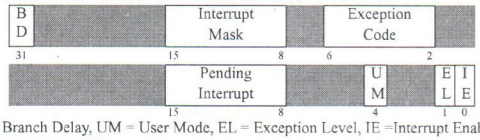


DATA ALIGNMENT

Double Word							
Word				Word			
Halfword		Halfword		Halfword		Halfword	
Byte	Byte	Byte	Byte	Byte	Byte	Byte	Byte
0	1	2	3	4	5	6	7

Value of three least significant bits of byte address (Big Endian)

EXCEPTION CONTROL REGISTERS: CAUSE AND STATUS



BD = Branch Delay, UM = User Mode, EL = Exception Level, IE =Interrupt Enable

EXCEPTION CODES

Number	Name	Cause of Exception	Number	Name	Cause of Exception
0	Int	Interrupt (hardware)	9	Bp	Breakpoint Exception
4	AdEL	Address Error Exception (load or instruction fetch)	10	RI	Reserved Instruction Exception
5	AdES	Address Error Exception (store)	11	CpU	Coprocessor Unimplemented
6	IBE	Bus Error on Instruction Fetch	12	Ov	Arithmetic Overflow Exception
7	DBE	Bus Error on Load or Store	13	Tr	Trap
8	Sys	Syscall Exception	15	FPE	Floating Point Exception

SIZE PREFIXES (10^x for Disk, Communication; 2^x for Memory)

SIZE	PREFIX	SIZE	PREFIX	SIZE	PREFIX	SIZE	PREFIX
10^3, 2^{10}	Kilo-	10^{15}, 2^{50}	Peta-	10^{-3}	milli-	10^{-15}	femto-
10^6, 2^{20}	Mega-	10^{18}, 2^{60}	Exa-	10^{-6}	micro-	10^{-18}	atto-
10^9, 2^{30}	Giga-	10^{21}, 2^{70}	Zetta-	10^{-9}	nano-	10^{-21}	zepto-
10^{12}, 2^{40}	Tera-	10^{24}, 2^{80}	Yotta-	10^{-12}	pico-	10^{-24}	yocto-

The symbol for each prefix is just its first letter, except μ is used for micro.

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MIPS Reference Data Card ("Green Card") 1. Pull along perforation to separate card 2. Fold bottom side (columns 3 and 4) together