Appendix 1: String functions

`char *strcat(char *dest, const char *src)` - appends the string pointed to by `src` to the end of the string pointed to by `dest`. This function returns a pointer to the resulting string `dest`.

`char *strncat(char *dest, const char *src, uint32_t n)` - appends the string pointed to by `src` to the end of the string pointed to by dest up to `n` characters long. This function returns a pointer to the resulting string `dest`.

`char *strcpy(char *dest, const char *src)` - copies the string pointed to, by `src` to `dest`. This returns a pointer to the destination string `dest`.

`int sprintf(char *str, const char *format, ...)` - writes formatted output to the string pointed to by `str`, using the format string and additional arguments in the same way as `printf`. Returns the number of characters written (excluding the null terminator), or a negative value on error.

`uint32_t strlen(const char *str)` - computes the length of the string pointed to by `str`, not including the terminating `'\0'` character. Returns the number of characters in the string.

`int strncmp(const char *str1, const char *str2, uint32_t n)` - compares at most the first `n` bytes of `str1` and `str2`. This function return values that are as follows −

- if Return value < 0 then it indicates `str1` is less than `str2`.
- if Return value > 0 then it indicates `str2` is less than `str1`.
- if Return value = 0 then it indicates `str1` is equal to `str2`.

`char *strchr(const char *str, char c)` - searches for the first occurrence of the character `c` (an `unsigned char`) in the string pointed to by the argument `str`. This returns a pointer to the first occurrence of the character `c` in the string `str`, or `NULL` if the character is not found.

`char *strrchr(const char *str, char c)` - searches for the last occurrence of the character `c` (an `unsigned char`) in the string pointed to, by the argument `str`. This function returns a pointer to the last occurrence of character in `str`. If the value is not found, the function returns a `null` pointer.

`char *strstr(const char *haystack, const char *needle)` - function finds the first occurrence of the substring `needle` in the string `haystack`. The terminating `'\0'` characters are not compared. This function returns a pointer to the first occurrence in `haystack` of any of the entire sequence of characters specified in `needle`, or a null pointer if the sequence is not present in `haystack`.

`char *strtok(char *str, const char *delim)` - breaks string `str` into a series of tokens using the delimiter `delim`. This function returns a pointer to the first token found in the string. A null pointer is returned if there are no tokens left to retrieve.

Appendix 2: `strtok` Operation

Appendix 3: ASCII Table

ASCII Table

Dec	Hex	Oct	Char	Dec	Hex	Oct	Char	Dec	Hex	Oct	Char	Dec	Hex	Oct	Char
0	0	0		32	20	40	[space]	64	40	100	@	96	60	140	`
1	1	1		33	21	41	!	65	41	101	A	97	61	141	a
2	2	2		34	22	42	"	66	42	102	B	98	62	142	b
3	3	3		35	23	43	#	67	43	103	C	99	63	143	c
4	4	4		36	24	44	$	68	44	104	D	100	64	144	d
5	5	5		37	25	45	%	69	45	105	E	101	65	145	e
6	6	6		38	26	46	&	70	46	106	F	102	66	146	f
7	7	7		39	27	47	'	71	47	107	G	103	67	147	g
8	8	10		40	28	50	(	72	48	110	H	104	68	150	h
9	9	11		41	29	51	)	73	49	111	I	105	69	151	i
10	A	12		42	2A	52	*	74	4A	112	J	106	6A	152	j
11	B	13		43	2B	53	+	75	4B	113	K	107	6B	153	k
12	C	14		44	2C	54	,	76	4C	114	L	108	6C	154	l
13	D	15		45	2D	55	-	77	4D	115	M	109	6D	155	m
14	E	16		46	2E	56	.	78	4E	116	N	110	6E	156	n
15	F	17		47	2F	57	/	79	4F	117	O	111	6F	157	o
16	10	20		48	30	60	0	80	50	120	P	112	70	160	p
17	11	21		49	31	61	1	81	51	121	Q	113	71	161	q
18	12	22		50	32	62	2	82	52	122	R	114	72	162	r
19	13	23		51	33	63	3	83	53	123	S	115	73	163	s
20	14	24		52	34	64	4	84	54	124	T	116	74	164	t
21	15	25		53	35	65	5	85	55	125	U	117	75	165	u
22	16	26		54	36	66	6	86	56	126	V	118	76	166	v
23	17	27		55	37	67	7	87	57	127	W	119	77	167	w
24	18	30		56	38	70	8	88	58	130	X	120	78	170	x
25	19	31		57	39	71	9	89	59	131	Y	121	79	171	y
26	1A	32		58	3A	72	:	90	5A	132	Z	122	7A	172	z
27	1B	33		59	3B	73	;	91	5B	133	[	123	7B	173	{
28	1C	34		60	3C	74	<	92	5C	134	\	124	7C	174	|
29	1D	35		61	3D	75	=	93	5D	135	]	125	7D	175	}
30	1E	36		62	3E	76	>	94	5E	136	^	126	7E	176	~
31	1F	37		63	3F	77	?	95	5F	137	_	127	7F	177	

Appendix 4: C Operator Precedence

Precedence	Operator	Description	Associativity
1	`++ --`	Suffix/postfix increment and decrement	Left-to-right
	`()`	Function call	
	`[]`	Array subscripting	
	`.`	Structure and union member access	
	`->`	Structure and union member access through pointer	
2	`++ --`	Prefix increment and decrement	Right-to-left
	`+ -`	Unary plus and minus	
	`! ~`	Logical NOT and bitwise NOT	
	`(`*`type`*`)`	Cast	
	`*`	Indirection (dereference)	
	`&`	Address-of	
	`sizeof`	Size of	
3	`* / %`	Multiplication, division, and remainder	Left-to-right
4	`+ -`	Addition and subtraction	
5	`<< >>`	Bitwise left shift and right shift	
6	`< <=`	For relational operators < and ≤ respectively	
	`> >=`	For relational operators > and ≥ respectively	
7	`== !=`	For relational = and ≠ respectively	
8	`&`	Bitwise AND	
9	`^`	Bitwise XOR (exclusive or)	
10	`|`	Bitwise OR (inclusive or)	
11	`&&`	Logical AND	
12	`||`	Logical OR	
13	`?:`	Ternary conditional	Right-to-left
14	`=`	Simple assignment	
	`+= -=`	Assignment by sum and difference	
	`*= /= %=`	Assignment by product, quotient, and remainder	
	`<<= >>=`	Assignment by bitwise left shift and right shift	
	`&= ^= |=`	Assignment by bitwise AND, XOR, and OR	

MIT 6.190 ISA Reference Card: Instructions

Instruction	Syntax	Description	Execution
LUI	`lui rd, luiConstant`	Load Upper Immediate	`reg[rd] <= luiConstant « 12`
JAL	`jal rd, label`	Jump and Link	`reg[rd] <= pc + 4` `pc <= label`
JALR	`jalr rd, offset(rs1)`	Jump and Link Register	`reg[rd] <= pc + 4` `pc <= {(reg[rs1] + offset)[31:1], 1'b0}`
BEQ	`beq rs1, rs2, label`	Branch if =	`pc <= (reg[rs1] == reg[rs2]) ? label: pc + 4`
BNE	`bne rs1, rs2, label`	Branch if ≠	`pc <= (reg[rs1] != reg[rs2]) ? label: pc + 4`
BLT	`blt rs1, rs2, label`	Branch if < (Signed)	`pc <= (reg[rs1] <$_s$ reg[rs2]) ? label: pc + 4`
BGE	`bge rs1, rs2, label`	Branch if ≥ (Signed)	`pc <= (reg[rs1] >=$_s$ reg[rs2]) ? label: pc + 4`
BLTU	`bltu rs1, rs2, label`	Branch if < (Unsigned)	`pc <= (reg[rs1] <$_u$ reg[rs2]) ? label: pc + 4`
BGEU	`bgeu rs1, rs2, label`	Branch if ≥ (Unsigned)	`pc <= (reg[rs1] >=$_u$ reg[rs2]) ? label: pc + 4`
LW	`lw rd, offset(rs1)`	Load Word	`reg[rd] <= mem[reg[rs1] + offset]`
SW	`sw rs2, offset(rs1)`	Store Word	`mem[reg[rs1] + offset] <= reg[rs2]`
ADDI	`addi rd, rs1, constant`	Add Immediate	`reg[rd] <= reg[rs1] + constant`
SLTI	`slti rd, rs1, constant`	Compare < Immediate (Signed)	`reg[rd] <= (reg[rs1] <$_s$ constant) ? 1 : 0`
SLTIU	`sltiu rd, rs1, constant`	Compare < Immediate (Unsigned)	`reg[rd] <= (reg[rs1] <$_u$ constant) ? 1 : 0`
XORI	`xori rd, rs1, constant`	Xor Immediate	`reg[rd] <= reg[rs1] ^ constant`
ORI	`ori rd, rs1, constant`	Or Immediate	`reg[rd] <= reg[rs1] | constant`
ANDI	`andi rd, rs1, constant`	And Immediate	`reg[rd] <= reg[rs1] & constant`
SLLI	`slli rd, rs1, shamt`	Shift Left Logical Immediate	`reg[rd] <= reg[rs1] « shamt`
SRLI	`srli rd, rs1, shamt`	Shift Right Logical Immediate	`reg[rd] <= reg[rs1] »$_u$ shamt`
SRAI	`srai rd, rs1, shamt`	Shift Right Arithmetic Immediate	`reg[rd] <= reg[rs1] »$_s$ shamt`
ADD	`add rd, rs1, rs2`	Add	`reg[rd] <= reg[rs1] + reg[rs2]`
SUB	`sub rd, rs1, rs2`	Subtract	`reg[rd] <= reg[rs1] - reg[rs2]`
SLL	`sll rd, rs1, rs2`	Shift Left Logical	`reg[rd] <= reg[rs1] « reg[rs2][4:0]`
SLT	`slt rd, rs1, rs2`	Compare < (Signed)	`reg[rd] <= (reg[rs1] <$_s$ reg[rs2]) ? 1 : 0`
SLTU	`sltu rd, rs1, rs2`	Compare < (Unsigned)	`reg[rd] <= (reg[rs1] <$_u$ reg[rs2]) ? 1 : 0`
XOR	`xor rd, rs1, rs2`	Xor	`reg[rd] <= reg[rs1] ^ reg[rs2]`
SRL	`srl rd, rs1, rs2`	Shift Right Logical	`reg[rd] <= reg[rs1] »$_u$ reg[rs2][4:0]`
SRA	`sra rd, rs1, rs2`	Shift Right Arithmetic	`reg[rd] <= reg[rs1] »$_s$ reg[rs2][4:0]`
OR	`or rd, rs1, rs2`	Or	`reg[rd] <= reg[rs1] | reg[rs2]`
AND	`and rd, rs1, rs2`	And	`reg[rd] <= reg[rs1] & reg[rs2]`

Note: *luiConstant* is a 20-bit value. *offset* and *constant* are signed 12-bit values that are sign-extended to 32-bit values. *label* is a 32-bit memory address or its alias name. *shamt* is a 5-bit unsigned shift amount.

MIT 6.190 ISA Reference Card: Pseudoinstructions

Pseudoinstruction	Description	Execution
`li rd, liConstant`	Load Immediate	`reg[rd] <= liConstant`
`mv rd, rs1`	Move	`reg[rd] <= reg[rs1] + 0`
`not rd, rs1`	Logical Not	`reg[rd] <= reg[rs1] ^ -1`
`neg rd, rs1`	Arithmetic Negation	`reg[rd] <= 0 - reg[rs1]`
`j label`	Jump	`pc <= label`
`jal label` `call label`	Jump and Link (with `ra`)	`reg[ra] <= pc + 4` `pc <= label`
`jr rs1`	Jump Register	`pc <= reg[rs1] & ~1`
`jalr rs1`	Jump and Link Register (with `ra`)	`reg[ra] <= pc + 4` `pc <= reg[rs1] & ~1`
`ret`	Return from Subroutine	`pc <= reg[ra]`
`bgt rs1, rs2, label`	Branch > (Signed)	`pc <= (reg[rs1] >$_s$ reg[rs2]) ? label : pc + 4`
`ble rs1, rs2, label`	Branch ≤ (Signed)	`pc <= (reg[rs1] <=$_s$ reg[rs2]) ? label : pc + 4`
`bgtu rs1, rs2, label`	Branch > (Unsigned)	`pc <= (reg[rs1] >$_s$ reg[rs2]) ? label : pc + 4`
`bleu rs1, rs2, label`	Branch ≤ (Unsigned)	`pc <= (reg[rs1] <=$_s$ reg[rs2]) ? label : pc + 4`
`beqz rs1, label`	Branch = 0	`pc <= (reg[rs1] == 0) ? label : pc + 4`
`bnez rs1, label`	Branch ≠ 0	`pc <= (reg[rs1] != 0) ? label : pc + 4`
`bltz rs1, label`	Branch < 0 (Signed)	`pc <= (reg[rs1] <$_s$ 0) ? label : pc + 4`
`bgez rs1, label`	Branch ≥ 0 (Signed)	`pc <= (reg[rs1] >=$_s$ 0) ? label : pc + 4`
`bgtz rs1, label`	Branch > 0 (Signed)	`pc <= (reg[rs1] >$_s$ 0) ? label : pc + 4`
`blez rs1, label`	Branch ≤ 0 (Signed)	`pc <= (reg[rs1] <=$_s$ 0) ? label : pc + 4`

Note: *liConstant* is a 32-bit value.

MIT 6.190 ISA Reference Card: Calling Convention

Registers	Symbolic names	Description	Saver
x0	zero	Hardwired zero	—
x1	ra	Return address	Caller
x2	sp	Stack pointer	Callee
x3	gp	Global pointer	—
x4	tp	Thread pointer	—
x5-x7	t0-t2	Temporary registers	Caller
x8-x9	s0-s1	Saved registers	Callee
x10-x11	a0-a1	Function arguments and return values	Caller
x12-x17	a2-a7	Function arguments	Caller
x18-x27	s2-s11	Saved registers	Callee
x28-x31	t3-t6	Temporary registers	Caller

MIT 6.190 ISA Reference Card: Instruction Encodings

31 25	24 20	19 15	14 12	11 7	6 0	
funct7	rs2	rs1	funct3	rd	opcode	R-type
imm[11:0]		rs1	funct3	rd	opcode	I-type
imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode	S-type
imm[12|10:5]	rs2	rs1	funct3	imm[4:1|11]	opcode	B-type
imm[31:12]				rd	opcode	U-type
imm[20|10:1|11|19:12]				rd	opcode	J-type

RV32I Base Instruction Set (MIT 6.190 subset)

imm[31:12]				rd	0110111	LUI
imm[20|10:1|11|19:12]				rd	1101111	JAL
imm[11:0]		rs1	000	rd	1100111	JALR
imm[12|10:5]	rs2	rs1	000	imm[4:1|11]	1100011	BEQ
imm[12|10:5]	rs2	rs1	001	imm[4:1|11]	1100011	BNE
imm[12|10:5]	rs2	rs1	100	imm[4:1|11]	1100011	BLT
imm[12|10:5]	rs2	rs1	101	imm[4:1|11]	1100011	BGE
imm[12|10:5]	rs2	rs1	110	imm[4:1|11]	1100011	BLTU
imm[12|10:5]	rs2	rs1	111	imm[4:1|11]	1100011	BGEU
imm[11:0]		rs1	010	rd	0000011	LW
imm[11:5]	rs2	rs1	010	imm[4:0]	0100011	SW
imm[11:0]		rs1	000	rd	0010011	ADDI
imm[11:0]		rs1	010	rd	0010011	SLTI
imm[11:0]		rs1	011	rd	0010011	SLTIU
imm[11:0]		rs1	100	rd	0010011	XORI
imm[11:0]		rs1	110	rd	0010011	ORI
imm[11:0]		rs1	111	rd	0010011	ANDI
0000000	shamt	rs1	001	rd	0010011	SLLI
0000000	shamt	rs1	101	rd	0010011	SRLI
0100000	shamt	rs1	101	rd	0010011	SRAI
0000000	rs2	rs1	000	rd	0110011	ADD
0100000	rs2	rs1	000	rd	0110011	SUB
0000000	rs2	rs1	001	rd	0110011	SLL
0000000	rs2	rs1	010	rd	0110011	SLT
0000000	rs2	rs1	011	rd	0110011	SLTU
0000000	rs2	rs1	100	rd	0110011	XOR
0000000	rs2	rs1	101	rd	0110011	SRL
0100000	rs2	rs1	101	rd	0110011	SRA
0000000	rs2	rs1	110	rd	0110011	OR
0000000	rs2	rs1	111	rd	0110011	AND

- For JAL and branch instructions (BEQ, BNE, BLT, BGE, BLTU, BGEU), the immediate encodes the target address as an offset from the current pc (i.e., $pc + imm = label$).
- Not all immediate bits are encoded. Missing lower bits are filled with zeros and missing upper bits are sign-extended.