CS2100 Comp Org Notes

AY23/24 Sem 1, github.com/gerteck

0. Computer Organisation

- Instruction set architecture (ISA) is the software stack and below it is the hardware stack.
- High level programming language → Assembly Language → Machine Code
- We first simplify the processor to three components: Arithmetic Logic Unit (ALU), Control Unit and Memory Unit.

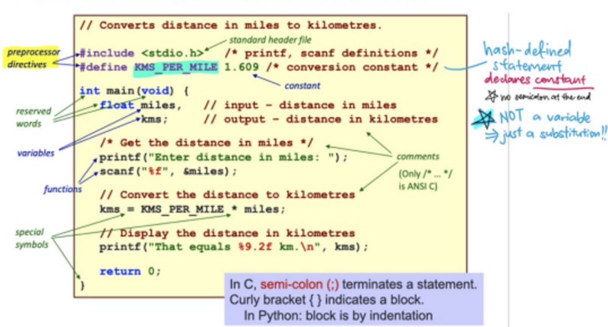
1. C syntax

```
#include <iostream>
#include <stdio.h>
int main(void) {
  printf("Hello World!\n");
  std::cout << "Hello World!\n";
  return 0;
}
```

- C programs generally structured as such:

```
#preprocessor directives
main function header {
    declaration of variables
    executable statements
}
```

- **Preprocessor:** Starts with #, `#include` allows us to use codes defined in another file, `#define` allows us to define a constant.
- Always declare variables at the beginning of a function, and initialize (assign initial value) before use.
- Three common C preprocessors: Header file inclusion, Macro expansions, conditional compilations.
  - uninitialised variables will contain random values



- C is **statically typed** language, type is the **property of the variable**. Once declared, variable can only store data of particular type.

Variable attributes: Name, Type, Address, Value.

- Names are case-sensitive, camelCase, PascalCase.
- All data in C is (or can be) represented as integers. Characters are represented by 8-bit "char" integers based on the ASCII table.
- Strings are then represented as: Array of char. Terminated by a null character (' \0' or 0)

Primitive Data Types in C:

Type	Size	Usage	Examples	Py	JS
`int`	4 bytes	Whole numbers	*Max:* 2^{31}-1, *Min:* -2^{31}	`int`	`number`
`float`	4 bytes	Real numbers	`12.34f`, `1.5e-2f` [1]	`float`	`number`
`double`	8 bytes	Real numbers	`12.34`, `1.5e-2`	`float`	`number`
`char`	1 byte	Characters	`'A'`, `'z'`, `'\n'`, `' '`, `'2'`	`str`	`string`

Format Specifiers:

Placeholder	Type	Fn Use
%c	char	printf/scanf
%d	int	printf/scanf
%f	float/double	printf/scanf

Placeholder	Type	Fn Use
%lf	double	scanf
%p	pointers	printf

Escape Sequences:

Sequence	Meaning	Result
\n	New line	Ouput new line
\t	Horizontal Tab	Move cursor
\"	Double quote	Display "

Sequence	Meaning	Result
%%	Percent	Display percent %
%p	pointers	printf
\a	alarm	Gen. bell sound

Typecasting in C:

```
/* syntax: (type) expression */
int ii = 5; float ff = 15.34
float a = (float) ii / 2; // a = 2.5
float b = (float) (ii / 2); // b = 2.0, floor division
int c = (int) ff / ii; // c = 3
```

Assignment Statements

- The value assigned is returned as result of evaluation.

```
a = b = c = 3 + 6;    // is possible
a = 5 + (b = 3);      // b = 3, a = 8
```

Associativity & Precedence

INCREASING PRECEDENCE

Operator Type	Operator	Associativity
Primary expression operators	`( )` *expr*`++` *expr*`--`	Left to right
Unary operators	`* & + -` `++`*expr* `--`*expr* (*typecast*)	Right to left
Binary operators	`* / %`	Left to right
	`+ -`	
Assignment operators	`= += -= *= /= %=`	Right to left

Selection

- We may define our own boolean library or (`#include <stdbool.h>`).

Non-zero values treated as true, but only 1 (==) equal true.

```
#define false 0
#define true  1
#define bool  char
```

- Short-circuit evaluation.

switch/case:

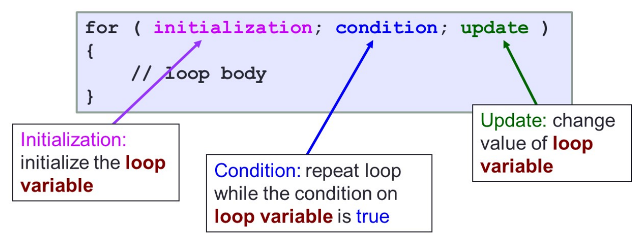
- **fall through behavior**: Removal of `break` allows subsequent cases to run.

```
switch(<variable_or_expression>) {
  case value1:
    /* ... */
    break; // Prevents spill over to next case

  case value2:
    /* ... */
    // no break can spill over to next case

  case value3:
    /* ... */
    break;

   default: // code to execute if equal none.
    /* ... */
    break;
}
```

loops:

```
while ( condition )
{
   // loop body
}
```

```
do
{
   // loop body
}  while ( condition );
```



2. C syntax (Pointers & Functions)

Every **memory location** in a computer is indexed with an address.
All variables in C must be stored in memory,

```
int main(void) {
   int a = 3, *b;     // b is a pointer to an int
   b = &a;            // b points to the address of a
   *b = 5;            // set a through b, a=5

   int *a_ptr;
   a_ptr = &a;
}
```

- **pointer variable** stores the address of another variable.
- **&** → address operator.
  `&x` → address of memory cell where value of x is stored, gets address of a variable.
- `*` → declares a pointer.
  `type *pointer_name` (e.g. `int *x`)
- `*` - dereferencing (access variable through pointer)
  `*x = 32` : following through the pointer to get the value
- Incrementing a pointer('s pointed value): `(*p)++;`
  without brackets: increments pointer to next address (depending on size of the data type) aka += sizeof(*p1)

```
double a, *b;
b = &a; // legal
double c, d;
*d = &c; // legal
double e, f;
f = &e; // ILLEGAL!
```

Call-by-Value / Pointer

- In C, the actual parameters are passed to the formal parameters by a mechanism known as call-by-value.
- The only way for a function to modify the value of a variable outside its scope, is to use pointers to access that variable. (Call-by-pointer)

3. C Arrays, Strings & Structs

Arrays

- a homogenous collection of data all of the same type, occupying contiguous memory locations.
- declaration: `arr = elementType[size]`
- arr refers to `&arr[0]`
- an array name is a **fixed (constant) pointer**, which points to the first element in the array and cannot be reassigned - `arr1 = arr2` is illegal.

```
// an array can ONLY be initialised at the time of declaration
.
int evens[5] = {2, 4, 6, 8, 10};
// if you initialise values, no need to declare length
int odds[] = {1, 3, 5};
// uninitialised values will be zero value
int some[5] = {1, 2, 3}; // some = [1, 2, 3, 0, 0]

int numbers[3];
printf("Enter 3 integers:");
for (i = 0; i < 3; i++) {
 scanf("%d", &numbers[i]); }
```

In function prototypes

```
// parameter names are optional
int sumArray(int [], int); // valid
int sumArray(int arr[], int size); // valid
int sumArray(int *, int); // pointer is valid too

// size can be specified but will be ignored
int sumArray(int arr[8], int size);

// function definition
int sumArray(int *arr, int size) { ... }
int sumArray(int arr[8], int size) { ... } // size ignored
```

Strings

- array of characters terminated with a null character: \0, which has ASCII value of 0.
- string functions: `#include <string.h>`

```
char my_str[] = "hello";
char my_str[] = {'h', 'e', 'l', 'l', 'o', '\0'};
```

I/O

- `in` : `fgets(str, size, stdin)` reads (size - 1) chars or until newline encountered.
- `in` : `scanf("%s", str)` - reads until whitespace.
- `out` : `puts(str)` - terminates with newline
- `out` : `printf("%sn", str)` - prints until '\0' in `str` encountered.

String functions

- `strlen(s)` : returns number of characters in s up to '\0'
- `strcmp(s1, s2)` : compares the ASCII values of corresponding characters, returns s1 - s2, negative number / positive number / 0 if they are equal.
- `strncmp(s1, s2, n)` : strcmp for first n characters of s1 and s2
- `strcpy(s1, s2)` : copy s2 into s1, ocannot directly assign s1 = "Hello", but can copy: strcpy(s1, "Hello")
- `strncpy(s1, s2, n)` : copy first n characters of s2 into s1

Structs

- allow grouping of heterogenous data
- passed by value into functions
  unless: passing array of structs to a function
  array members of structs are **deeply copied**
- can be reassigned
- no memory is allocated to a type.

create new types called box_t and nested_box_t:

```
// declare BEFORE function prototypes
typedef struct {
 int length, width;
 float height;
} box_t;

typedef struct {
 int id;
 box_t smaller_box;
} nested_box_t;

// initialising struct variables
box_t mybox = {2, 3, 5.1};
nested_box_t big_box = {0, {4, 3, 6.7}};

// accessing members
box.length = 1;
big_box.smaller_box.width = 2;
```

Arrow Operator `->`

- `(*player_ptr).name` is equivalent to `player_ptr->name`
- `*player_ptr.name` means `*(player_ptr.name)` (dot has higher precedence

4. Number Systems

Data Representation

- 1 byte = 8 bits
- word = multiple of a byte (e.g. 1 byte, 2 bytes, 4 bytes)
  64-bit machine → 1 word is 8 bytes
- N bits can represent up 2^N to values
- to represent values: ceil $[log_2 M]$ bits required

Weighted Number systems

- weighted number system → has a base (radix)
  base/radix R has weights in powers of R

Prefixes in C

- prefix `0` for octal (e.g. `032` = $(32)_8$)
- prefix `0x` for hexadecimal (e.g. `0x32` = $(32)_16$)
- prefix `0b` for binary

Conversion

- **decimal to binary:**
  whole numbers: repeated **division** by 2, LSB → MSB
  fractions: repeated **multiplication** by 2, MSB → LSB
- **decimal to base-R:**
  for whole numbers: repeated **division** by R for fractions: repeated **multiplication** by R
- binary → octal: partition in groups of 3
- octal → binary: convert each digit into 3-bit binary
- binary → hexadecimal: partition in groups of 4
- hexadecimal → binary: convert each digit to 4-bit binary

ASCII

- American Standard Code for Information Interchange
- 7 bits plus 1 parity bit (for error checking): $2^7 = 128$
- in C: `char` datatype is 1 byte = 8 bit integer
  corresponds to ASCII - can typecast int/char
  e.g. convert uppercase char to lowercase: `c = c + 'a'– 'A'`

Negative Numbers

- **unsigned** numbers: only non-negative values
- **signed** numbers: include all values (positive and negative)
- for negating non-whole numbers: same as whole numbers (ignore the decimal point, then put it back)

Overflow

- positive + positive = negative, OR
- negative + negative = positive

1s addition: If carry out, add 1 to the result (wrap around)

```
  -2        1101
+ -5      + 1010
----      -------
  -7       10111
----      +    1
          -------
            1000
          -------
```
No overflow

```
  -3        1100
+ -7      + 1000
----      -------
 -10       10100
----      +    1
          -------
            0101
          -------
```
Overflow!

2s addition:: Ignore the carry out.

Sign-and-Magnitude:

- MSB represents the sign (0 is positive)
- **range (8-bit):** -127_{10} to $+127_{10}$
  2 zeroes: `00000000` $(+0_{10})$ and `10000000` (-0_{10})
- **negating a number**: reverse the first bit
- **issues**
  1. there are two zeroes (which may be useful for limits!)
  2. not good for performing arithmetic due to the zero in front

1s Complement:

- negated value of x, $-x = 2^n - x - 1$
- **negating a number**: invert the bits
- **range (8-bit)**: -127_{10} to $+127_{10}$
  2 zeroes: `00000000` $(+0_{10})$ and `11111111` $(-0_{10}$)
  range (n-bits): -2^{n-1} to 2^{n-1}

2s Complement

- = 1s complement + 1
- negated value of x, $-x = 2^n - x$
- **negating a number**
  invert the bits, then **add 1**
- **range (8-bit):** -128_{10} to 127_10
  zero: `00000000` $= +0_{10}$ **range (n-bits):** -2^{n-1} to $2^{n-1}-1$

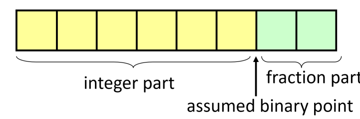
Excess Representation

- Allows the range of values to be distributed evenly between the positive and negative values, by a simple translation.
- `00..00` $= -2^n$
- `10..00` $= 0$
- to express n in Excess-M representation: $n + M$
  E.g. express 5 in excess 8 (4 bit): $5 + 8 = 13$ OR `1101`

5. Number Representations

Fixed-point representation

- In fixed-point representation, the number of bits allocated for the whole number part and fractional part are fixed.
- Issue: limited range.



- If 2s complement is used, we can represent values like:
  $011010.11_{2s} = 26.75_{10}$
  $111110.11_{2s} = -000001.01_2 = -1.25_{10}$

Floating-point representation

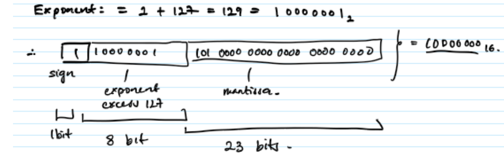
- IEEE 754 floating-point representation
  - exponent is **excess-127**
- 3 components: **sign**, **exponent** and **mantissa (fraction)**

single-precision (32 bit format): 1-bit sign / 8-bit exponent / 23-bit mantissa

- **mantissa** is normalised with an implicit leading bit 1
  to maximise the numbers to be stored
  normalise it to the rightmost bit is always 1, no need to store it.
- better range and accuracy, but more complex

$-6.5_{10} = -110.1_2 = -1.101_2 \times 2^2$

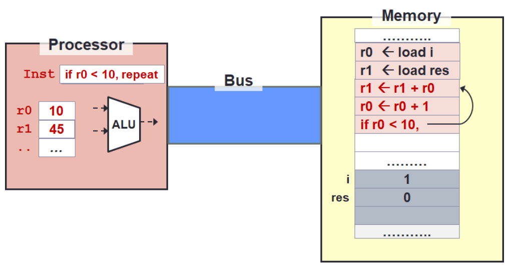
Exponent: $= 2 + 127 = 129 = 10000001_2$



6. MIPS + ISA

Instruction Set Architecture

- **ISA:** abstraction of the interface between the hardware and low-level software
  Software is translated into the instruction set.
  Hardware implements the instruction set.
- **Complier** turns high level language into assembly code.
  Assembler translates assembly language to machine code.
- **stored-memory concept (von Neumann architecture)**: both instructions and data are stored in memory.
- **The load-store model:** *Limit memory operations and relies on registers for storage during execution.



- major types of assembly instruction:
  ○ **memory**: move values between memory and registers ○ **calculation**: arithmetic and other operations
  ○ **control flow**: change the sequential execution (sequence in which instructions are executed)

Registers

- Registers close to processors, fast speed of access. Values in registers are simply binaries, no data types associated.
- Typical architecture has 16 to 32 registers
- MIPS register can hold any 32-bit number

- There are **32 registers** in **MIPS** assembly language:
  - Can be referred by a number (`$0`, `$1`, …, `$31`) OR
  - Referred by a name (eg: `$a0`, `$t1`)

Name	Register number	Usage
`$zero`	0	Constant value 0
`$v0-$v1`	2-3	Values for results and expression evaluation
`$a0-$a3`	4-7	Arguments
`$t0-$t7`	8-15	Temporaries
`$s0-$s7`	16-23	Program variables

Name	Register number	Usage
`$t8-$t9`	24-25	More temporaries
`$gp`	28	Global pointer
`$sp`	29	Stack pointer
`$fp`	30	Frame pointer
`$ra`	31	Return address

$at (register 1) is reserved for the assembler.
$k0-$k1 (registers 26-27) are reserved for the operating system.

6. MIPS Assembly Language

Instructions

Operation	Opcode in MIPS	Meaning
Addition	`add $rd, $rs, $rt`	`$rd = $rs + $rt`
	`addi $rt, $rs, C16`$_{2s}$	`$rt = $rs + C16`$_{2s}$
Subtraction	`sub $rd, $rs, $rt`	`$rd = $rs - $rt`
Shift left logical	`sll $rd, $rt, C5`	`$rd = $rt << C5`
Shift right logical	`srl $rd, $rt, C5`	`$rd = $rt >> C5`
AND bitwise	`and $rd, $rs, $rt`	`$rd = $rs & $rt`
	`andi $rt, $rs, C16`	`$rt = $rs & C16`
OR bitwise	`or $rd, $rs, $rt`	`$rd = $rs | $rt`
	`ori $rt, $rs, C16`	`$rt = $rs | C16`
NOR bitwise	`nor $rd, $rs, $rt`	`$rd = $rs ↓ $rt`
XOR bitwise	`xor $rd, $rs, $rt`	`$rd = $rs ^ $rt`
	`xori $rt, $rs, C16`	`$rt = $rs ^ C16`

`C5` is $[0 \text{ to } 2^5-1]$ `C16`$_{2s}$ is $[-2^{15} \text{ to } 2^{15}-1]$ `C16` is a 16-bit pattern

- `add $s0, $s1, $zero` synonymous with `move $s0, $s1`
- to get a **"NOT" operation**: `nor $t0, $t0, $zero`
- `lui` → load upper immediate (sets upper 16 bits of reg)

Loading Large Constants

- use `lui` to set the upper 16 bits (`lui $t0, 0xAAAA`), lower bits filled with zeroes
- use `ori` to set the lower-order bits (`ori $t0, $t0, 0xF0F0`)

Memory Instructions

- `lw target, dis(src)` : load Mem[src+dis] content to target
- `sw src, disp(target)` : store src content to Mem[targ+disp]
- `lb / sb` : Load/Store byte (doesn't need word-align)

Control Flow

- `bne` : branch if Not Equal (`bne $t0, $t1, label`)
- `beq` : branch if Equal (`beq $t0, $t1, label`)
- `j` : jump unconditionally (`beq $t0, $t1, label`)
- `slt` : set to 1 on less than, else 0 (`slt dest, src1, src2`)

MIPS Instructions Format

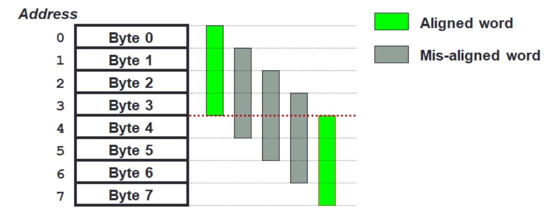
R-format (Register format: `op $r1, $r2, $r3`)
- Instructions which use 2 source registers and 1 destination register
- e.g. `add, sub, and, or, nor, slt, etc`
- **Special cases:** `srl, sll`, etc.

I-format (Immediate format: `op $r1, $r2, Immd`)
- Instructions which use 1 source register, 1 immediate value and 1 destination register
- e.g. `addi, andi, ori, slti, lw, sw, beq, bne`, etc.

J-format (Jump format: `op Immd`)
- `j` instruction uses only one immediate value

Memory Organisation

- each location has an address: an index into the array
  ○ for a k-bit address, the address space is of size 2^k
  ○ largest address possible: $2^k - 1$, bc start from 0
- byte addressing: one byte (8 bits) in every location/address
  ○ more than one byte: word addressing
- load-store architectures can only load data at **word boundaries** (divisible by n bytes)
  e.g. If word consists of 4 bytes:



MIPS:

- Microprocessor without Interlocked Pipelined Stages
- load-store register architecture
  ○ 32 registers, each 32-bit (4 bytes) long
  ○ each word contains 4 bytes
  ○ memory addresses are 32-bit long
- 2^{30} memory words ($2^{32}/4$)
  ○ accessed only by data transfer instructions (aka **memory instructions**)
- MIPS uses byte addresses: consecutive words (word boundaries) differ by 4
  ○ e.g. Mem[0], Mem[4], ...

7. MIPS Instruction Encoding

Refer to **MIPS Reference Data** (midterms handout last slide)

R Format:

6	5	5	5	5	6
opcode	rs	rt	rd	shamt	funct

each field is a 5/6-bit **unsigned** integer
opcode always = 0, shamt set to 0 for all non-shift instructions
rs set to 0 for sll/srl

I Format:

6	5	5	16
opcode	rs	rt	immediate

immediate is a **signed integer 2s complement** (up to 2^{16} values)

J Format:

6 bits	26 bits
opcode	target address

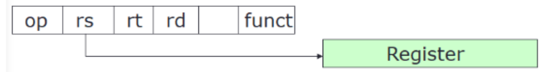
- MIPS will take the 4 MSBs from PC+4 (next instruction after the jump instruction)
- omit 2 LSB (rightmost) since instruction addresses are word-aligned
- maximum jump range = $2^{26+2+4} = 2^{32}$

PC-Relative Addressing

- Program Counter (PC): special register that keeps address of the instruction being executed in the processor
- target address = PC + 16-bit `immediate` field
  - can branch $+-2^{15}$ words = 2^{17} bytes from the PC
  - interpret `immediate` as the number of words since instructions are word-aligned: larger range!
- next branch calculation:
  - if branch is not taken: **PC+4**
  - if branch is taken: **(PC+4) + (immediate x 4)**

Addressing Modes

- **Register Addressing**: operands are registers. (R format Instructions)

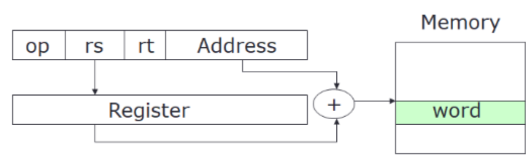


Here, the field `$rs`, `$rt` and `$rd` all points to a register.

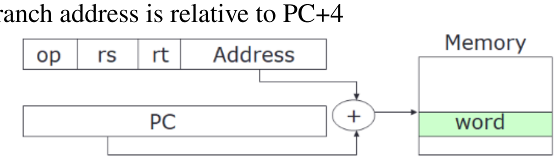
- **Immediate Addressing**: operand is a constant within the instruction itself. e.g. `andi`, `addi`, `ori` `slti` etc.

op	rs	rt	immediate

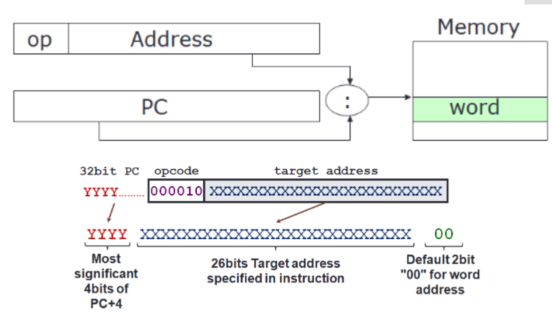
- **Base/Displacement Addressing**: operand is at the memory location whose address is the sum of a register and a constant in the instruction. `lw`, `sw`: (base address) + immediate (displacement)



- **PC-relative Addressing**: address is the sum of PC and constant in the instruction (e.g. `beq`, `bne`). branch address is relative to PC+4



- **Pseudo-direct Addressing**: 26-bit of instruction concatenated with the 4 MSBs of PC (e.g. `j`)



Summary

MIPS assembly language				
Category	Instruction	Example	Meaning	Comments
	add	`add $s1, $s2, $s3`	`$s1 = $s2 + $s3`	Three operands; data in registers
Arithmetic	subtract	`sub $s1, $s2, $s3`	`$s1 = $s2 - $s3`	Three operands; data in registers
	add immediate	`addi $s1, $s2, 100`	`$s1 = $s2 + 100`	Used to add constants
	load word	`lw $s1, 100($s2)`	`$s1` = Memory[`$s2` + 100	Word from memory to register
	store word	`sw $s1, 100($s2)`	Memory[`$s2` + 100] = `$s1`	Word from register to memory
Data transfer	load byte	`lb $s1, 100($s2)`	`$s1` = Memory[`$s2` + 100	Byte from memory to register
	store byte	`sb $s1, 100($s2)`	Memory[`$s2` + 100] = `$s1`	Byte from register to memory
	load upper immediate	`lui $s1, 100`	`$s1` = 100 * 2^{16}	Loads constant in upper 16 bits
	branch on equal	`beq $s1, $s2, 25`	if (`$s1 == $s2`) go to PC + 4 + 100	Equal test; PC-relative branch
	branch on not equal	`bne $s1, $s2, 25`	if (`$s1 != $s2`) go to PC + 4 + 100	Not equal test; PC-relative
Conditional branch	set on less than	`slt $s1, $s2, $s3`	if (`$s2 < $s3`) `$s1` = 1; else `$s1` = 0	Compare less than; for beq, bne
	set less than immediate	`slti $s1, $s2, 100`	if (`$s2 < 100`) `$s1` = 1; else `$s1` = 0	Compare less than constant
	jump	`j 2500`	go to 10000	Jump to target address
Unconditional jump	jump register	`jr $ra`	go to `$ra`	For switch, procedure return
	jump and link	`jal 2500`	`$ra` = PC + 4; go to 10000	For procedure call

8. Instruction Set Architecture