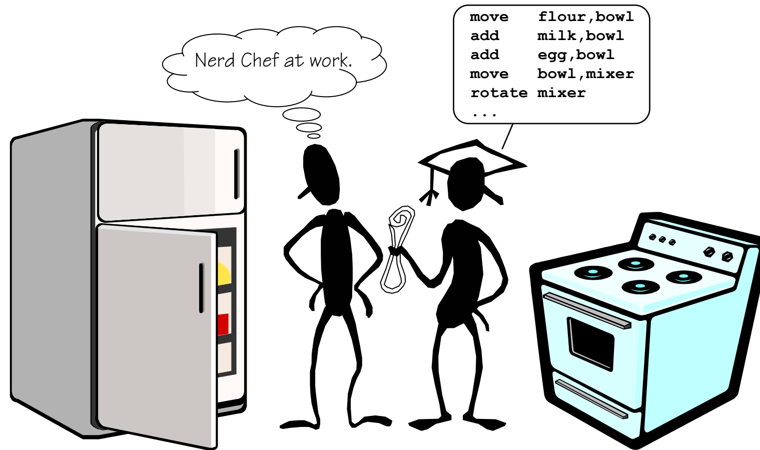
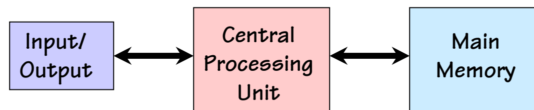
Concocting an Instruction Set

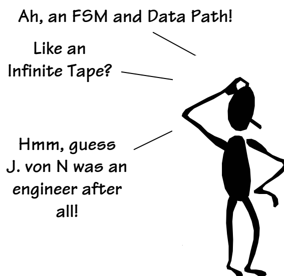


A General-Purpose Computer

The von Neumann Model

Many architectural approaches to the general purpose computer have been explored. The one on which nearly all modern, practical computers is based was proposed by John von Neumann in the late 1940s. Its major components are:





Central Processing Unit (CPU): containing several registers, as well as logic for performing a specified set of operations on their contents.

Memory: storage of N *words* of W bits each, where W is a fixed architectural parameter, and N can be expanded to meet needs.

I/O: Devices for communicating with the outside world.

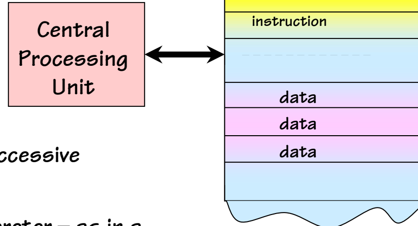
The Stored Program Computer

The von Neumann architecture easily addresses the first two limitations of our simple programmable machine example:

- A richer repertoire of operations, and
- An expandable memory.

But how does it achieve *programmability?*

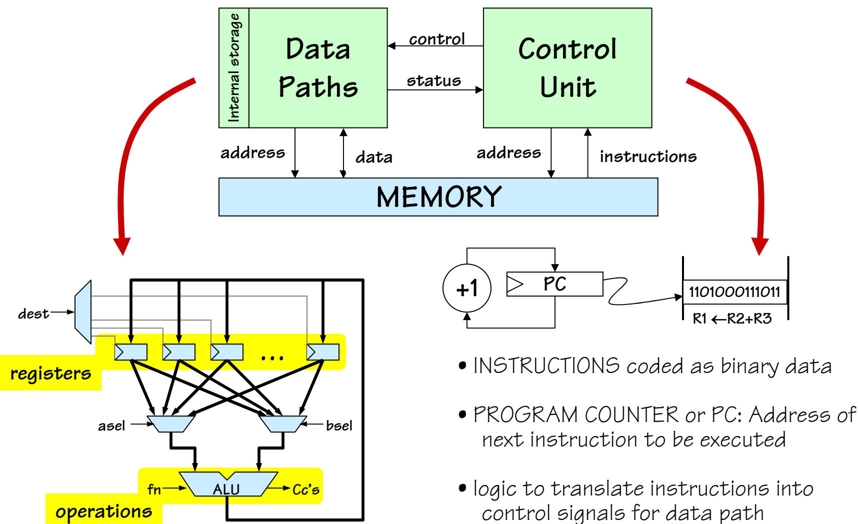
Key idea: Memory holds not only data, but *coded instructions* that make up a *program.*



CPU fetches and executes – interprets – successive instructions of the program ...

- Program is simply data for the interpreter – as in a Universal Turing Machine!
- Single expandable resource pool – main memory – constrains both data and program size.

Anatomy of a von Neumann Computer



- INSTRUCTIONS coded as binary data
- PROGRAM COUNTER or PC: Address of next instruction to be executed
- logic to translate instructions into control signals for data path

Instruction Set Architecture (ISA)

Coding of instructions raises some interesting choices...

- Tradeoffs: performance, compactness, programmability
- Uniformity. Should different instructions
  - Be the same size?
  - Take the same amount of time to execute?
    - Trend: Uniformity. Affords simplicity, speed, pipelining.
- Complexity. How many different instructions? What level operations?
  - Level of support for particular software operations: array indexing, procedure calls, "polynomial evaluate", etc
    - "Reduced Instruction Set Computer" (RISC) philosophy: simple instructions, optimized for speed

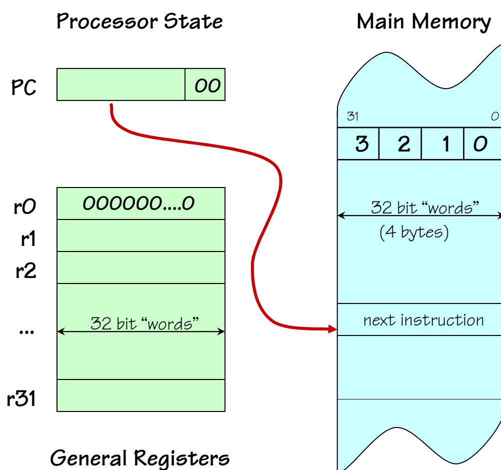
Mix of Engineering & Art...

Trial (by simulation) is our best technique for making choices!

Our representative example: the miniMIPS architecture!

MIPS Programming Model

a representative, simple, contemporary RISC



In Comp 120 we'll use a clean and sufficient subset of the MIPS R2000 core Instruction set that I'll call miniMIPS.

Fetch/Execute loop:

- fetch Mem[PC]
- PC = PC + 4†
- execute fetched instruction (may change PC!)
- repeat!

*†MIPS uses byte memory addresses. However, each instruction is 32-bits wide, and *must* be aligned on a multiple of 4 (word) address. Each word contains four 8-bit bytes. Addresses of consecutive instructions (words) differ by 4.*

MIPS Instruction Formats

All MIPs instructions fit in a single 32-bit word. Every instruction includes various "fields" that encode combinations of

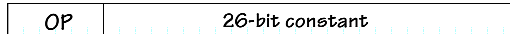
- a 6-bit operation or "OPCODE"
  - specifying one of < 64 basic operations
  - escape codes to enable extended functions
- several 5-bit OPERAND fields, for specifying the sources and destination of the operation, usually one of the 32 registers
- Embedded constants ("immediate" values) of various sizes, 16-bits, 5-bits, and 26-bits. Sometimes treated as signed values, sometimes not.

There are three basic instruction formats:

- R-type, 3 register operands (2 sources, destination)

- I-type, 2 register operands, 16-bit literal constant

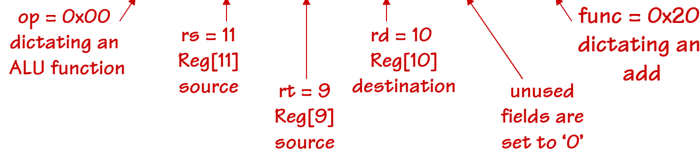
- J-type, no register operands, 26-bit literal constant



MIPS ALU Operations

Sample coded operation: ADD instruction

R-type: 0 0 0 0 0 0 | 0 1 0 1 1 | 0 1 0 0 1 | 0 1 0 1 0 | 0 0 0 0 0 | 1 0 0 0 0 0



References to register contents are prefixed by a "$" to distinguish them from constants or memory addresses

What we prefer to write: `add $10, $11, $9` ("assembly language")

The convention with MIPS assembly language is to specify the destination operand first, followed by source operands.

`add rd, rs, rt:`

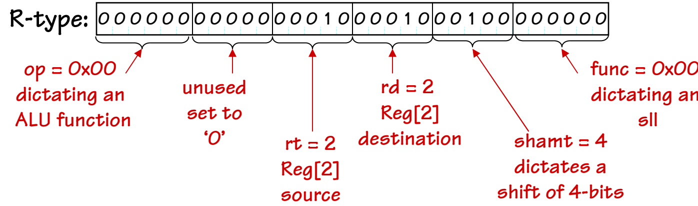
Reg[rd] = Reg[rs] + Reg[rt]

"Add the contents of rs to the contents of rt; store the result in rd"

Similar instructions for other ALU operations:
- arithmetic: add, sub, addu, subu, mult, multu, div, divu
- compare: slt, sltu
- logical: and, or, xor, nor
- shift: sll, srl, sra, sllv, srav, srlv

MIPS Shift Operations

Sample coded operation: SHIFT LOGICAL LEFT instruction



This is peculiar syntax for MIPS, in this ALU instruction the rt operand precedes the rs operand. Usually, it's the other way around

Assembly: `sll $2, $2, 4`

`sll rd, rt, shamt:`

Reg[rd] = Reg[rt] << shamt

"Shift the contents of *rt* to the left by *shamt*; store the result in *rd*"

Assembly: `sllv $2, $2, $8`

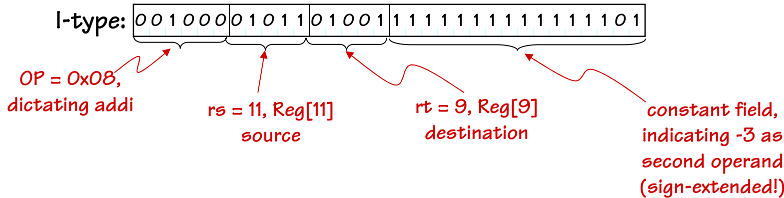
`sllv rd, rt, rs:`

Reg[rd] = Reg[rt] << Reg[rs]

"Shift the contents of *rt* left by the contents of *rs*; store the result in *rd*"

MIPS ALU Operations with Immediate

addi instruction: adds register contents, signed-constant:



Symbolic version: `addi $9, $11, -3`

`addi rt, rs, imm:`

Reg[rt] = Reg[rs] + sxt(imm)

"Add the contents of rs to const; store the result in rt"

Similar instructions for other ALU operations:

arithmetic: addi, addiu
compare: slti, sltiu
logical: andi, ori, xori, lui

Immediate values are sign-extended for arithmetic and compare operations, but not for logical operations.

Why Do Built-in Constants?

Solutions? Why not?

- put constants in memory (was common in older instruction sets)
- create more hard-wired registers for constants (like $0).

SMALL constants are used frequently (50% of operands)

- In a C compiler (gcc) 52% of ALU operations involve a constant
- In a circuit simulator (spice) 69% involve constants
- *e.g., B = B + 1; C = W & 0x00ff; A = B + 0;*

ISA Design Principle: *Make the common cases fast*

MIPS Instructions:

```
addi    $29, $29, 4
slti    $8, $18, 10
andi    $29, $29, 6
ori     $29, $29, 4
```

How large of constants should we allow for? If they are too big, we won't have enough bits leftover for the instructions.

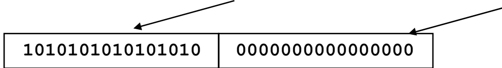
Why are there so many different sized constants in the MIPS ISA? Couldn't the shift amount have been encoded using the I-format?

One way to answer architectural questions is to evaluate the consequences of different choices using <u>carefully chosen</u> representative benchmarks (programs and/or code sequences). Make choices that are "best" according to some metric (cost, performance, ...).

How About Larger Constants?

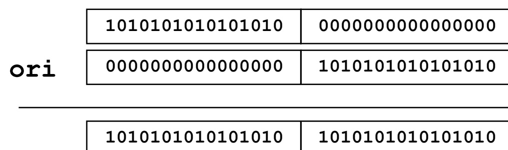
In order to load a 32-bit constant into a register a two instruction sequence is used, "load upper immediate"

```
lui $8, 1010101010101010
```



Then must get the lower order bits right, i.e.,

```
ori $8, $8, 1010101010101010
```



Reminder: In MIPS, Logical Immediate instructions do not sign-extend their constant operand

First MIPS Program

(fragment)

Suppose you want to compute the following expression:

f = (g + h) – (i + j)

Where the variables f, g, h, i, and j are assigned to registers $16, $17, $18, $19, and $20 respectively. What is the MIPS assembly code?

```
add $8,$17,$18        # (g + h)
add $9,$19,$20        # (i + j)
sub $16,$8,$9         # f = (g + h) – (i + j)
```

These three instructions do what our little ad-hoc factorial machine did. Of course, limiting ourselves to registers for storage falls short of our ambitions.... it amounts to the finite storage limitations of an FSM!

Needed: instruction-set support for reading and writing locations in main memory...

MIPS Load & Store Instructions

MIPS is a LOAD/STORE architecture. This means that data memory accesses are limited to load and store instructions, which transfer register contents to-and-from memory. ALU operations work only on registers.

I-type:

OP	rs	rt	16-bit signed constant

`lw rt, imm(rs)` Reg[rt] = Mem[Reg[rs] + sxt(const)]

"Fetch into rt the contents of the memory location whose address is *const* plus the contents of rs"
Abbreviation: `lw rt, imm` for `lw rt, imm($0)`

`sw rt, imm(rs)` Mem[Reg[rs] + sxt(const)] = Reg[rt]

"Store the contents of rt into the memory location whose address is *const* plus the contents of rs"
Abbreviation: `sw rt, imm` for `sw rt, imm($0)`

BYTE ADDRESSES, but lw and sw 32-bit word access word-aligned addresses. Lowest two address bits must be 0!

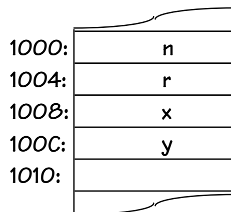
Storage Conventions

Addr assigned at compile time

- Data and Variables are stored in memory
- Operations done on registers
- Registers hold Temporary results

```
int x, y;
y = x + 37;
```

Compilation approach:
LOAD, COMPUTE, STORE



translates to

```
lw   $t0, 0x1008($0)
add  $t0, $t0, 37
sw   $t0, 0x100C($0)
```

or, more humanely, to

```
x=0x1008
y=0x100C
lw   $t0, x
add  $t0, $t0, 37
sw   $t0, y
```

rs defaults to Reg[0] (0)

MIPS Register Usage Conventions

By convention, the MIPS registers are assigned to specific uses, and names. These are supported by the assembler, and higher-level languages. We'll use these names increasingly.

Name	Register number	Usage
$zero	0	the constant value 0
$at	1	assembler temporary
$v0-$v1	2-3	values for results and expression evaluation
$a0-$a3	4-7	arguments
$t0-$t7	8-15	temporaries
$s0-$s7	16-23	saved
$t8-$t9	24-25	more temporaries
$gp	28	global pointer
$sp	29	stack pointer
$fp	30	frame pointer
$ra	31	return address

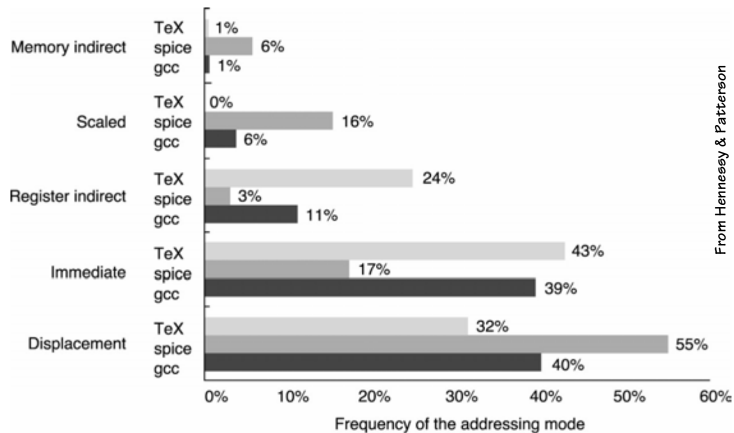
Common "Addressing Modes"

MIPS can do these with appropriate choices for Ra and const

- Absolute: lw $8, 0x1000
  - Value = Mem[constant]
  - Use: accessing static data
- Indirect: lw $8, ($9)
  - Value = Mem[Reg[x]]
  - Use: pointer accesses
- Displacement: lw $8, 16($9)
  - Value = Mem[Reg[x] + constant]
  - Use: access to local variables
- Indexed:
  - Value = Mem[Reg[x] + Reg[y]]
  - Use: array accesses (base+index)
- Memory indirect:
  - Value = Mem[Mem[Reg[x]]]
  - Use: access thru pointer in mem
- Autoincrement:
  - Value = Mem[Reg[x]]; Reg[x]++
  - Use: sequential pointer accesses
- Autodecrement:
  - Value = Reg[X]--; Mem[Reg[x]]
  - Use: stack operations
- Scaled:
  - Value = Mem[Reg[x] + c + d*Reg[y]]
  - Use: array accesses (base+index)

Argh! Is the complexity worth the cost?
Need a cost/benefit analysis!

Memory Operands: Usage



Usage of different memory operand modes

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Capability so far: Expression Evaluation

Translation of an Expression:

```
int x, y;
y = (x-3)*(y+123456)

x:      .word 0
y:      .word 0
c:      .word 123456
    ...
    lw          $t0, x
    addi        $t0, $t0, -3
    lw          $t1, y
    lw          $t2, c
    add         $t1, $t1, $t2
    mul         $t0, $t0, $t1
    sw          $t0, y
```

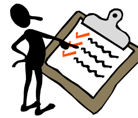
- VARIABLES are allocated storage in main memory
- VARIABLE references translate to LD or ST
- OPERATORS translate to ALU instructions
- SMALL CONSTANTS translate to ALU instructions w/ built-in constant
- "LARGE" CONSTANTS translate to initialized variables

NB: Here we assume that variable addresses fit into 16-bit constants!

Can We Run *Any* Algorithm?

Model thus far:

- Executes instructions sequentially –
- Number of operations executed = number of instructions in our program!

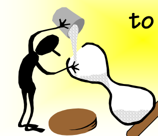


Good news: programs can't "loop forever"!

- Halting problem is solvable for our current MIPS subset!

Bad news: can't compute Factorial:

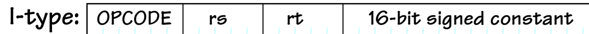
- Only supports bounded-time computations;
- Can't do a loop, e.g. for Factorial!



Needed: ability to change the PC.

MIPS Branch Instructions

MIPS *branch instructions* provide a way of conditionally changing the PC to some nearby location...



I-type:	OPCODE	rs	rt	16-bit signed constant

```
beq rs, rt, label  # Branch if equal

    if (REG[RS] == REG[RT])
     {
       PC = PC + 4 + 4*offset;
     }
```

```
bne rs, rt, label  # Branch if not equal

    if (REG[RS] != REG[RT])
     {
       PC = PC + 4 + 4*offset;
     }
```

NB: Branch targets are specified relative to the current instruction (actually relative to the next instruction, which would be fetched by default). The assembler hides the calculation of these offset values from the user, by allowing them to specify a target address (usually a label) and it does the job of computing the offset's value. The size of the constant field (16-bits) limits the range of branches.

MIPS Jumps

The range of MIPS branch instructions is limited to approximately ± 64K instructions from the branch instruction. In order to branch farther an unconditional jump instruction is used.

Instructions:

```
j label          # jump to label (PC = PC[31-28] || CONST[25:0]<<2)
jal label  # jump to label and store PC+4 in $31
jr $t0           # jump to address specified by register's contents
jalr $t0, $ra    # jump to address specified by register's contents
```

Formats:

- J-type: used for j

OP = 2	26-bit constant

- J-type: used for jal

OP = 3	26-bit constant

- R-type, used for jr

OP = 0	r_s	0	0	0	func = 8

- R-type, used for jalr

OP = 0	r_s	0	r_d	0	func = 9

Now we can do Factorial...

Synopsis (in C):

- Input in n, output in ans
- r1, r2 used for temporaries
- follows algorithm of our earlier data paths.

```
int n, ans;
r1 = 1;
r2 = n;
while (r2 != 0) do
  { r1 = r1 * r2;
    r2 = r2 - 1 }
ans = r1;
```

MIPS code, in assembly language:

```
n:      .word   123
ans:    .word   0
        ...
        addi    $0, 1, $t0          # t0 = 1
        lw      $t1, n              # t1 = n
loop:   beq     $t1, $0, done       # while (t1 != 0)
        mul     $t0, $t0, $t1       # t0 = t0 * t1
        addi    $t1, $t1, -1        # t1 = t1 - 1
        beq     $0, $0, loop        # Always branch
done:   sw      $t0, ans            # ans = r1
```


To summarize:

MIPS operands

Name	Example	Comments
32 registers	`$s0-$s7, $t0-$t9, $zero, $a0-$a3, $v0-$v1, $gp, $fp, $sp, $ra, $at`	Fast locations for data. In MIPS, data must be in registers to perform arithmetic. MIPS register $zero always equals 0. Register $at is reserved for the assembler to handle large constants.
2^{30} memory words	Memory[0], Memory[4], ..., Memory[4294967292]	Accessed only by data transfer instructions. MIPS uses byte addresses, so sequential words differ by 4. Memory holds data structures, such as arrays, and spilled registers, such as those saved on procedure calls.

MIPS assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	`add $s1, $s2, $s3`	`$s1 = $s2 + $s3`	Three operands; data in registers
	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
Data transfer	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
	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
Conditional branch	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
	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
Unconditional jump	jump	`j 2500`	go to 10000	Jump to target address
	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

MIPS Instruction Decoding Ring

OP	000	001	010	011	100	101	110	111
000	ALU		j	jal	beq	bne		
001	addi	addiu	slti	sltiu	andi	ori	xori	lui
010								
011								
100				lw				
101				sw				
110								
111								

ALU	000	001	010	011	100	101	110	111
000	sll		srl	sra	sllv		srlv	srav
001	jr	jalr						
010								
011	mult	multu	div	divu				
100	add	addu	sub	subu	and	or	xor	nor
101			slt	sltu				
110								
111								

Summary

- We will use a subset of MIPS instruction set as a prototype
  - Fixed-size 32-bit instructions
  - Mix of three basic instruction formats
    - R-type - Mostly 2 source and 1 destination register
    - I-type - 1-source, a small (16-bit) constant, and a destination register
    - J-type - A large (26-bit) constant used for jumps
  - Load/Store architecture
  - 31 general purpose registers, one hardwired to 0, and, by convention, several are used for specific purposes.
- ISA design requires tradeoffs, usually based on
  - History
  - Art
  - Engineering
  - Benchmark results