Levels of Representation (abstractions)

High Level Language Program (e.g., C)

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Compiler

Assembly Language Program (e.g.,MIPS)

```
lw   $t0, 0($s2)
lw   $t1, 4($s2)
sw   $t1, 0($s2)
sw   $t0, 4($s2)
```

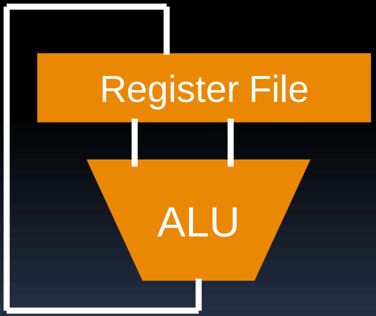
Assembler

Machine Language Program (MIPS)

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```

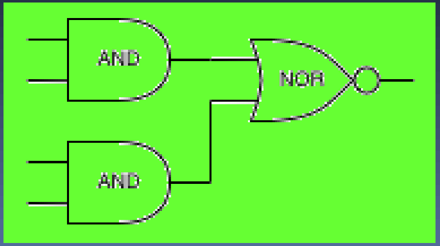
Machine Interpretation

Hardware Architecture Description (e.g., block diagrams)



Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)



Overview – Instruction Representation

- **Big idea: stored program**
  - consequences of stored program
- **Instructions as numbers**
- **Instruction encoding**
- **MIPS instruction format for Add instructions**
- **MIPS instruction format for Immediate, Data transfer instructions**

Big Idea: Stored-Program Concept

- **Computers built on 2 key principles:**
  - Instructions are represented as bit patterns - can think of these as numbers.
  - Therefore, entire programs can be stored in memory to be read or written just like data.
- **Simplifies SW/HW of computer systems:**
  - Memory technology for data also used for programs

Consequence #1: Everything Addressed

- **Since all instructions and data are stored in memory, everything has a memory address: instructions, data words**
  - both branches and jumps use these
- **C pointers are just memory addresses: they can point to anything in memory**
  - Unconstrained use of addresses can lead to nasty bugs; up to you in C; limits in Java
- **One register keeps address of instruction being executed: "Program Counter" (PC)**
  - Basically a pointer to memory: Intel calls it Instruction Address Pointer, a better name

Consequence #2: Binary Compatibility

- **Programs are distributed in binary form**
  - Programs bound to specific instruction set
  - Different version for Macintoshes and PCs
- **New machines want to run old programs (“binaries”) as well as programs compiled to new instructions**
- **Leads to “backward compatible” instruction set evolving over time**
- **Selection of Intel 8086 in 1981 for 1st IBM PC is major reason latest PCs still use 80x86 instruction set (Pentium 4); could still run program from 1981 PC today**

Instructions as Numbers (1/2)

- **Currently all data we work with is in words (32-bit blocks):**
  - Each register is a word.
  - `lw` and `sw` both access memory one word at a time.
- **So how do we represent instructions?**
  - Remember: Computer only understands 1s and 0s, so “`add $t0,$0,$0`” is meaningless.
  - MIPS wants simplicity: since data is in words, make instructions be words too

Instructions as Numbers (2/2)

- **One word is 32 bits, so divide instruction word into "fields".**
- **Each field tells processor something about instruction.**
- **We could define different fields for each instruction, but MIPS is based on simplicity, so define 3 basic types of instruction formats:**
  - R-format
  - I-format
  - J-format

Instruction Formats

- I-format: used for instructions with immediates, `lw` and `sw` (since offset counts as an immediate), and branches (`beq` and `bne`),
  - (but not the shift instructions; later)
- J-format: used for `j` and `jal`
- R-format: used for all other instructions
- It will soon become clear why the instructions have been partitioned in this way.

R-Format Instructions (1/5)

- Define "fields" of the following number of bits each: 6 + 5 + 5 + 5 + 5 + 6 = 32

6	5	5	5	5	6

- For simplicity, each field has a name:

`opcode`	`rs`	`rt`	`rd`	`shamt`	`funct`

- Important: On these slides and in book, each field is viewed as a 5- or 6-bit unsigned integer, not as part of a 32-bit integer.
  - Consequence: 5-bit fields can represent any number 0-31, while 6-bit fields can represent any number 0-63.

R-Format Instructions (2/5)

- **What do these field integer values tell us?**
  - `opcode`: partially specifies what instruction it is
    - Note: This number is equal to `0` for all R-Format instructions.
  - `funct`: combined with `opcode`, this number exactly specifies the instruction
- **Question: Why aren't `opcode` and `funct` a single 12-bit field?**
  - We'll answer this later.

R-Format Instructions (3/5)

- **More fields:**
  - `rs` (Source Register): *usually* used to specify register containing first operand
  - `rt` (Target Register): *usually* used to specify register containing second operand (note that name is misleading)
  - `rd` (Destination Register): *usually* used to specify register which will receive result of computation

R-Format Instructions (4/5)

- **Notes about register fields:**
  - Each register field is exactly 5 bits, which means that it can specify any unsigned integer in the range 0-31. Each of these fields specifies one of the 32 registers by number.
  - The word “usually” was used because there are exceptions that we’ll see later. E.g.,
    - **`mult`** and **`div`** have nothing important in the **`rd`** field since the dest registers are **`hi`** and **`lo`**
    - **`mfhi`** and **`mflo`** have nothing important in the **`rs`** and **`rt`** fields since the source is determined by the instruction (see COD)

R-Format Instructions (5/5)

- **Final field:**
    - `shamt`: This field contains the amount a shift instruction will shift by. Shifting a 32-bit word by more than 31 is useless, so this field is only 5 bits (so it can represent the numbers 0-31).
    - This field is set to `0` in all but the shift instructions.
- **For a detailed description of field usage for each instruction, see green insert in COD**
  (You can bring with you to all exams)

R-Format Example (1/2)

- **MIPS Instruction:**

  `add   $8,$9,$10`

  `opcode` = 0 (look up in table in book)

  `funct` = 32 (look up in table in book)

  `rd` = 8 (destination)

  `rs` = 9 (first *operand*)

  `rt` = 10 (second *operand*)

  `shamt` = 0 (not a shift)

R-Format Example (2/2)

- **MIPS Instruction:**

  `add    $8,$9,$10`

  Decimal number per field representation:

0	9	10	8	0	32

  Binary number per field representation:

000000	01001	01010	01000	00000	100000

hex

  hex representation: `012A 4020`$_{hex}$

  decimal representation: `19,546,144`$_{ten}$

  Called a Machine Language Instruction

I-Format Instructions (1/4)

- **What about instructions with immediates?**
  - 5-bit field only represents numbers up to the value 31: immediates may be much larger than this
  - Ideally, MIPS would have only one instruction format (for simplicity): unfortunately, we need to compromise
- **Define new instruction format that is partially consistent with R-format:**
  - First notice that, if instruction has immediate, then it uses at most 2 registers.

I-Format Instructions (2/4)

- **Define "fields" of the following number of bits each: 6 + 5 + 5 + 16 = 32 bits**

6	5	5	16

  - Again, each field has a name:

`opcode`	`rs`	`rt`	`immediate`

  - Key Concept: Only one field is inconsistent with R-format. Most importantly, `opcode` is still in same location.

I-Format Instructions (3/4)

- **What do these fields mean?**
  - `opcode`: same as before except that, since there's no `funct` field, `opcode` uniquely specifies an instruction in I-format
  - This also answers question of why R-format has two 6-bit fields to identify instruction instead of a single 12-bit field: in order to be consistent as possible with other formats while leaving as much space as possible for immediate field.
  - `rs`: specifies a register operand (if there is one)
  - `rt`: specifies register which will receive result of computation (this is why it's called the *target* register "`rt`") or other operand for some instructions.

I-Format Instructions (4/4)

- **The Immediate Field:**
  - **`addi`**, **`slti`**, **`sltiu`**, the immediate is sign-extended to 32 bits. Thus, it's treated as a signed integer.
  - 16 bits ➔ can be used to represent immediate up to 2^{16} different values
  - This is large enough to handle the offset in a typical **`lw`** or **`sw`**, plus a vast majority of values that will be used in the **`slti`** instruction.
  - We'll see what to do when the number is too big in our next lecture…

I-Format Example (1/2)

- **MIPS Instruction:**

  `addi   $21,$22,-50`

  `opcode` = 8 (look up in table in book)

  `rs` = 22 (register containing operand)

  `rt` = 21 (target register)

  `immediate` = -50 (by default, this is decimal)

I-Format Example (2/2)

- **MIPS Instruction:**

```
addi   $21,$22,-50
```

Decimal/field representation:

8	22	21	-50

Binary/field representation:

001000	10110	10101	1111111111001110

hexadecimal representation: `22D5 FFCE`$_{hex}$

decimal representation: `584,449,998`$_{ten}$

Peer Instruction

Which instruction has same representation as 35_{ten}?

a) add \$0, \$0, \$0	`opcode`	`rs`	`rt`	`rd`	`shamt`	`funct`
b) subu \$s0,\$s0,\$s0	`opcode`	`rs`	`rt`	`rd`	`shamt`	`funct`
c) lw \$0, 0(\$0)	`opcode`	`rs`	`rt`	`offset`		
d) addi \$0, \$0, 35	`opcode`	`rs`	`rt`	`immediate`		
e) subu \$0, \$0, \$0	`opcode`	`rs`	`rt`	`rd`	`shamt`	`funct`

Registers numbers and names:

0: \$0, .. 8: \$t0, 9:\$t1, ..15: \$t7, 16: \$s0, 17: \$s1, .. 23: \$s7

Opcodes and function fields (if necessary)

- **`add`**: opcode = 0, funct = 32
- **`subu`**: opcode = 0, funct = 35
- **`addi`**: opcode = 8
- **`lw`**: opcode = 35

In conclusion…

- Simplifying MIPS: Define instructions to be same size as data word (one word) so that they can use the same memory (compiler can use lw and sw).
- Computer actually stores programs as a series of these 32-bit numbers.
- MIPS Machine Language Instruction: 32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt	immediate		