Instructions: Language of the Computer (1)

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Instruction Set

The repertoire of instructions of a computer

Different computers have different instruction sets

- But with many aspects in common

Early computers had very simple instruction sets

- Simplified implementation

Many modern computers also have simple instruction sets

The MIPS Instruction Set

Used as the example throughout the book

Stanford MIPS commercialized by MIPS Technologies (www.mips.com)

Large share of embedded core market

- Applications in consumer electronics, network/storage equipment, cameras, printers, ...

Typical of many modern ISAs

- See MIPS Reference Data tear-out card, and Appendixes B and E

Arithmetic Operations

Add and subtract, three operands

- Two sources and one destination

```
add a, b, c          # a gets b + c
```

All arithmetic operations have this form

Design Principle 1: Simplicity favors regularity

- Regularity makes implementation simpler
- Simplicity enables higher performance at lower cost

Arithmetic Example

C code:

```
f = (g + h) - (i + j);
```

Compiled MIPS code:

```
add t0, g, h          # temp t0 = g + h
add t1, i, j          # temp t1 = i + j
sub f, t0, t1         # f = t0 - t1
```

Register Operands

Arithmetic instructions use register operands

MIPS has a 32 × 32-bit register file

- Use for frequently accessed data
- Numbered 0 to 31
- 32-bit data called a "word"

Assembler names

- $t0, $t1, ..., $t9 for temporary values
- $s0, $s1, ..., $s7 for saved variables

Design Principle 2: Smaller is faster

- c.f. main memory: millions of locations

Register Operand Example

C code:

```
f = (g + h) - (i + j);
```

- f, ..., j in $s0, ..., $s4

Compiled MIPS code:

```
add $t0, $s1, $s2
add $t1, $s3, $s4
sub $s0, $t0, $t1
```

Memory Operands

Main memory used for composite data

- Arrays, structures, dynamic data

To apply arithmetic operations

- Load values from memory into registers
- Store result from register to memory

Memory is byte addressed

- Each address identifies an 8-bit byte

Words are aligned in memory

- Address must be a multiple of 4

Byte Ordering

MIPS is Big Endian

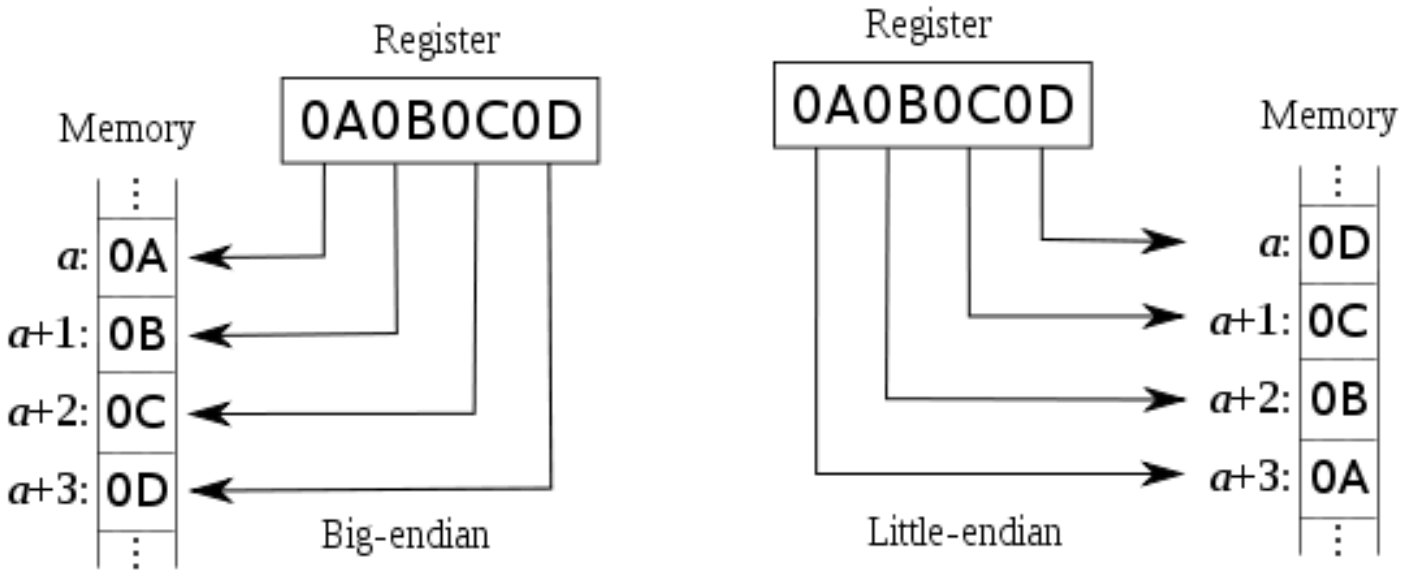
- Most-significant byte at least address of a word
- c.f. Little Endian: least-significant byte at least address

Big endian

- Least significant byte has highest address

Little endian

- Least significant byte has lowest address



Memory Operand Example 1

C code:

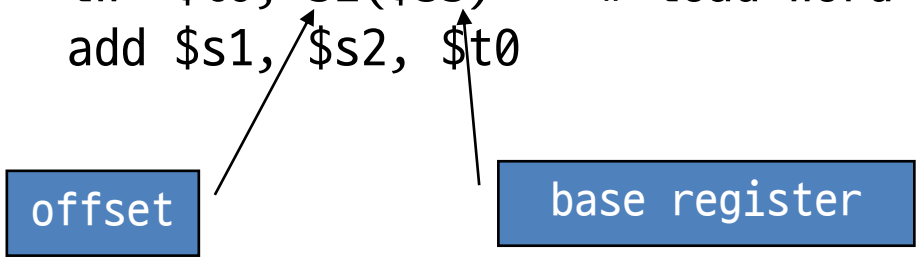
```
g = h + A[8];
```

- g in $s1, h in $s2, base address of A in $s3

Compiled MIPS code:

- Index 8 requires offset of 32
  - 4 bytes per word

```
lw  $t0, 32($s3)    # load word
add $s1, $s2, $t0
```



Memory Operand Example 2

C code:

```
A[12] = h + A[8];
```

- h in $s2, base address of A in $s3

Compiled MIPS code:

- Index 8 requires offset of 32

```
lw  $t0, 32($s3)            # load word
add $t0, $s2, $t0
sw  $t0, 48($s3)            # store word
```

Registers vs. Memory

Registers are much much faster to access than memory

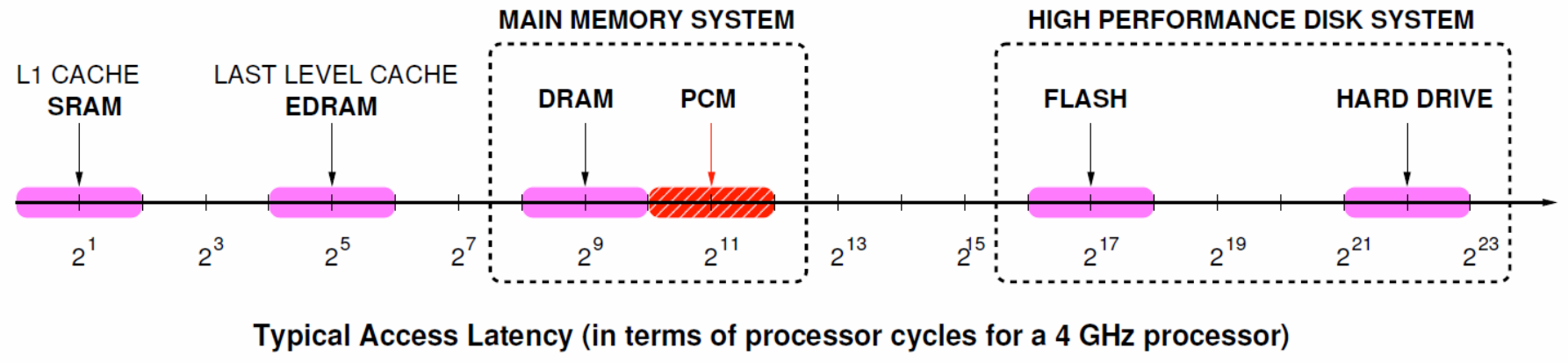
Operating on memory data requires loads and stores

- More instructions to be executed

Compiler must use registers for variables as much as possible

- Only spill to memory for less frequently used variables
- Register optimization is important!

Registers vs. Memory



Qureshi (IBM Research) et al., Scalable High Performance Main Memory System Using Phase-Change Memory Technology, *ISCA* 2009.

Immediate Operands

Constant data specified in an instruction

```
addi $s3, $s3, 4
```

No subtract immediate instruction

- Just use a negative constant
- addi $s2, $s1, -1

Design Principle 3: Make the common case fast

- add vs. addi
- Small constants are common
- Immediate operand avoids a load instruction

The Constant Zero

MIPS register 0 ($zero) is the constant 0

- Cannot be overwritten

Useful for common operations

- E.g., move between registers

```
add $t2, $s1, $zero
```

Unsigned Binary Integers

Given an n-bit number

$$x = x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

Range: 0 to $+2^n-1$

Example

- $0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 1011_2$
  $= 0 + \ldots + 1\times2^3 + 0\times2^2 + 1\times2^1 + 1\times2^0$
  $= 0 + \ldots + 8 + 0 + 2 + 1 = 11_{10}$

Using 32 bits

- 0 to +4,294,967,295

2s-Complement Signed Integers

Given an n-bit number

$$x = -x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

Range: -2^{n-1} to $+2^{n-1}-1$

Example

- $1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1100_2$
  $= -1\times2^{31} + 1\times2^{30} + \ldots + 1\times2^2 + 0\times2^1 + 0\times2^0$
  $= -2{,}147{,}483{,}648 + 2{,}147{,}483{,}644 = -4_{10}$

Using 32 bits

- -2,147,483,648 to +2,147,483,647

2s-Complement Signed Integers

Bit 31 is sign bit

- 1 for negative numbers
- 0 for non-negative numbers

Non-negative numbers have the same unsigned and 2s-complement representation

Some specific numbers

- 0: 0000 0000 … 0000
- -1: 1111 1111 … 1111
- Most-negative: 1000 0000 … 0000
- Most-positive: 0111 1111 … 1111

Signed Negation

Complement and add 1

- Complement means 1 → 0, 0 → 1

$$x + \bar{x} = 1111\ldots111_2 = -1$$

$$\bar{x} + 1 = -x$$

Example: negate +2

- +2 = 0000 0000 … 0010_2
- -2 = 1111 1111 … 1101_2 + 1
  = 1111 1111 … 1110_2

Sign Extension (Ex. 8bit -> 16bit)

Representing a number using more bits

- Preserve the numeric value

In MIPS instruction set

- addi: extend immediate value
- lb, lh: extend loaded byte/halfword
- beq, bne: extend the displacement

Replicate the sign bit to the left

- c.f. unsigned values: extend with 0s

Examples: 8-bit to 16-bit

- +2: 0000 0010 => 0000 0000 0000 0010
- -2: 1111 1110 => 1111 1111 1111 1110

Representing Instructions

Instructions are encoded in binary

- Called machine code

MIPS instructions

- Encoded as 32-bit instruction words
- Small number of formats encoding operation code (opcode), register numbers, ...
- Regularity!

Register numbers

- $t0 – $t7 are reg's 8 – 15
- $t8 – $t9 are reg's 24 – 25
- $s0 – $s7 are reg's 16 – 23

Stored Program Computers

Instructions represented in binary, just like data

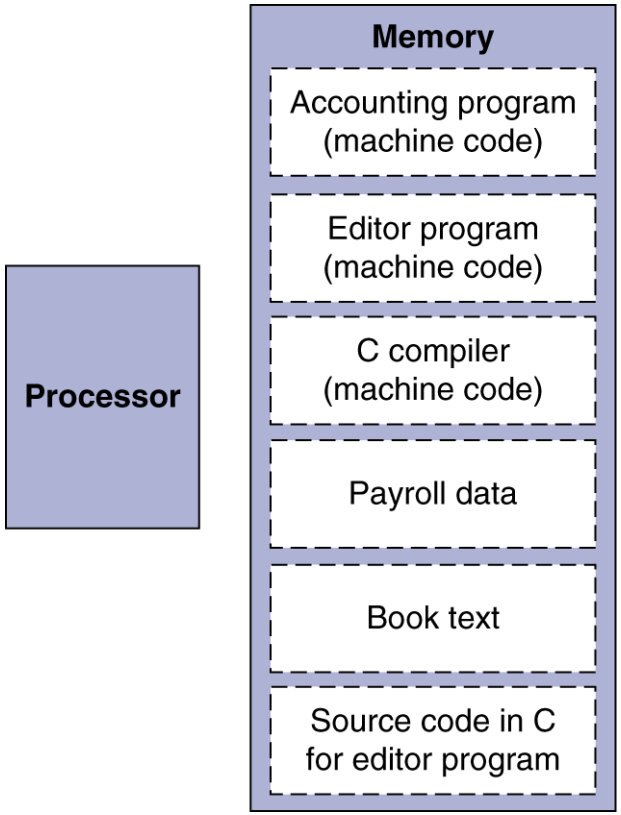
Instructions and data stored in memory

Programs can operate on programs

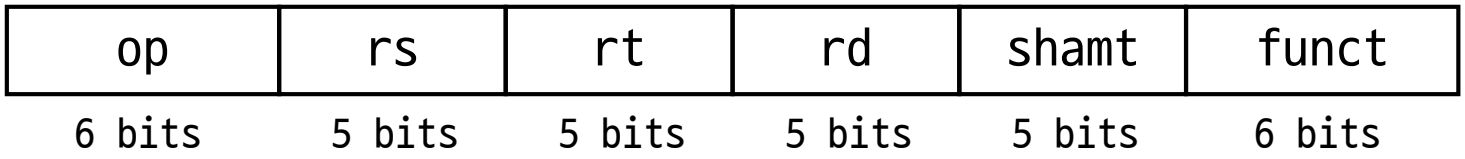
- e.g., compilers, linkers, …

Binary compatibility allows compiled programs to work on different computers

- Standardized ISAs



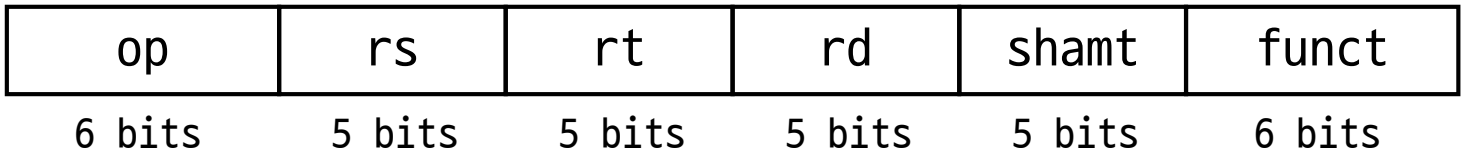
MIPS R-format Instructions



Instruction fields

- op: operation code (opcode)
- rs: first source register number
- rt: second source register number
- rd: destination register number
- shamt: shift amount (00000 for now)
- funct: function code (extends opcode)

R-format Example

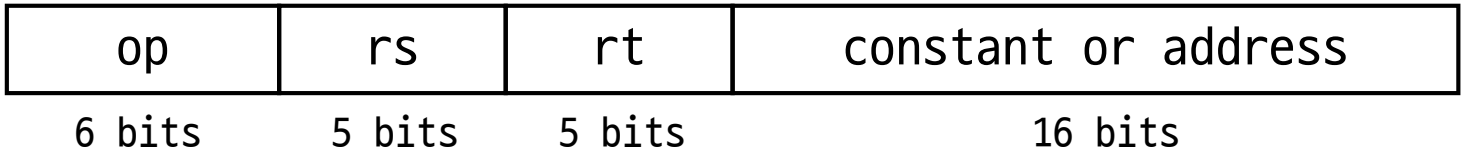



```
add $t0, $s1, $s2
```

special	$s1	$s2	$t0	0	add
0	17	18	8	0	32
000000	10001	10010	01000	00000	100000

$00000100011001001000000000100000_2 = 02324020_{16}$

MIPS I-format Instructions

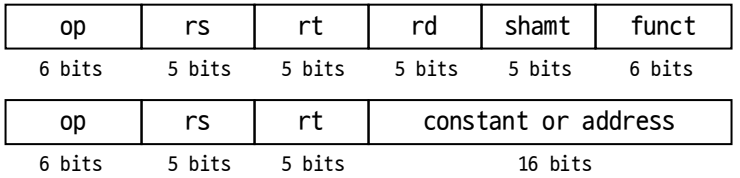


Immediate arithmetic and load/store instructions

- rt: destination or source register number
- Constant: -2^{15} to $+2^{15} - 1$
- Address: offset added to base address in rs
- E.g.
  - addi $s3, $s3, 4
  - lw $t0, 32($s3)

Design Principle 4: Good design demands good compromises

- Different formats complicate decoding
- Keep formats as similar as possible



Logical Operations

Instructions for bitwise manipulation

Operation	C	Java	MIPS
Shift left	<<	<<	sll
Shift right	>>	>>>	srl
Bitwise AND	&	&	and, andi
Bitwise OR	¦	¦	or, ori
Bitwise NOT	~	~	nor

Useful for extracting and inserting groups of bits in a word

Shift Operations

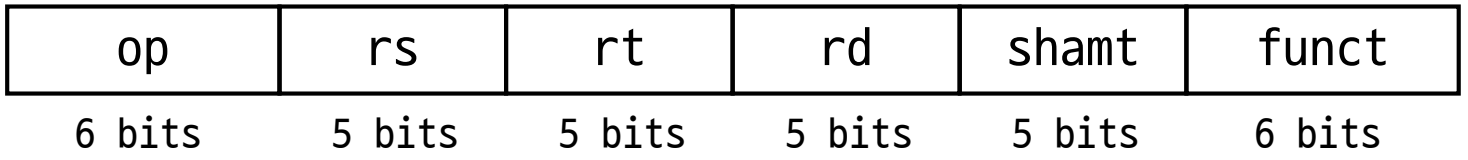
Shift left logical

- Shift left and fill with 0 bits
- sll by i bits multiplies by 2^i

Shift right logical

- Shift right and fill with 0 bits
- srl by i bits divides by 2^i (unsigned only)

shamt: how many positions to shift

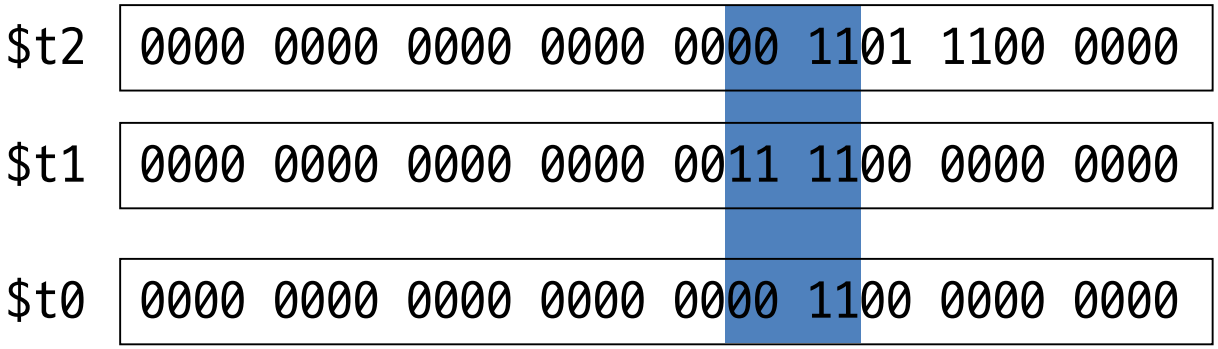


AND Operations

Useful to mask bits in a word

- Select some bits, clear others to 0

```
and $t0, $t1, $t2
```

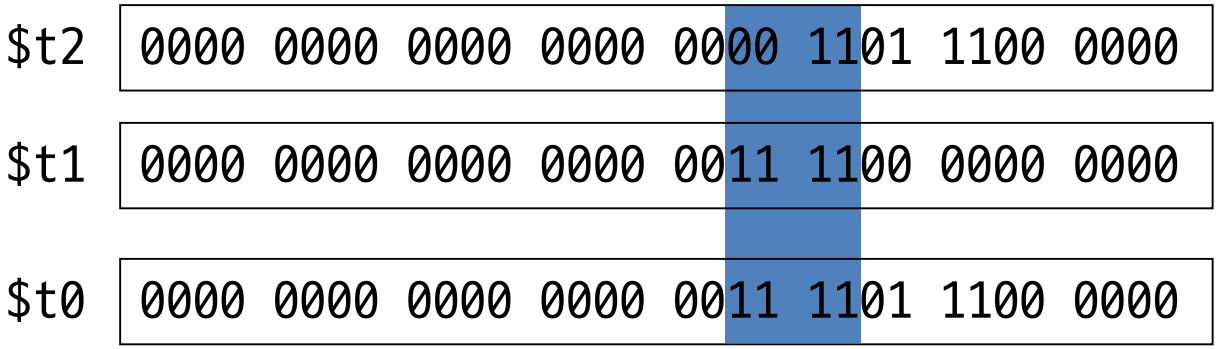


OR Operations

Useful to include bits in a word

- Set some bits to 1, leave others unchanged

```
or $t0, $t1, $t2
```



NOT Operations

Useful to invert bits in a word

- Change 0 to 1, and 1 to 0

MIPS has NOR 3-operand instruction

- a NOR b == NOT (a OR b)

```
nor $t0, $t1, $zero
```

Register 0: always read as zero

$t1	0000 0000 0000 0000 0011 1100 0000 0000
$t0	1111 1111 1111 1111 1100 0011 1111 1111

Conditional Operations

Branch to a labeled instruction if a condition is true

- Otherwise, continue sequentially

`beq rs, rt, L1`

- if (rs == rt) branch to instruction labeled L1;

`bne rs, rt, L1`

- if (rs != rt) branch to instruction labeled L1;

`j L1`

- unconditional jump to instruction labeled L1

Compiling If Statements

C code:

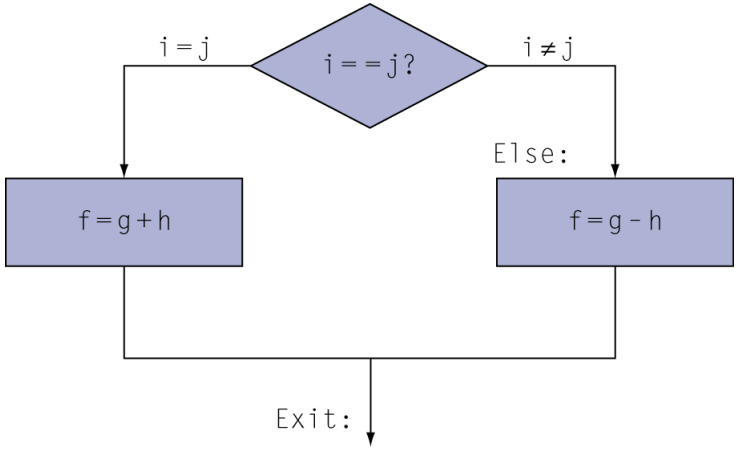
```
if (i==j) f = g + h;
else f = g - h;
```

- f, g, … in $s0, $s1, …

Compiled MIPS code:

```
      bne $s3, $s4, Else
      add $s0, $s1, $s2
      j   Exit
Else: sub $s0, $s1, $s2
Exit: …
```

Assembler calculates addresses



Compiling Loop Statements

C code:

```
while (save[i] == k) i += 1;
```

- i in $s3, k in $s5, address of save in $s6

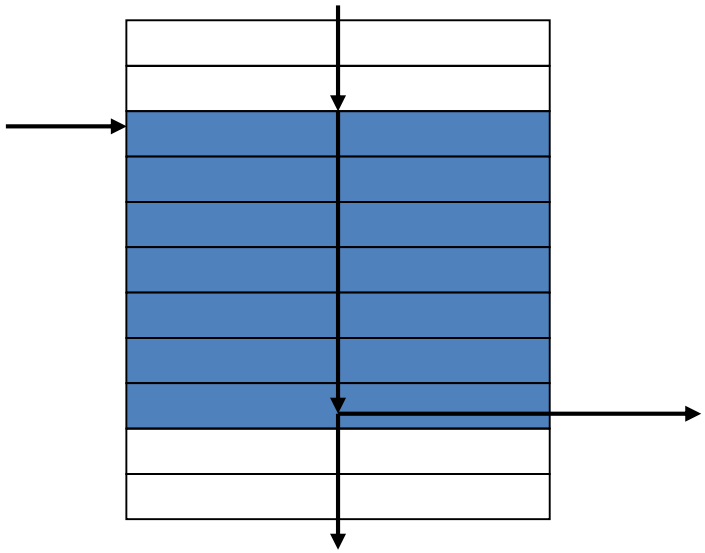
Compiled MIPS code:

```
Loop:  sll  $t1, $s3, 2
       add  $t1, $t1, $s6
       lw   $t0, 0($t1)
       bne  $t0, $s5, Exit
       addi $s3, $s3, 1
       j    Loop
Exit:  …
```

Basic Blocks

A basic block is a sequence of instructions with

- No embedded branches (except at end)
- No branch targets (except at beginning)



A compiler identifies basic blocks for optimization

An advanced processor can accelerate execution of basic blocks

More Conditional Operations

Set result to 1 if a condition is true

- Otherwise, set to 0

slt rd, rs, rt

- if (rs < rt) rd = 1; else rd = 0;

slti rt, rs, constant

- if (rs < constant) rt = 1; else rt = 0;

Use in combination with beq, bne

- slt $t0, $s1, $s2 # if ($s1 < $s2)
- bne $t0, $zero, L # branch to L

Branch Instruction Design

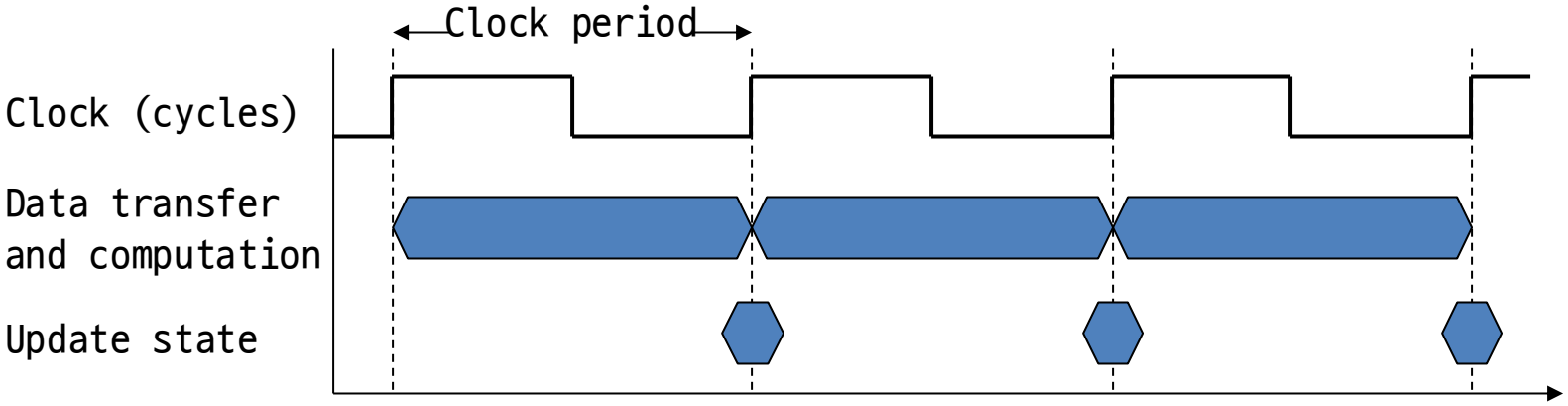
Why not blt, bge, etc?

For hardware, <, ≥, … slower than =, ≠

- Combining with branch involves more work per instruction, requiring a slower clock
- All instructions penalized!

beq and bne are the common case

This is a good design compromise



Signed vs. Unsigned

Signed comparison: slt, slti

Unsigned comparison: sltu, sltui

Example

- $s0 = 1111 1111 1111 1111 1111 1111 1111 1111
- $s1 = 0000 0000 0000 0000 0000 0000 0000 0001
- slt $t0, $s0, $s1 # signed
  - -1 < +1 ⇒ $t0 = 1
- sltu $t0, $s0, $s1 # unsigned
  - +4,294,967,295 > +1 ⇒ $t0 = 0