Topic 4

Instruction Coding

Representing Instructions

- Assembly instructions are translated into binary information
  - Called *machine code*
- MIPS instructions
  - Encoded as 32-bit instruction words
  - Stored in 32-bit long memory locations
  - Small number of formats encode operation code (opcode), register numbers, …
  - **Regularity!**

Representing Instructions

- Three formats (types) to represent MIPS instructions
  - R-type (register)
  - I-type (immediate)
  - J-type (jump)

R-format

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- 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)

Register Operands

- $zero: constant 0 (reg 0, also written as $0)
- $at: Assembler Temporary (reg 1, or $1)
- $v0, $v1: result values (reg's 2 and 3, or $2 and $3)
- $a0 – $a3: arguments (reg's 4 – 7, or $4 - $7)
- $t0 – $t7: temporaries (reg's 8 – 15, or $8 - $15)
- $s0 – $s7: saved (reg's 16 – 23, or $16 - $23)
- $t8, $t9: temporaries (reg's 24 and 25, or $24 and $25)
- $k0, $k1: reserved for OS kernel (reg's 26 and 27, $26/27)
- $gp: global pointer for static data (reg 28, or $28)
- $sp: stack pointer (reg 29, or $29)
- $fp: frame pointer (reg 30, or $30)
- $ra: return address (reg 31, or $31)

R-format Example

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

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

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

$00000010001100100100000000100000_2 = 02324020_{16}$

MIPS Reference Card

I-format

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

- 16-bit immediate number or address
  - rs: source or base address register
  - rt: destination or source register
  - Constant: -2^{15} to $+2^{15}-1$
  - Address: offset added to base address in rs
- *Design Principle 4:* Good design demands good compromises
  - Different formats complicate decoding, but allow 32-bit instructions uniformly
  - Keep formats as similar as possible

I-format Example 1

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

```
addi $t0, $s0, 4
```

op	\$s0	\$t0	4
8	16	8	4
001000	10000	01000	0000000000000100

$00100010000010000000000000000100_2 = 22080004_{16}$

I-format Example 2

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

```
lw $t0, 4($s0)
```

op	$s0	$t0	4
23H	16	8	4
100011	10000	01000	0000000000000100

$10001110000010000000000000000100_2 = 8E080004_{16}$

I-format Example 3

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

```
beq $s0, $t0, LOOP
```

op	$s0	$t0	Relative Address
4	16	8	Relative Address
000100	10000	01000	Relative Address

LOOP = PC+4+Relative Address*4

J-format

op	address
6 bits	26 bits

- Encode full address in instruction
- (Pseudo) Direct jump
  - Target address = PC[31:28] : (address × 4)

Target Addressing Example

- 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: …
```

Target Addressing Example

- Assume Loop at location 00080000 (hex)

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

0x00080000	0	0	19	9	2	0
0x00080004	0	9	22	9	0	32
0x00080008	35	9	8	0		
0x0008000C	5	8	21	2		
0x00080010	8	19	19	1		
0x00080014	2	0020000				
0x00080018						

Branching Far Away

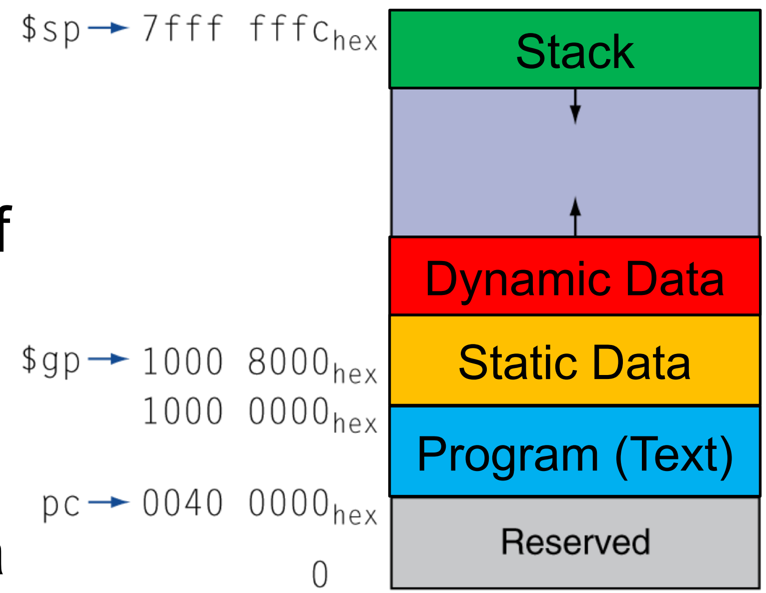
- If branch target is too far to encode with 16-bit offset, assembler rewrites the code
- Example

```
        beq $s0,$s1, L1
                ↓
        bne $s0,$s1, L2
        j L1
    L2: …
```

- May jump anywhere by **`jr`**

Big Picture – Recall

- Text: program code
  - PC initialized to 0x00400000
- Static data: global/static variables
  - $gp initialized to the middle of this segment, 0x10008000 allowing $\pm$offset
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: storage for temporary variable in functions
  - $sp initialized to 0x7ffffffc, growing towards low address



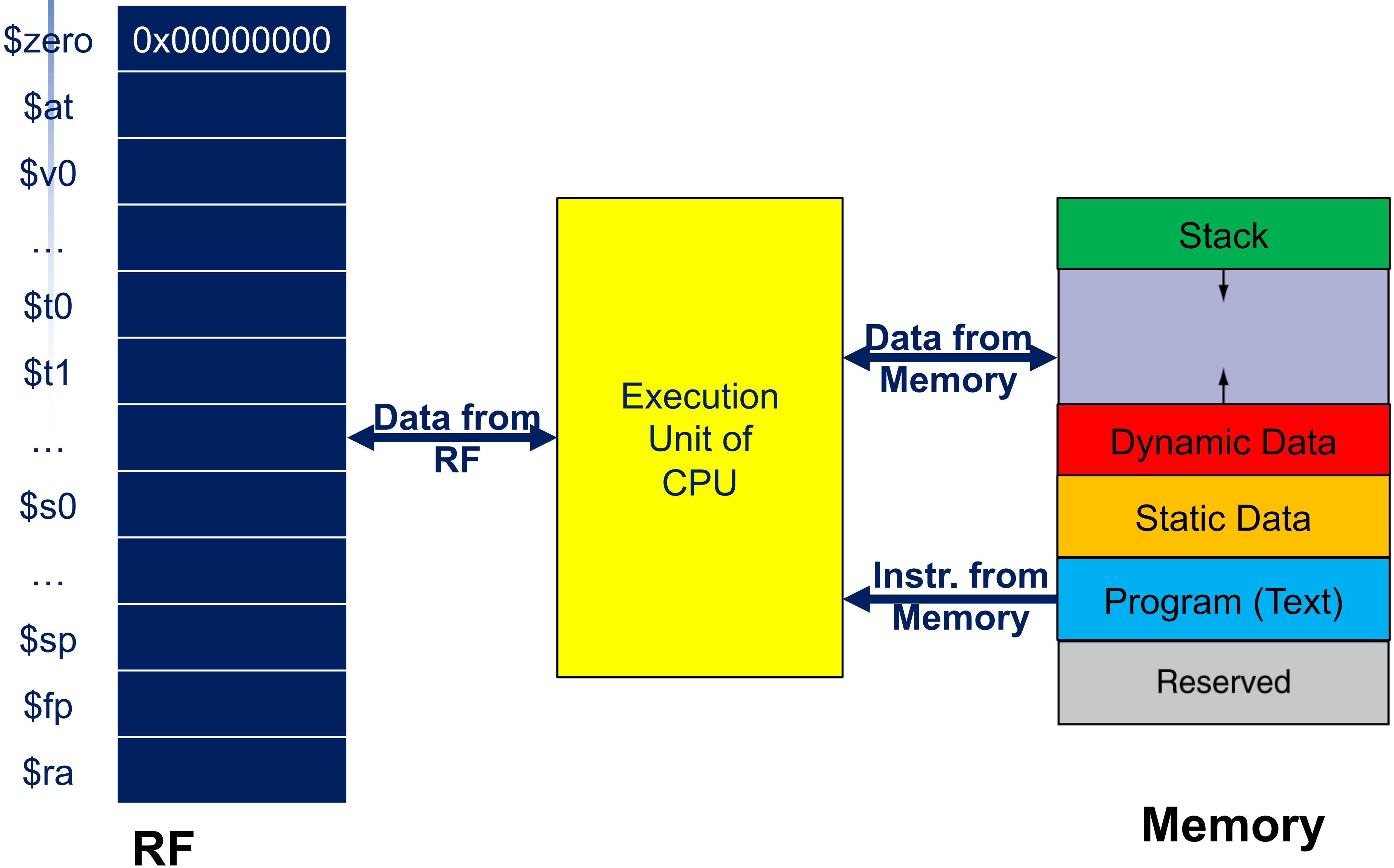
Big Picture - Recall

```
int leaf_example (int g, h, i, j)
{ int f;
  f = (g + h) - (i + j);
  return f;}
```

- g, …, j in $a0, …, $a3, f in $s0, result in $v0

```
leaf_example:
  addi $sp, $sp, -4    #create spaces on stack
  sw   $s0, 0($sp)     #store data on stack
  add  $t0, $a0, $a1
  add  $t1, $a2, $a3
  sub  $s0, $t0, $t1
  add  $v0, $s0, $zero
  lw   $s0, 0($sp)     #restore data from stack
  addi $sp, $sp, 4     #destroy spaces on stack
  jr   $ra             #return from function
```

Big Picture – Stored Program



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`
    - $-1 < +1 \Rightarrow$ \$t0 = 1
  - `sltu $t0, $s0, $s1  # unsigned`
    - $+4{,}294{,}967{,}295 > +1 \Rightarrow$ \$t0 = 0

2's-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

Byte/Halfword Operations

- MIPS byte/halfword load/store
  - Useful for string processing – a common case

```
lb rt, offset(rs)      lh rt, offset(rs)
```

  - Sign extend to 32 bits in rt

```
lbu rt, offset(rs)     lhu rt, offset(rs)
```

  - Zero extend to 32 bits in rt

```
sb rt, offset(rs)      sh rt, offset(rs)
```

  - Store just byte/halfword

NOTE: reference card wrong

Sign Extension

- Needed when want to represent a number using more bits while preserving the numeric value
  - Positive or negative
- 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

MIPS Addressing Mode

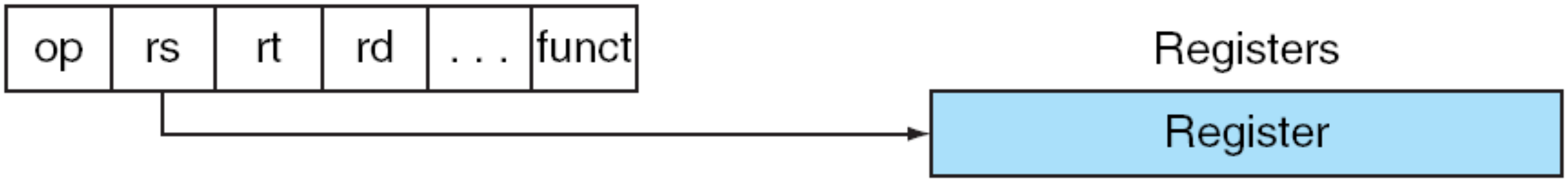
- How to get addresses?
  - Immediate Addressing
  - Register Addressing
  - Base Addressing
  - PC-relative addressing
  - Pseudodirect addressing

Immediate Addressing

op	rs	rt	Immediate

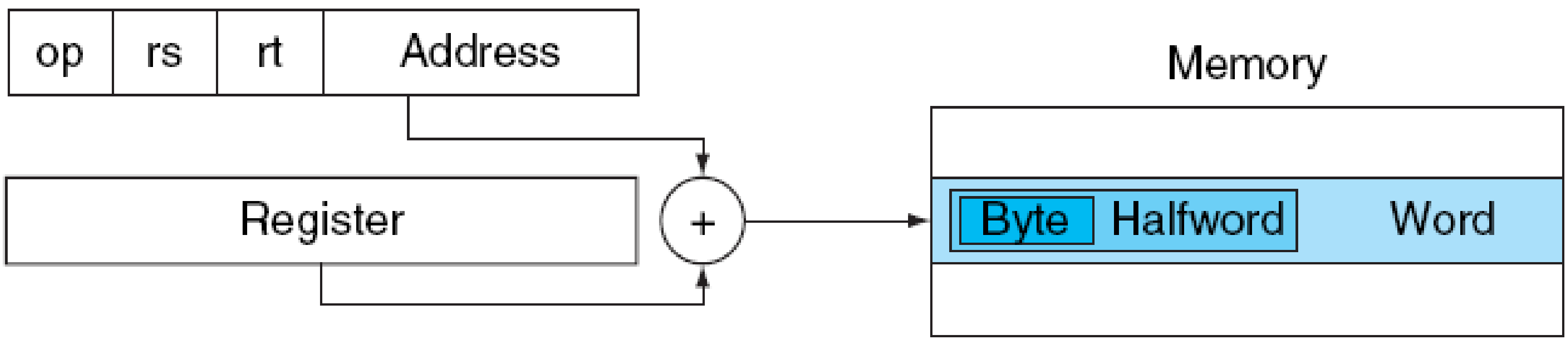
- Operands are immediately provided in the instruction
- In I-type instructions
- Example
  - addi $t0, $s0, -1

Register Addressing



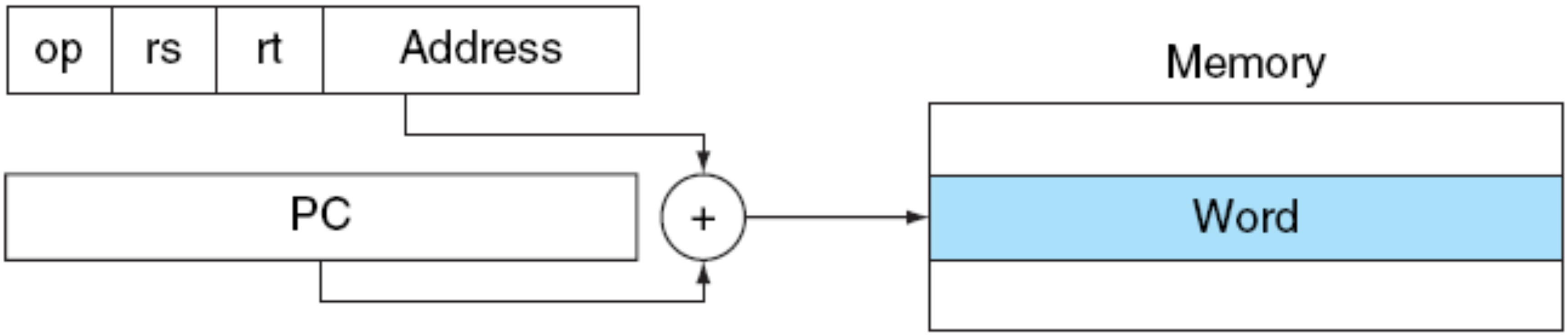
- All or some operands provided by register IDs directly
- Used in R-type and I-type instructions
- Example:
  - add $t0, $s0, $s1
  - beq $s0, $s1, FUNCTION

Base Addressing



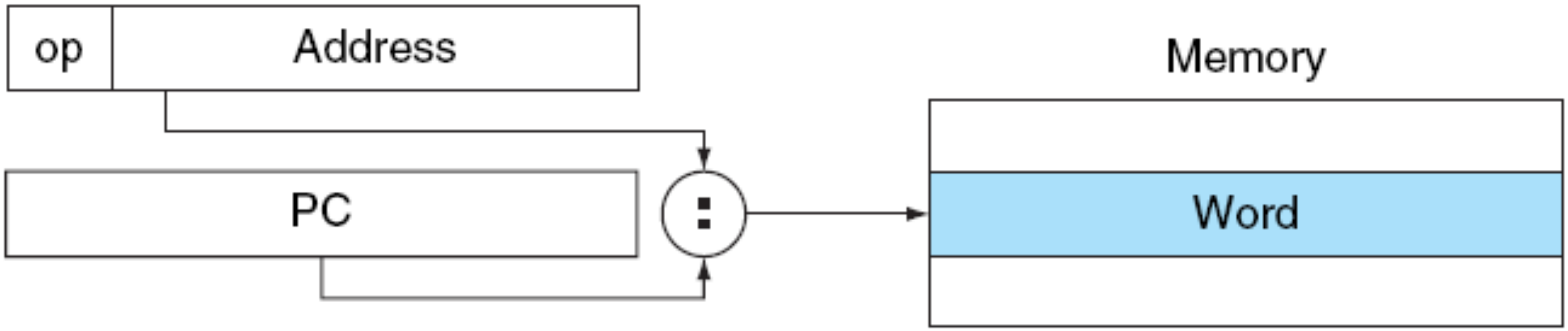
- Operands are provided by using base address of memory location
- Used in I-type
- Example
  - lw $t0, 32($s0)

PC-relative Addressing



- Operand relative to PC
- Used for near branch
  - Forward or backward
  - Target address = new PC + offset $\times$ 4
  - New PC = PC+4
- Example:
  - beq \$s0, \$s1, LESS (I-type)

Pseudodirect Addressing



- Operand is a pseudodirect address of PC
  - Encode full address in instruction
- (Pseudo) Direct jump addressing
  - Target address = $PC_{31\ldots28}$: (address $\times$ 4)
- Used in J-type instructions
  - j and jal (there is another jump: jr, R-type)