Topic 2

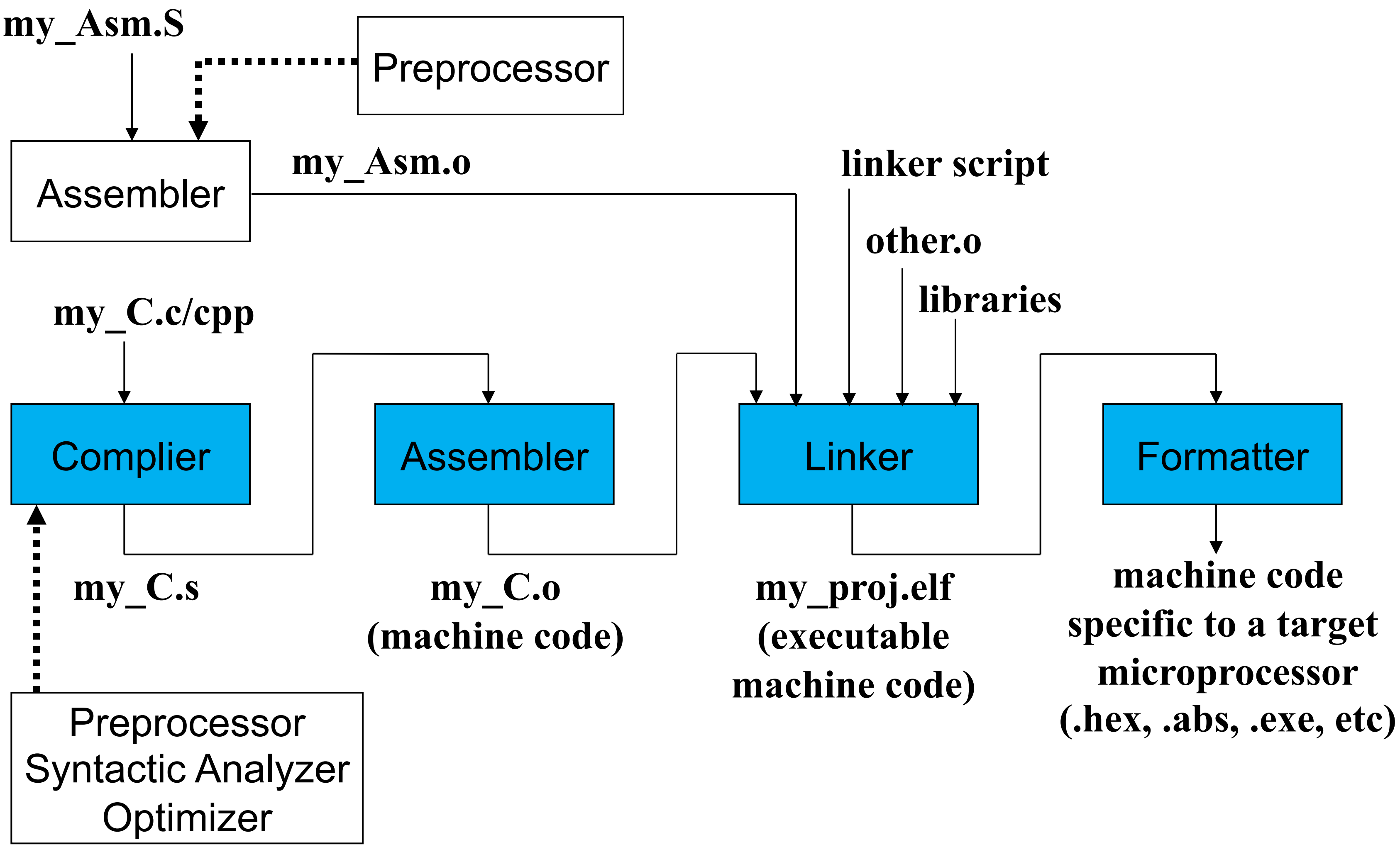
Assembly Programming

- Operations and Operands

Levels of Program Code

- High-level language (translator: compiler)
  - Level of abstraction closer to problem domain
  - Provides productivity and portability
- Assembly language (translator: assembler)
  - Low-level language
  - Symbolic representation of binary machine code
  - Direct correspondence to machine code
  - More readable than machine code
- Machine language
  - Binary digits (bits) – language of digital circuits
  - Composed of instructions (commands for computer) and data
  - Instructions and data encoded in binary digitals

Processing Different Languages



Assembly Language

- When to use?
  - Compilers introduce uncertainty about execution time and size
  - Use when speed and size of program are critical
  - Can mix high-level language with assembly

Assembly Language

- Drawbacks of Assembly language
  - Can be very time consuming
  - No assembler optimization
  - Almost impossible to be portable
    - Different computers support different assembly languages that requires different assembler
    - Assembly languages are similar
  - Hard to debug

Instruction Set

- or ISA, all commands that a computer understands
- Different computers have different instruction sets
  - But with many common aspects
- Types of
  - Reduced Instruction Set Computer – RISC
  - Complex Instruction Set Computer – CISC

The MIPS Instruction Set

- Used as the example throughout the book
  - Originated from Stanford MIPS commercialized by MIPS Technologies (www.mips.com)
- Large share of embedded core market
- Typical features of many modern ISAs
  - See MIPS Reference Card, and Appendixes B and E

Arithmetic Operations

- Add and subtract, three operands
  - Two sources and one destination

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

- All MIPS arithmetic operations have this regular form
- *Design Principle 1:* Simplicity favors regularity
  - Regularity makes implementation simpler
  - Simplicity enables higher performance at lower cost

Arithmetic Example

- C/C++ code:

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

- Compiled pseudo-MIPS assembly code:

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

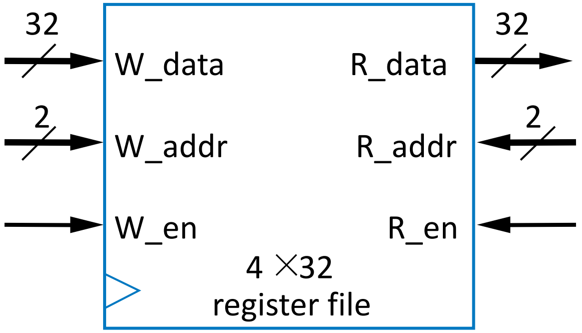
Operands in MIPS Assembly

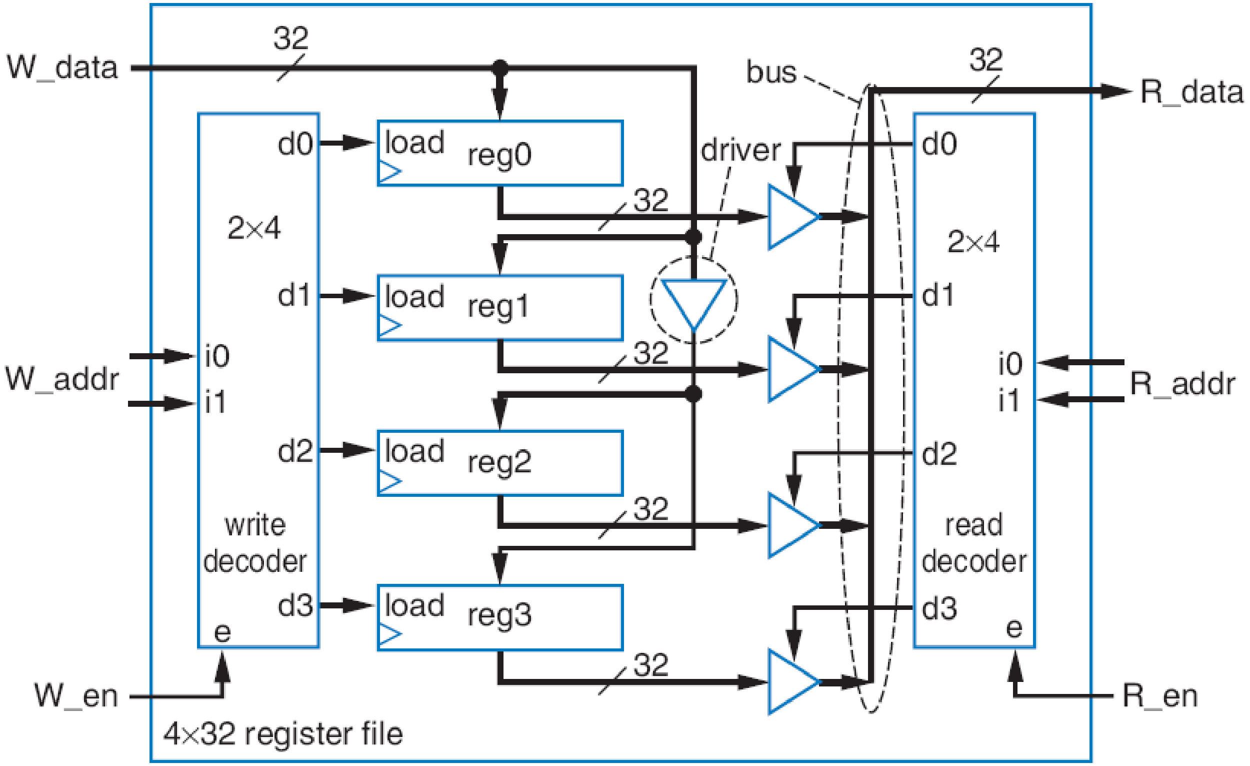
- Register operands
- Memory operands
- Immediate operands (constant)

Register Operands

- Arithmetic instructions use register operands
- MIPS architecture has a 32 × 32-bit register file
  - Used for frequently accessed data
  - Numbered 0 to 31
  - Each register is a 32-bit word
- Names recognized by MIPS assembler
  - $t0~$t9, $s0~$s7, etc.
  - Or $0-$31, accepted by certain assemblers
- *Design Principle 2:* Smaller is faster

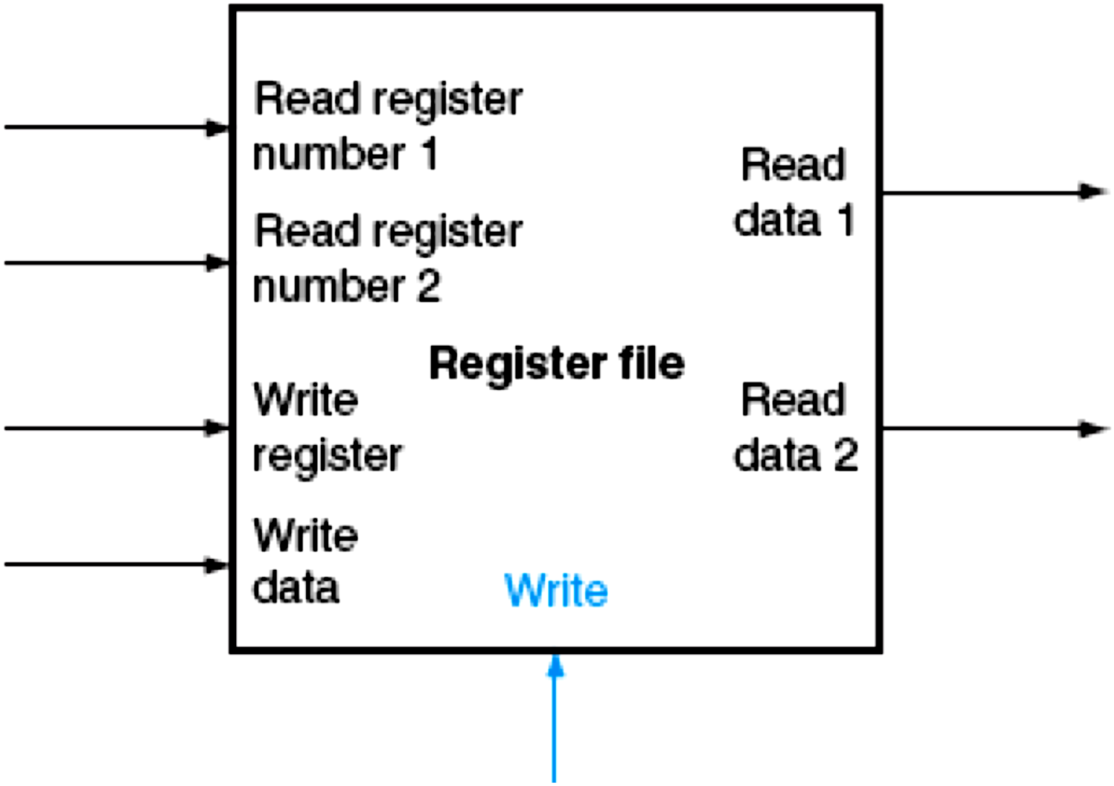
Register File





Register File

The register file we are going to use in this class is a bit different.



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)

Register Operand Example

- C/C++ code:

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

  - Put f, g, h, i, and j in $s0, $s1, $s2, $s3, and $s4, respectively

- Compiled MIPS code:

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

Operands in MIPS Assembly

- Register operands
- Memory operands
- Immediate operands (constant)

Memory Operands

- Memory used mainly for composite data
  - Arrays, structures, dynamic data
- Steps to use memory operands
  - Load values from memory into registers
  - Perform arithmetic operations with registers
  - Store result from register back to memory

MIPS Memory organization

- MIPS memory is byte addressable
  - Each address identifies an 8-bit byte
- Memory is organized in words
  - Word address must be a multiple of 4 – alignment restriction
- MIPS is Big Endian (except some MIPS extension)
  - Most-significant byte at least address of a word
  - Little Endian: least-significant byte at least address
  - E.g.: 32-bit number 1020A0B0

Big Endian

Address	0xffff_0000	0xffff_0001	0xffff_0002	0xffff_0003
Content	10	20	A0	B0

Little Endian

Address	0xffff_0003	0xffff_0002	0xffff_0001	0xffff_0000
Content	10	20	A0	B0

Memory Operand Example 1

- C/C++ code:

```
g = h + A[8]; //g, h, A are words
```

  - g in $s1, h in $s2, base address of A in $s3
- Compiled MIPS code:
  - Index 8 requires offset of 32 (4 bytes/word)

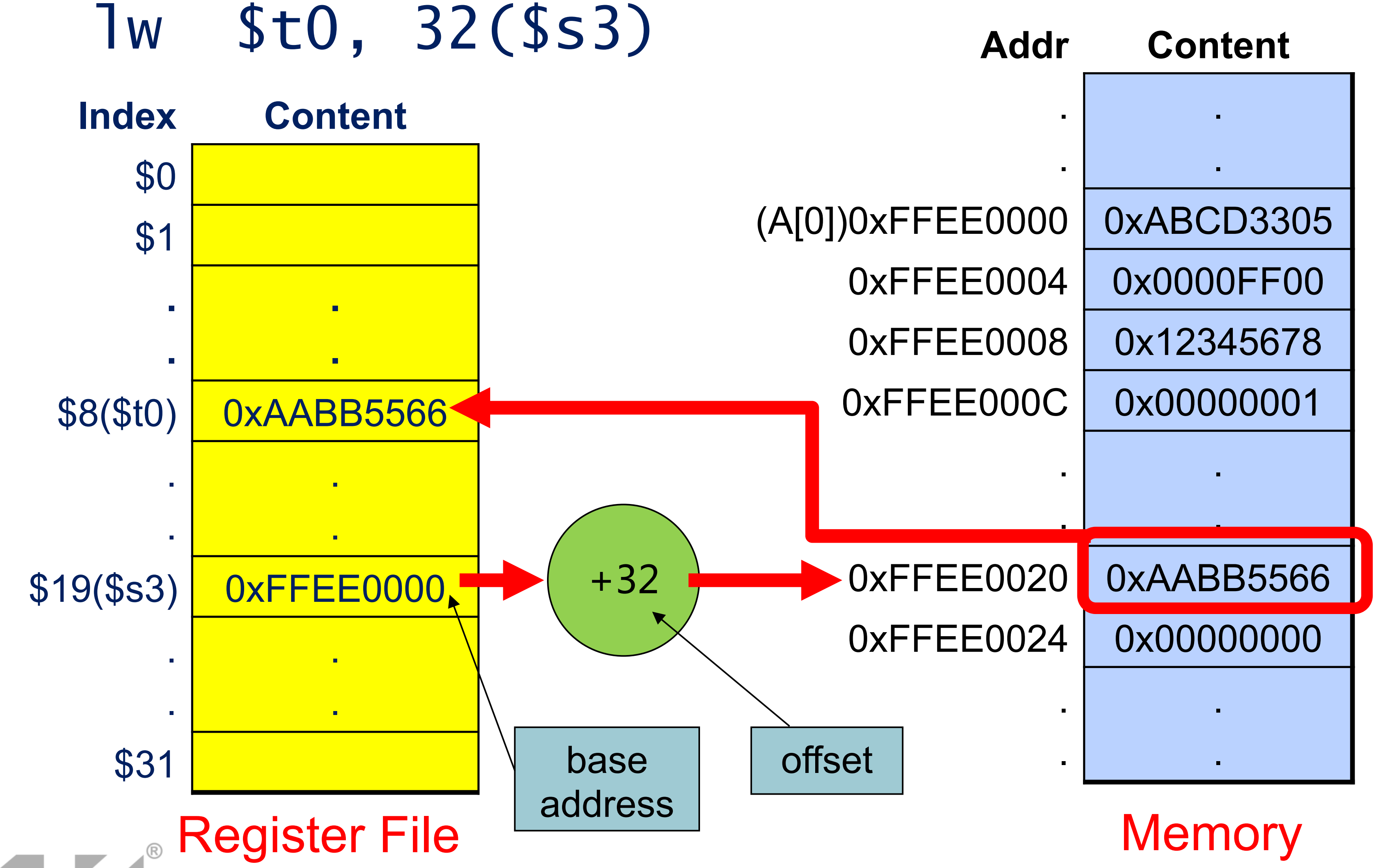
```
lw  $t0, 32($s3)    # load word
add $s1, $s2, $t0
```

offset

base address register

Load Word

```
lw  $t0, 32($s3)
```



Index	Content
$0	
$1	
.	.
.	.
$8($t0)	0xAABB5566
.	.
.	.
$19($s3)	0xFFEE0000
.	.
.	.
$31	

Register File

Addr	Content
.	.
.	.
(A[0])0xFFEE0000	0xABCD3305
0xFFEE0004	0x0000FF00
0xFFEE0008	0x12345678
0xFFEE000C	0x00000001
.	.
.	.
0xFFEE0020	0xAABB5566
0xFFEE0024	0x00000000
.	.
.	.

Memory

+32

base address

offset

Memory Operand Example 2

- C code:

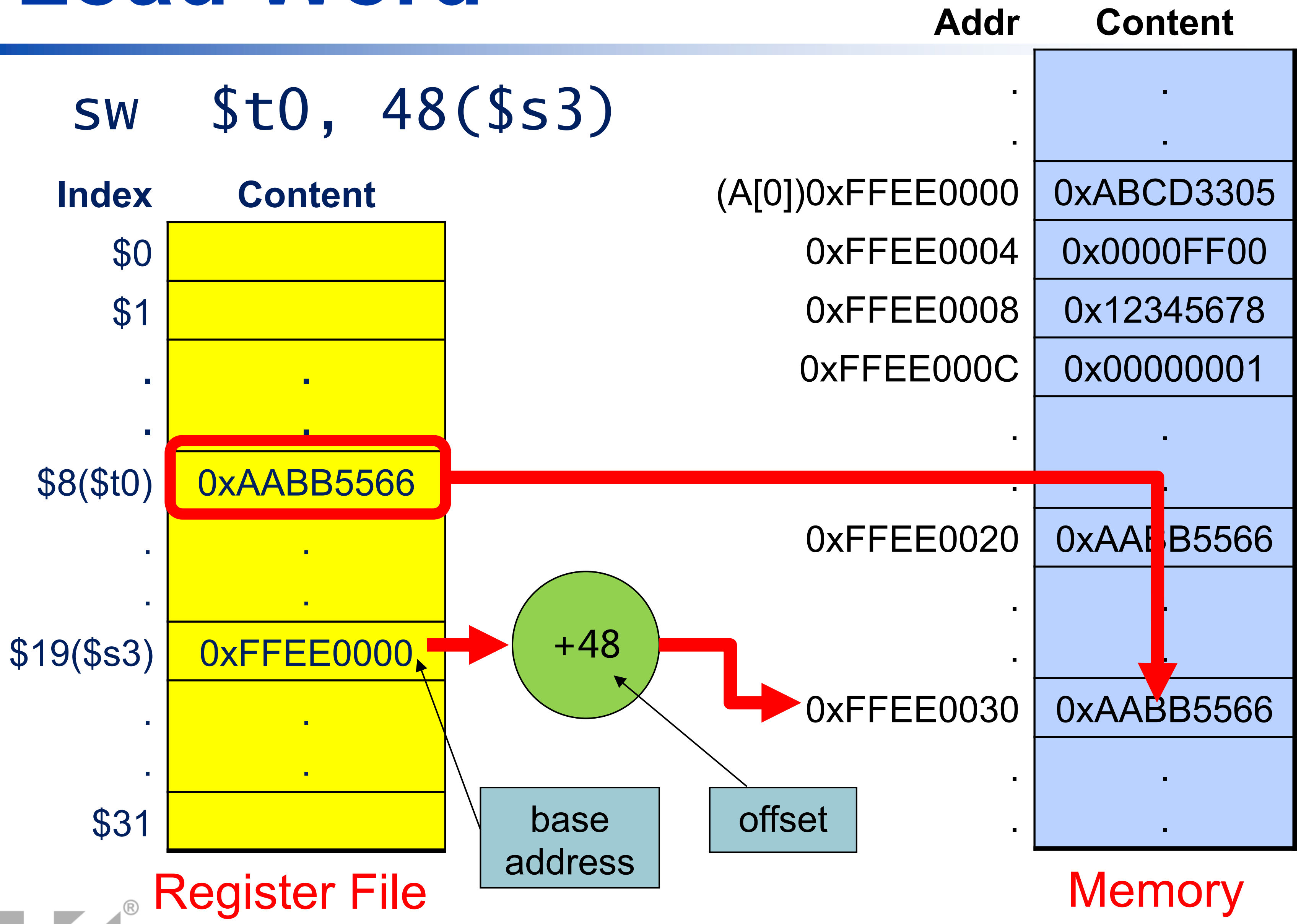
```
A[12] = h + A[8];
```

  - 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
```

Load Word

```
sw  $t0, 48($s3)
```



Index	Content
$0	
$1	
.	.
.	.
$8($t0)	0xAABB5566
.	.
.	.
$19($s3)	0xFFEE0000
.	.
.	.
$31	

Register File

Addr	Content
.	.
.	.
(A[0])0xFFEE0000	0xABCD3305
0xFFEE0004	0x0000FF00
0xFFEE0008	0x12345678
0xFFEE000C	0x00000001
.	.
.	.
0xFFEE0020	0xAABB5566
.	.
.	.
0xFFEE0030	0xAABB5566
.	.
.	.

Memory

Registers vs. Memory

- Registers are 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!

Operands in MIPS Assembly

- Register operands
- Memory operands
- Immediate operands (constant)

Immediate Operands

- 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
  - Small constants are common
  - Immediate operand avoids loading data from memory

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
    ```

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

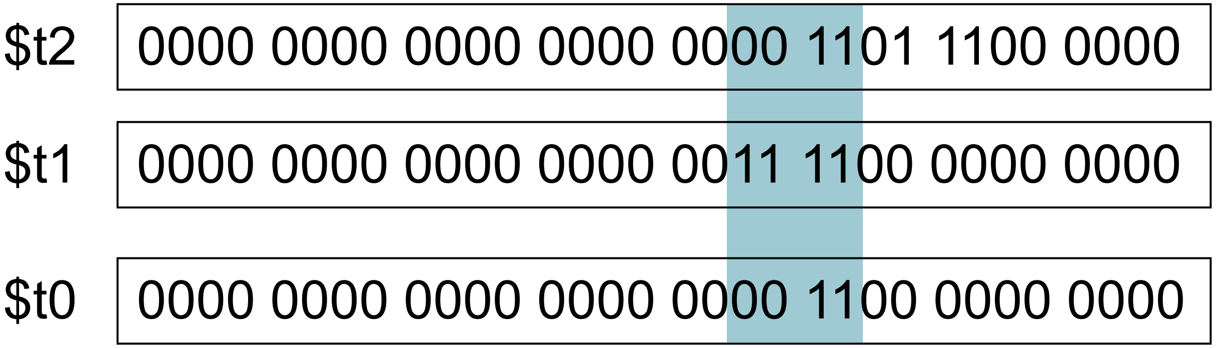
sll/srl rd, rt, shamt

- rt: source register
- rd: destination register
- shamt: how many bits to shift
- Shift left logical
  - Shift left and fill vacated bits with 0 bits
  - `sll` by *i* bits = multiplies by 2^i
- Shift right logical
  - Shift right and fill vacated bits with 0 bits
  - `srl` by *i* bits = divides by 2^i (unsigned only)

AND Operations

- Useful to mask bits in a word
  - Select some bits, clear others to 0

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

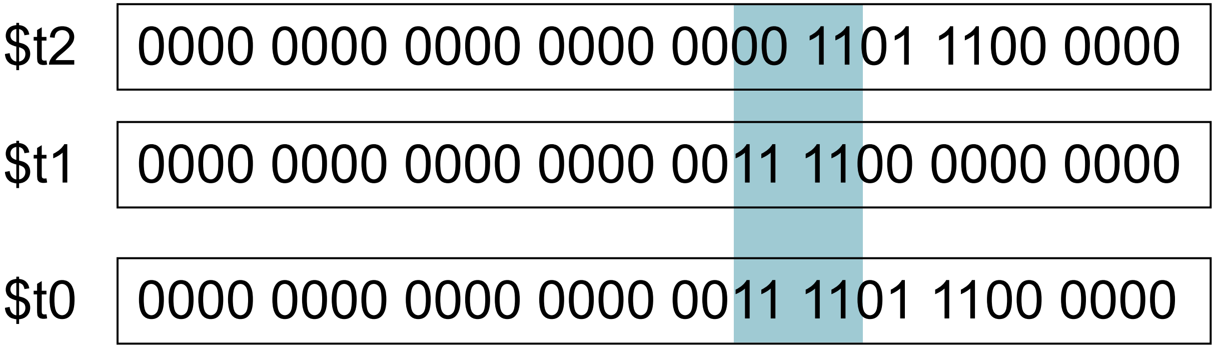


$t2	0000 0000 0000 0000 0000 1101 1100 0000
$t1	0000 0000 0000 0000 0011 1100 0000 0000
$t0	0000 0000 0000 0000 0000 1100 0000 0000

OR Operations

- Useful to include bits in a word
  - Set some bits to 1, leave others unchanged

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



$t2 0000 0000 0000 0000 0000 1101 1100 0000

$t1 0000 0000 0000 0000 0011 1100 0000 0000

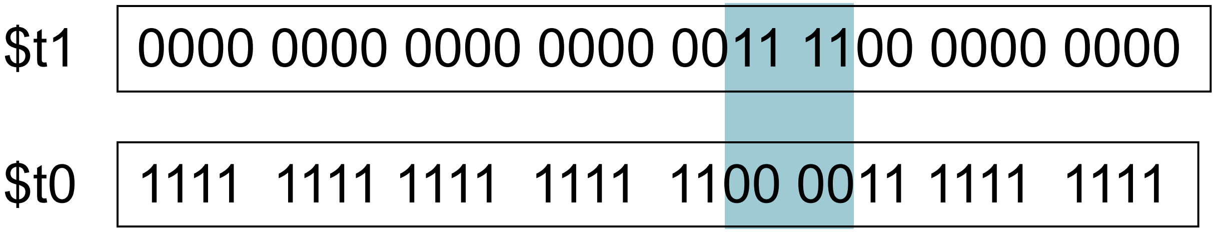
$t0 0000 0000 0000 0000 0011 1101 1100 0000

NOT Operations

- Useful to invert bits in a word
  - Change 0 to 1, and 1 to 0
- MIPS doesn't have NOT instruction, implemented with NOR instruction

```
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

Load 32-bit Constants

- Most constants are small
  - 16-bit immediate is sufficient
- For the occasional 32-bit constant

```
lui rt, constant
```

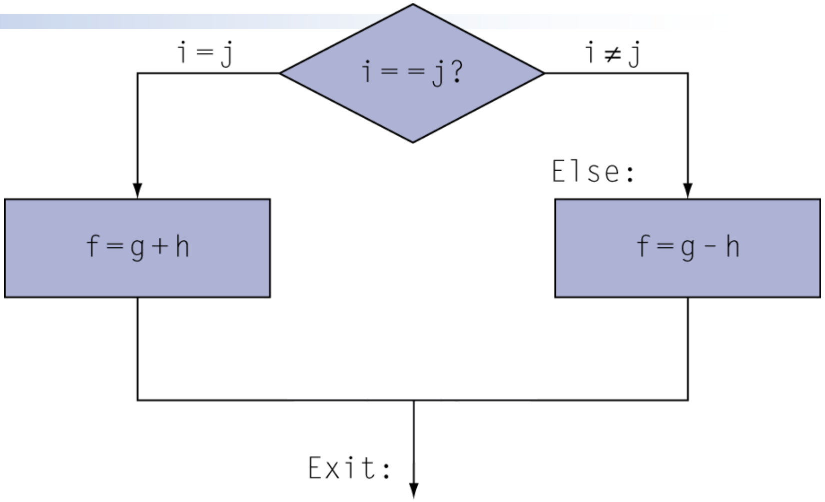
  - Copies 16-bit constant to left 16 bits of rt
  - Clears right 16 bits of rt to 0

`lui $s0, 61`	0000 0000 0011 1101	0000 0000 0000 0000
`ori $s0, $s0, 2304`	0000 0000 0011 1101	0000 1001 0000 0000

Branch/Jump 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,h,i,j in $s0, $s1, $s2, $s3, $s4 respectively

- 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: …
```

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
```

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

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

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

Branch Instruction Design

- Why not `blt`, `bge`, etc?
- Hardware for <, ≥, … slower than =, ≠
  - Combining branch involves more work per instruction, requiring a slower clock
  - All instructions penalized!
- beq and bne are the common cases
- This is a good design compromise

Assembler Pseudoinstructions

- Most assembly instructions and machine instructions have one-to-one correspondence
- Pseudoinstructions: not a real implementation, assembler's imagination

```
move $t0, $t1     →  add $t0, $t1, $zero
blt $t0, $t1, L    →  slt $at, $t0, $t1
                      bne $at, $zero, L
```

  - $at (register 1): assembler temporary

Benchmark Programs

- Measure MIPS instruction executions in benchmark programs
  - Consider making the common case fast
  - Consider compromises

Instruction class	MIPS examples	SPEC CPU2006 INT	SPEC CPU2006 FP
Arithmetic	`add, sub, addi`	16%	48%
Data transfer	`lw, sw, lb, lbu, lh, lhu, sb, lui`	35%	36%
Logical	`and, or, nor, andi, ori, sll, srl`	12%	4%
Cond. Branch	`beq, bne, slt, slti, sltiu`	34%	8%
Jump	`j, jr, jal`	2%	0%