THE ESSENTIALS OF

Computer Organization and Architecture

THIRD EDITION

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Chapter 5

A Closer Look at Instruction Set Architectures

Chapter 5 Objectives

- Understand the factors involved in instruction set architecture design.
- Gain familiarity with memory addressing modes.
- Understand the concepts of instruction-level pipelining and its affect upon execution performance.

5.1 Introduction

- This chapter builds upon the ideas in Chapter 4.
- We present a detailed look at different instruction formats, operand types, and memory access methods.
- We will see the interrelation between machine organization and instruction formats.
- This leads to a deeper understanding of computer architecture in general.

> Employers frequently prefer to hire people with assembly language background, not because they need an assembly language programmer, but because they need someone who can understand computer architecture to write more efficient and more effective programs.

5.2 Instruction Formats

Instruction sets are differentiated by the following:

- Number of bits per instruction.
- Stack-based or register-based.
- Number of explicit operands per instruction.
- Operand location.
- Types of operations.
- Type and size of operands.

5.2 Instruction Formats

Instruction set architectures are measured according to:

- Main memory space occupied by a program.
- Instruction complexity.
- Instruction length (in bits).
- Total number of instructions in the instruction set.

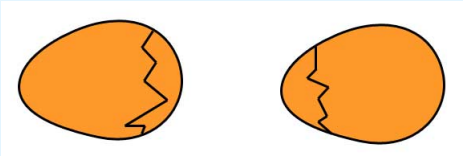
5.2 Instruction Formats

In designing an instruction set, consideration is given to:

- Instruction length.
  - Whether short, long, or variable.
- Number of operands.
- Number of addressable registers.
- Memory organization.
  - Whether byte- or word addressable.
- Addressing modes.
  - Choose any or all: direct, indirect or indexed.

5.2 Instruction Formats

- Byte ordering, or *endianness*, is another major architectural consideration.
- If we have a two-byte integer, the integer may be stored so that the least significant byte is followed by the most significant byte or vice versa.
  - *Big endian* machines store the most significant byte first (at the lower address).
  - In *little endian* machines, the least significant byte is followed by the most significant byte.



5.2 Instruction Formats

- As an example, suppose we have the hexadecimal number 12345678.
- The big endian and little endian arrangements of the bytes are shown below.

Address →	00	01	10	11
Big Endian	12	34	56	78
Little Endian	78	56	34	12

5.2 Instruction Formats

- Big endian:
  - Is more natural.
  - The sign of the number can be determined by looking at the byte at address offset 0.
  - Strings and integers are stored in the same order.
- Little endian:
  - Makes it easier to place values on non-word boundaries.
  - Conversion from a 16-bit integer address to a 32-bit integer address does not require any arithmetic.

5.2 Instruction Formats

- The next consideration for architecture design concerns how the CPU will store data.
- We have three choices:
  1. A stack architecture
  2. An accumulator architecture
  3. A general purpose register architecture.
- In choosing one over the other, the tradeoffs are simplicity (and cost) of hardware design with execution speed and ease of use.

5.2 Instruction Formats

- In a stack architecture, operands are implicitly taken from the stack.
  - A stack cannot be accessed randomly.
- In an accumulator architecture, one operand of a binary operation is implicitly in the accumulator.
  - One operand is in memory, creating lots of bus traffic.
- In a general purpose register (GPR) architecture, registers can be used instead of memory.
  - Faster than accumulator architecture.
  - Efficient implementation for compilers.
  - Results in longer instructions.

5.2 Instruction Formats

- Most systems today are GPR systems.
- There are three types:
  - Memory-memory where two or three operands may be in memory.
  - Register-memory where at least one operand must be in a register.
  - Load-store where only the load and store instructions can access memory.
- The number of operands and the number of available registers has a direct affect on instruction length.

5.2 Instruction Formats

- Stack machines use one- and zero-operand instructions.
- **`PUSH`** and **`POP`** instructions require a single memory address operand.
- **`PUSH`** and **`POP`** operations involve only the stack's top element.
- Other instructions use operands from the stack implicitly.
- Binary instructions (e.g., **`ADD`**, **`MULT`**) use the top two items on the stack.

5.2 Instruction Formats

- Stack architectures require us to think about arithmetic expressions a little differently.
- We are accustomed to writing expressions using *infix* notation, such as: Z = X + Y.
- Stack arithmetic requires that we use *postfix* notation: Z = XY+.
  - This is also called *reverse Polish notation*, (somewhat) in honor of its Polish inventor, Jan Lukasiewicz (1878 - 1956).

5.2 Instruction Formats

- The principal advantage of postfix notation is that parentheses are not used.
- For example, the infix expression,

  Z = (X × Y) + (W × U)

  becomes:

  Z = X Y × W U × +

  in postfix notation.

5.2 Instruction Formats

- Example: Convert the infix expression (2+3) - 6/3 to postfix:

2 3+ - 6/3	The sum 2 + 3 in parentheses takes precedence; we replace the term with 2 3 +.

5.2 Instruction Formats

- Example: Convert the infix expression (2+3) - 6/3 to postfix:

2 3 + - 6 3 /	The division operator takes next precedence; we replace 6/3 with 6 3 /.

5.2 Instruction Formats

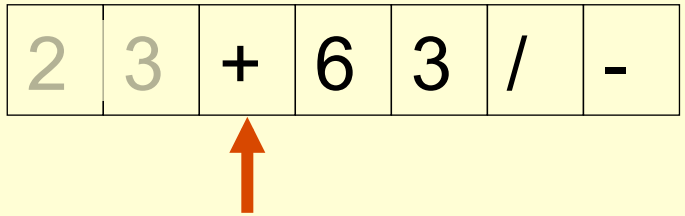
- Example: Convert the infix expression (2+3) - 6/3 to postfix:

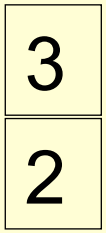
2 3 + 6 3 / -	The quotient 6/3 is subtracted from the sum of 2 + 3, so we move the - operator to the end.

5.2 Instruction Formats

- Example: Use a stack to evaluate the postfix expression 2 3 + 6 3 / - :

Scanning the expression from left to right, push operands onto the stack, until an operator is found

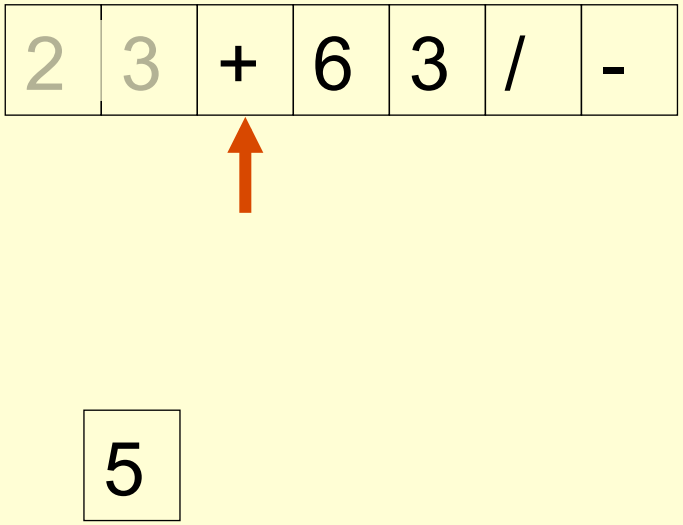




5.2 Instruction Formats

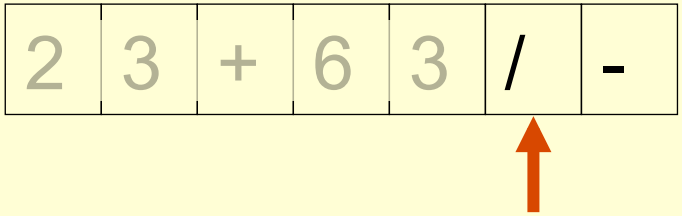
- Example: Use a stack to evaluate the postfix expression 2 3 + 6 3 / - :

Pop the two operands and carry out the operation indicated by the operator. Push the result back on the stack.

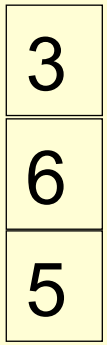


5.2 Instruction Formats

- Example: Use a stack to evaluate the postfix expression 2 3 + 6 3 / - :

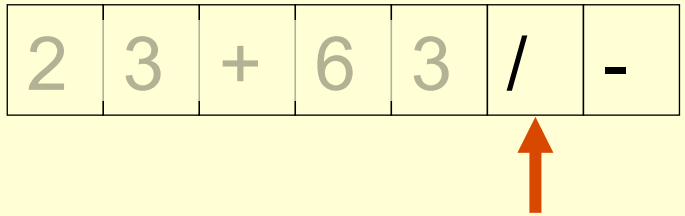


Push operands until another operator is found.

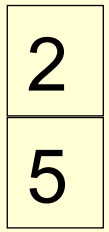


5.2 Instruction Formats

- Example: Use a stack to evaluate the postfix expression 2 3 + 6 3 / - :



Carry out the operation and push the result.

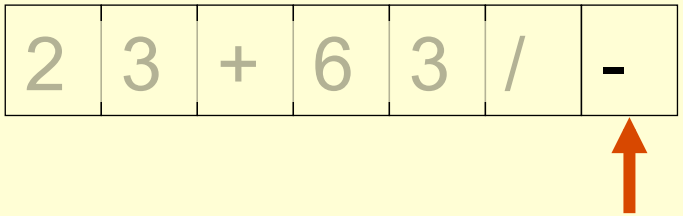


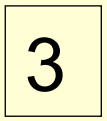
5.2 Instruction Formats

- Example: Use a stack to evaluate the postfix expression 2 3 + 6 3 / - :

Finding another operator, carry out the operation and push the result.

The answer is at the top of the stack.





5.2 Instruction Formats

Let's see how to evaluate an infix expression using different instruction formats.

With a three-address ISA, (e.g.,mainframes), the infix expression,

Z = X × Y + W × U

might look like this:

```
MULT R1,X,Y
MULT R2,W,U
ADD  Z,R1,R2
```

5.2 Instruction Formats

- In a two-address ISA, (e.g.,Intel, Motorola), the infix expression,

  Z = X × Y + W × U

  might look like this:

```
LOAD  R1,X
MULT  R1,Y
LOAD  R2,W
MULT  R2,U
ADD   R1,R2
STORE Z,R1
```

Note: One-address ISAs usually require one operand to be a register.

5.2 Instruction Formats

- In a one-address ISA, like MARIE, the infix expression,

  Z = X × Y + W × U

  looks like this:

```
LOAD X
MULT Y
STORE TEMP
LOAD W
MULT U
ADD TEMP
STORE Z
```

5.2 Instruction Formats

- In a stack ISA, the postfix expression,

  Z = X Y × W U × +

  might look like this:

```
PUSH X
PUSH Y
MULT
PUSH W
PUSH U
MULT
ADD
POP Z
```

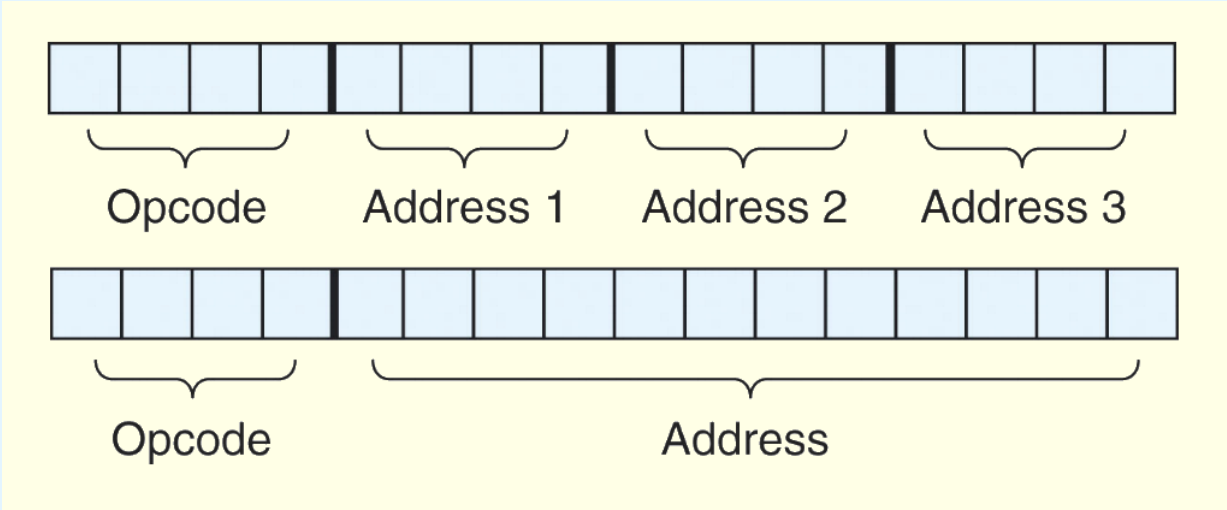
Note: The result of a binary operation is implicitly stored on the top of the stack!

5.2 Instruction Formats

- We have seen how instruction length is affected by the number of operands supported by the ISA.
- In any instruction set, not all instructions require the same number of operands.
- Operations that require no operands, such as **`HALT`**, necessarily waste some space when fixed-length instructions are used.
- One way to recover some of this space is to use expanding opcodes.

5.2 Instruction Formats

- A system has 16 registers and 4K of memory.
- We need 4 bits to access one of the registers. We also need 12 bits for a memory address.
- If the system is to have 16-bit instructions, we have two choices for our instructions:



5.2 Instruction Formats

- If we allow the length of the opcode to vary, we could create a very rich instruction set:

```
0000 R1   R2   R3
1110 R1   R2   R3          } 15 3-address codes

1111 0000 R1   R2
1111 1101 R1   R2          } 14 2-address codes

1111 1110 0000 R1
1111 1111 1110 R1          } 31 1-address codes

1111 1111 1111 0000
1111 1111 1111 1111        } 16 0-address codes
```

Is there something missing from this instruction set?

5.2 Instruction Formats

- Example: Given 8-bit instructions, is it possible to allow the following to be encoded?
  - 3 instructions with two 3-bit operands.
  - 2 instructions with one 4-bit operand.
  - 4 instructions with one 3-bit operand.

We need:

$3 * 2^3 * 2^3 = 192$ bits for the 3-bit operands

$2 * 2^4 =$ 32 bits for the 4-bit operands

$4 * 2^3 =$ 32 bits for the 3-bit operands.

Total: 256 bits.

5.2 Instruction Formats

- With a total of 256 bits required, we can exactly encode our instruction set in 8 bits! ($256 = 2^8$)

We need:

$3 * 2^3 * 2^3 = 192$ bits for the 3-bit operands

$2 * 2^4 = 32$ bits for the 4-bit operands

$4 * 2^3 = 32$ bits for the 3-bit operands.

Total: 256 bits.

One such encoding is shown on the next slide.

5.2 Instruction Formats

```
00 xxx xxx
01 xxx xxx
10 xxx xxx
11 – escape opcode
1100 xxxx
1101 xxxx
1110 – escape opcode
1111 – escape opcode
11100 xxx
11101 xxx
11110 xxx
11111 xxx
```

3 instructions with two 3-bit operands

2 instructions with one 4-bit operand

4 instructions with one 3-bit operand

5.3 Instruction types

Instructions fall into several broad categories that you should be familiar with:

- Data movement.
- Arithmetic.
- Boolean.
- Bit manipulation.
- I/O.
- Control transfer.
- Special purpose.

Can you think of some examples of each of these?

5.4 Addressing

- Addressing modes specify where an operand is located.
- They can specify a constant, a register, or a memory location.
- The actual location of an operand is its *effective address*.
- Certain addressing modes allow us to determine the address of an operand dynamically.

5.4 Addressing

- *Immediate addressing* is where the data is part of the instruction.
- *Direct addressing* is where the address of the data is given in the instruction.
- *Register addressing* is where the data is located in a register.
- *Indirect addressing* gives the address of the address of the data in the instruction.
- *Register indirect addressing* uses a register to store the address of the data.

5.4 Addressing

- *Indexed addressing* uses a register (implicitly or explicitly) as an offset (displacement), which is added to the address in the operand to determine the effective address of the data.
- *Based addressing* is similar except that a base register is used instead of an index register.
- The difference between these two is that an index register holds an offset relative to the address given in the instruction, a base register holds a base address where the address field represents a displacement from this base.

5.4 Addressing

- In *stack addressing* the operand is assumed to be on top of the stack.
- There are many variations to these addressing modes including:
  - Indirect indexed.
  - Base/offset.
  - Self-relative
  - Auto increment - decrement.
- We won't cover these in detail.

Let's look at an example of the principal addressing modes.

5.4 Addressing

- For the instruction shown, what value is loaded into the accumulator for each addressing mode?

Memory

800	900
...	
900	1000
...	
1000	500
...	
1100	600
...	
1600	700

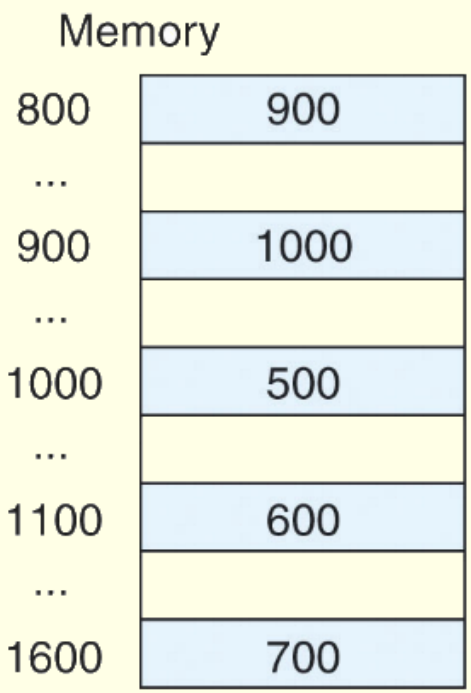
R1 | 800

```
LOAD 800
```

Mode	Value Loaded into AC
Immediate	
Direct	
Indirect	
Indexed	

5.4 Addressing

- These are the values loaded into the accumulator for each addressing mode.



LOAD 800

Mode	Value Loaded into AC
Immediate	800
Direct	900
Indirect	1000
Indexed	700

5.4 Addressing

- Summary of basic addressing modes.

Addressing Mode	To Find Operand
Immediate	Operand value present in the instruction
Direct	Effective address of operand in address field
Register	Operand value located in register
Indirect	Address field points to address of the actual operand
Register Indirect	Register contains address of actual operand
Indexed or Based	Effective address of operand generated by adding value in address field to contents of a register
Stack	Operand located on stack

5.5 Instruction-Level Pipelining

- Some CPUs divide the fetch-decode-execute cycle into smaller steps.
- These smaller steps can often be executed in parallel to increase throughput.
- Such parallel execution is called *instruction-level pipelining*.
- Instruction pipelining is one method used to exploit *Instruction-level parallelism* (*ILP*).

The next slide shows an example of instruction-level pipelining.

5.5 Instruction-Level Pipelining

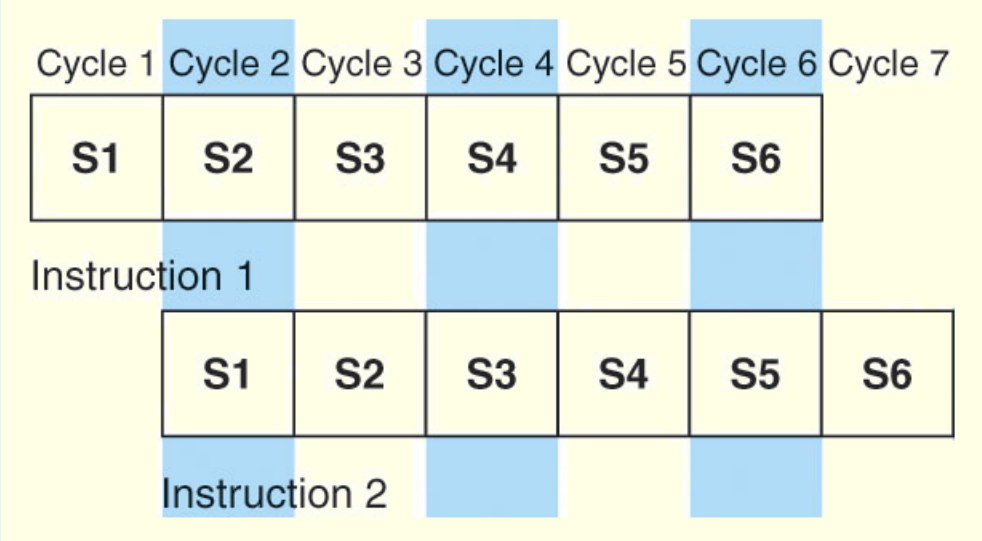
- Suppose a fetch-decode-execute cycle were broken into the following smaller steps:

1. Fetch instruction.
2. Decode opcode.
3. Calculate effective address of operands.
4. Fetch operands.
5. Execute instruction.
6. Store result.

- Suppose we have a six-stage pipeline. S1 fetches the instruction, S2 decodes it, S3 determines the address of the operands, S4 fetches them, S5 executes the instruction, and S6 stores the result.

5.5 Instruction-Level Pipelining

- For every clock cycle, one small step is carried out, and the stages are overlapped.



S1. Fetch instruction.
S2. Decode opcode.
S3. Calculate effective address of operands.
S4. Fetch operands.
S5. Execute.
S6. Store result.

5.5 Instruction-Level Pipelining

- The theoretical speedup offered by a pipeline can be determined as follows:

  Let t_p be the time per stage. Each instruction represents a task, T, in the pipeline.

  The first task (instruction) requires $k \times t_p$ time to complete in a k-stage pipeline. The remaining $(n - 1)$ tasks emerge from the pipeline one per cycle. So the total time to complete the remaining tasks is $(n - 1)t_p$.

  Thus, to complete n tasks using a k-stage pipeline requires:

$$(k \times t_p) + (n - 1)t_p = (k + n - 1)t_p.$$

5.5 Instruction-Level Pipelining

- If we take the time required to complete *n* tasks without a pipeline and divide it by the time it takes to complete *n* tasks using a pipeline, we find:

$$\text{Speedup } S = \frac{n t_n}{(k + n - 1)\, t_p}$$

where $t_n = kt_p$.

- If we take the limit as *n* approaches infinity, ($k + n - 1$) approaches *n,* which results in a theoretical speedup of:

$$\text{Speedup } S = \frac{k t_p}{t_p} = k$$

5.5 Instruction-Level Pipelining

- Our neat equations take a number of things for granted.
- First, we have to assume that the architecture supports fetching instructions and data in parallel.
- Second, we assume that the pipeline can be kept filled at all times. This is not always the case. Pipeline *hazards* arise that cause pipeline conflicts and stalls.

5.5 Instruction-Level Pipelining

- An instruction pipeline may stall or be flushed for any of the following reasons:
  - Resource conflicts.
  - Data dependencies.
  - Conditional branching.
- Measures can be taken at the software level as well as at the hardware level to reduce the effects of these hazards, but they cannot be totally eliminated.

5.6 Real-World Examples of ISAs

- We return briefly to the Intel and MIPS architectures from the last chapter, using some of the ideas introduced in this chapter.
- Intel uses a little endian, two-address architecture, with variable-length instructions.
- Intel introduced pipelining to their processor line with its Pentium chip.
- The first Pentium had two five-stage pipelines. Each subsequent Pentium processor had a longer pipeline than its predecessor with the Pentium IV having a 24-stage pipeline.
- The Itanium (IA-64) has only a 10-stage pipeline.

5.6 Real-World Examples of ISAs

- Intel processors are byte-addressable, register-memory architectures, and support a wide array of addressing modes.
- The original 8086 provided 17 ways to address memory, most of them variants on the methods presented in this chapter.
- Owing to their need for backward compatibility, the Pentium chips also support these 17 addressing modes.
- The Itanium, having a RISC core, supports only one: register indirect addressing with optional post increment.

5.6 Real-World Examples of ISAs

- MIPS was an acronym for *Microprocessor Without Interlocked Pipeline Stages*.
- The architecture is little endian and word-addressable with three-address, fixed-length instructions.
- Like Intel, the pipeline size of the MIPS processors has grown: The R2000 and R3000 have five-stage pipelines; the R4000 and R4400 have 8-stage pipelines.

5.6 Real-World Examples of ISAs

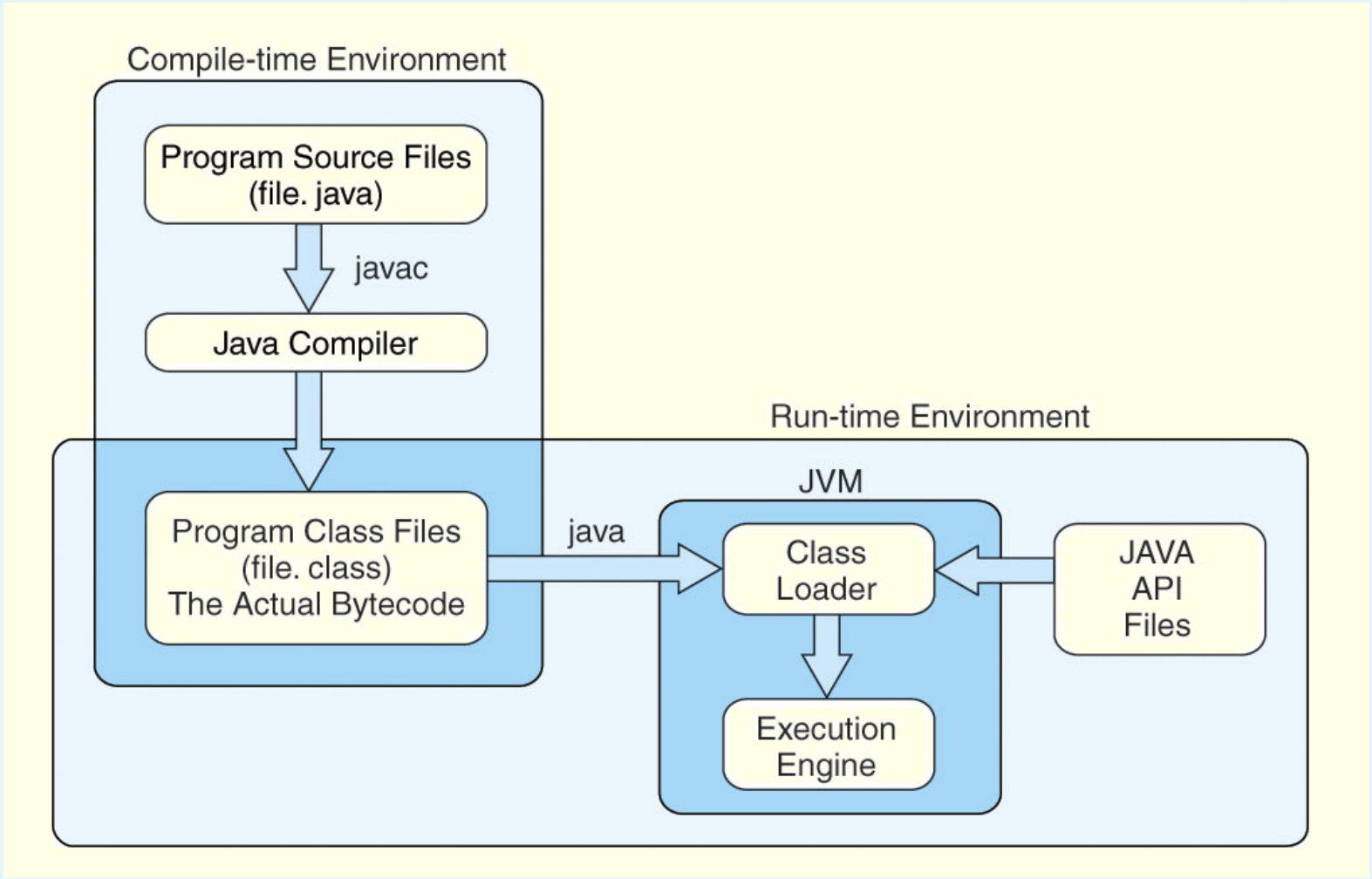
- The R10000 has three pipelines: A five-stage pipeline for integer instructions, a seven-stage pipeline for floating-point instructions, and a six-stage pipeline for **`LOAD/STORE`** instructions.
- In all MIPS ISAs, only the **`LOAD`** and **`STORE`** instructions can access memory.
- The ISA uses only base addressing mode.
- The assembler accommodates programmers who need to use immediate, register, direct, indirect register, base, or indexed addressing modes.

5.6 Real-World Examples of ISAs

- The Java programming language is an interpreted language that runs in a software machine called the *Java Virtual Machine* (JVM). (A virtual machine is a software emulation of a real machine.)
- A JVM is written in a native language for a wide array of processors, including MIPS and Intel.
- Like a real machine, the JVM has an ISA all of its own, called *bytecode*. This ISA was designed to be compatible with the architecture of any machine on which the JVM is running.

The next slide shows how the pieces fit together.

5.6 Real-World Examples of ISAs



5.6 Real-World Examples of ISAs

- Java bytecode is a stack-based language.
- Most instructions are zero address instructions.
- The JVM has four registers that provide access to five regions of main memory.
- All references to memory are offsets from these registers. Java uses no pointers or absolute memory references.
- Java was designed for platform interoperability, not performance!

5.6 Real-World Examples of ISAs

A Java program to find the minimum of two numbers

```
public class Minimum {
    public static void main(String[] args) {
        System.out.println(min(42, 56));
    }

    static int min(int a, int b) {
        int m;
        if (a < b)
            m = a;
        else
            m = b;
        return m;
    }
}
```

5.6 Real-World Examples of ISAs

After we compile the program (using `javac Minimum.java`) we can disassemble it to examine the bytecode, by issuing the following command:

```
javap -c Minimum
```

```
Compiled from "Minimum.java"
public class Minimum extends java.lang.Object{
public Minimum();
  Code:
   0: aload_0
   1: invokespecial     #1; //Method java/lang/
                                Object."<init>":()V
   4: return
```

5.6 Real-World Examples of ISAs

```
0: bipush 42
2: istore_1
3: bipush 56
5: istore_2
6: getstatic #2; //Field java/lang/
                    System.out:Ljava/io/PrintStream;
9: iload_1
10: iload_2
11: invokestatic  #3; //Method min:(II)I
14: invokevirtual #4; //Method java/io/
                         PrintStream.println:(I)V
17: return
```

5.6 Real-World Examples of ISAs

```
static int min(int, int);
  Code:
   0: iload_0
   1: iload_1
   2: if_icmpge 10
   5: iload_0
   6: istore_2
   7: goto  12
   10: iload_1
   11: istore_2
   12: iload_2
   13: ireturn
}
```

Chapter 5 Conclusion

- ISAs are distinguished according to their bits per instruction, number of operands per instruction, operand location and types and sizes of operands.
- Endianness as another major architectural consideration.
- CPU can store store data based on
  1. A stack architecture
  2. An accumulator architecture
  3. A general purpose register architecture.

Chapter 5 Conclusion

- Instructions can be fixed length or variable length.
- To enrich the instruction set for a fixed length instruction set, expanding opcodes can be used.
- The addressing mode of an ISA is also another important factor. We looked at:
  - Immediate
  - Direct
  - Register
  - Register Indirect
  - Indirect
  - Indexed
  - Based
  - Stack

Chapter 5 Conclusion

- A *k*-stage pipeline can theoretically produce execution speedup of *k* as compared to a non-pipelined machine.
- Pipeline hazards such as resource conflicts and conditional branching prevents this speedup from being achieved in practice.
- The Intel, MIPS, and JVM architectures provide good examples of the concepts presented in this chapter.

End of Chapter 5