CISC 260 Machine Organization and Assembly Language

Performance

[Adapted from Mary Jane Irwin (www.cse.psu.edu/~mji) www.cse.psu.edu/~cg431
and from *Computer Organization and Design*, Patterson & Hennessy, © 2005, UCB]

Performance Metrics

- Purchasing perspective: given a collection of machines, which has the
    - best performance ?
    - least cost ?
    - best performance/cost ?
- Design perspective: faced with design options, which has the
    - best performance improvement ?
    - least cost ?
    - best performance/cost?
- Both require
    - basis for comparison
    - metric for evaluation
- Our goal is to understand what factors in the architecture contribute to overall system performance and the relative importance (and cost) of these factors

Defining (Speed) Performance

- Normally interested in reducing
  - Response time (aka execution time) – the time between the start and the completion of a task: Important to individual users
  - Thus, to maximize performance, need to minimize execution time

$$\text{performance}_X = 1 / \text{execution\_time}_X$$

If X is n times faster than Y, then

$$\frac{\text{performance}_X}{\text{performance}_Y} = \frac{\text{execution\_time}_Y}{\text{execution\_time}_X} = n$$

- Throughput – the total amount of work done in a given time: Important to data center managers
- Decreasing response time almost always improves throughput

Performance Factors

- Want to distinguish elapsed time and the time spent on our task
- CPU execution time (CPU time) – time the CPU spends working on a task
  - Does not include time waiting for I/O or running other programs

$$\text{CPU execution time for a program} = \text{\# CPU clock cycles for a program} \times \text{clock cycle time}$$

or

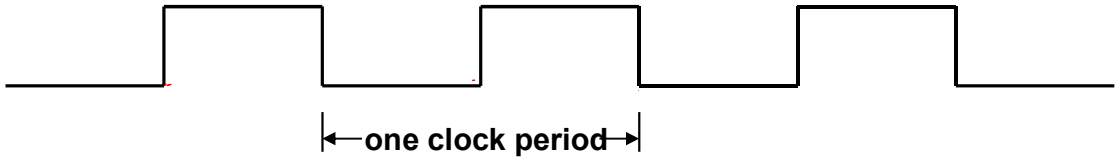
$$\text{CPU execution time for a program} = \frac{\text{\# CPU clock cycles for a program}}{\text{clock rate}}$$

- Can improve performance by reducing either the length of the clock cycle or the number of clock cycles required for a program

Review: Machine Clock Rate

- Clock rate (MHz, GHz) is inverse of clock cycle time (clock period)

$$CC = 1 / CR$$



10 nsec clock cycle => 100 MHz clock rate

5 nsec clock cycle => 200 MHz clock rate

2 nsec clock cycle => 500 MHz clock rate

1 nsec clock cycle => 1 GHz clock rate

500 psec clock cycle => 2 GHz clock rate

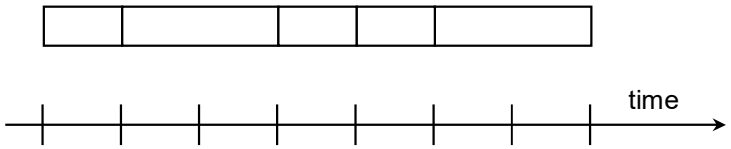
250 psec clock cycle => 4 GHz clock rate

200 psec clock cycle => 5 GHz clock rate

10^{-9} sec

10^{9} cycles

Different numbers of cycles for different instructions



- Multiplication takes more time than addition
- Floating point operations take longer than that of integer
- Accessing memory takes more time than accessing registers

- *Important point: changing the cycle time often changes the number of cycles required for various instructions (more later)*

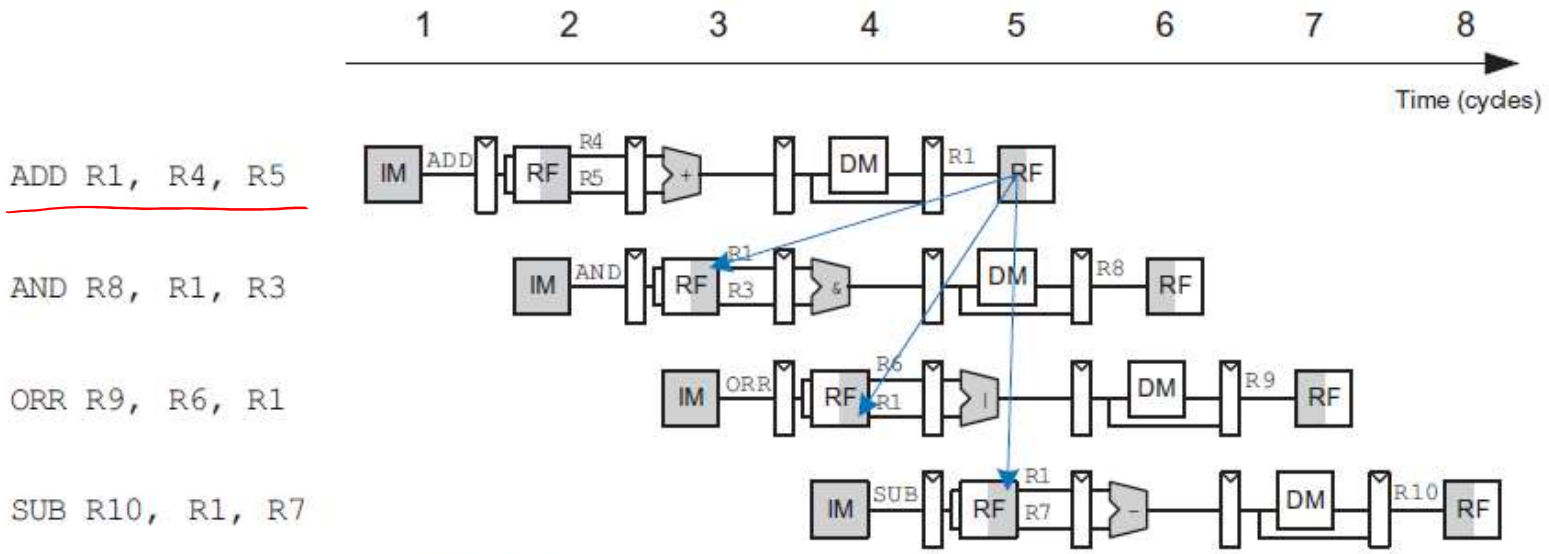


Figure 7.48 Abstract pipeline diagram illustrating hazards

Clock Cycles per Instruction

- Not all instructions take the same amount of time to execute
  - One way to think about execution time is that it equals the number of instructions executed multiplied by the average time per instruction

$$\text{\# CPU clock cycles for a program} = \text{\# Instructions for a program} \times \text{Average clock cycles per instruction}$$

- Clock cycles per instruction (CPI) – the average number of clock cycles each instruction takes to execute
  - A way to compare two different implementations of the same ISA

	CPI for this instruction class		
	A	B	C
CPI	1	2	3

Effective CPI

- Computing the overall effective CPI is done by looking at the different types of instructions and their individual cycle counts and averaging

$$\text{Overall effective CPI} = \sum_{i=1}^{n} (CPI_i \times IC_i)$$

  - Where IC_i is the count (percentage) of the number of instructions of class i executed
  - CPI_i is the (average) number of clock cycles per instruction for that instruction class
  - n is the number of instruction classes

- The overall effective CPI varies by instruction mix – a measure of the dynamic frequency of instructions across one or many programs

The Performance Equation

The basic performance equation is:

$$\text{CPU time} = \text{Instruction\_count} \times \text{CPI} \times \text{clock\_cycle}$$

or

$$\text{CPU time} = \frac{\text{Instruction\_count} \times \text{CPI}}{\text{clock\_rate}}$$

- These equations separate the three key factors that affect performance
  - Can measure the CPU execution time by running the program
  - The clock rate is usually given
  - Can measure overall instruction count by using profilers/ simulators without knowing all of the implementation details
  - CPI varies by instruction type and ISA implementation for which we must know the implementation details

Determinates of CPU Performance

CPU time = Instruction_count x CPI x clock_cycle

	Instruction_ count	CPI	clock_cycle
Algorithm			
Programming language			
Compiler			
ISA			
Processor organization			
Chip Technology			

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CPU time = Instruction_count x CPI x clock_cycle

	Instruction_ count	CPI	clock_cycle
Algorithm	**X**	X	
Programming language	**X**	X	
Compiler	**X**	**X**	
ISA	**X**	**X**	**X**
Processor organization		**X**	**X**
Chip Technology			**X**

A Simple Example

Op	Freq	CPI_i	Freq x CPI_i
ALU	50%	1	.
Load	20%	5	
Store	10%	3	
Branch	20%	2	
			Σ =

- How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?
- How does this compare with using branch prediction to shave a cycle off the branch time?
- What if two ALU instructions could be executed at once?

A Simple Example

Op	Freq	CPI_i	Freq x CPI_i
ALU	50%	1	.5
Load	20%	5	1.0
Store	10%	3	.3
Branch	20%	2	.4
			$\sum$ = 2.2

.5	.5	.25
.4	1.0	1.0
.3	.3	.3
.4	.2	.4
1.6	2.0	1.95

- How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?

  CPU time new = 1.6 x IC x CC so 2.2/1.6 means 37.5% faster

- How does this compare with using branch prediction to shave a cycle off the branch time?

  CPU time new = 2.0 x IC x CC so 2.2/2.0 means 10% faster

- What if two ALU instructions could be executed at once?

  CPU time new = 1.95 x IC x CC so 2.2/1.95 means 12.8% faster

Comparing and Summarizing Performance

- How do we summarize the performance for benchmark set with a single number?
  - The average of execution times that is directly proportional to total execution time is the arithmetic mean (AM)

$$AM = 1/n \sum_{i=1}^{n} Time_i$$

  - Where $Time_i$ is the execution time for the i^{th} program of a total of n programs in the workload
  - A smaller mean indicates a smaller average execution time and thus improved performance

- Guiding principle in reporting performance measurements is reproducibility – list everything another experimenter would need to duplicate the experiment (version of the operating system, compiler settings, input set used, specific computer configuration (clock rate, cache sizes and speed, memory size and speed, etc.))

Amdahl's Law

- execution_time_after = exe time_unaffected + exe time_affected/ speedup.
- execution_time_before = exe_time_unaffected + exe_time_affected.

$$\text{Speedup\_overall} = \frac{\text{execution\_time\_before}}{\text{execution\_time\_after}}$$

$$= \frac{1}{(1 - \text{fraction\_enhanced}) + \text{fraction\_enhanced}/\ \text{speedup}}$$

E.g., A program runs 100s (80s for multiplication and 20s for others)

How much speedup for mul is needed to speedup the program 5 times faster?

E.g., Old CPU (40% on computation, and 60% on IO). New CPU is 10x faster on computation in Web service applications. What's the overall speedup?

Amdahl's Law

E.g., A program runs 100s (80s for multiplication and 20s for others)

How much speedup for mul is needed to speedup the program 5 times faster?

Answer: let speedup for mul be x.

time_after = 20s = 80s / x + 20 => 80s / x = 0 => no such x possible.

E.g., Old CPU (40% on computation, and 60% on IO). New CPU is 10x faster on computation in Web service applications. What's the overall speedup?

Amdahl's Law

E.g., Old CPU (40% on computation, and 60% on IO). New CPU is 10x faster on computation in Web service applications. What's the overall speedup?

Answer: fraction_enhanced = 0.4

speedup_enhanced = 10

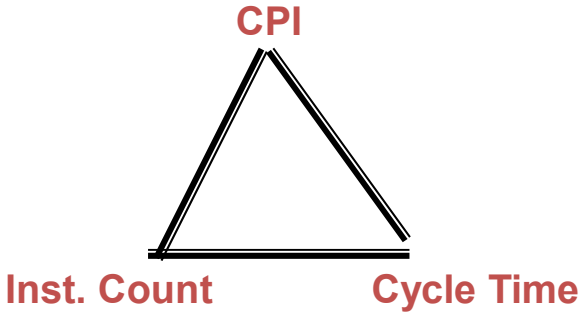
Speedup_overall = 1 / [0.6 + 0.4/10] = 1 / 0.64 ≈ 1.56.

Summary: Evaluating ISAs

- Design-time metrics:
  - Can it be implemented, in how long, at what cost?
  - Can it be programmed? Ease of compilation?
- Static Metrics:
  - How many bytes does the program occupy in memory?
- Dynamic Metrics:
  - How many instructions are executed? How many bytes does the processor fetch to execute the program?
  - How many clocks are required per instruction?
  - How "lean" a clock is practical?

Best Metric: Time to execute the program!

depends on the instructions set, the processor organization, and compilation techniques.



Is the following instruction a real ARM instruction?

```
LDR r0, =0x12345678
```

A: Yes

B: No

How many bytes does the following ARM instruction occupy in memory when assembled into machine binary?

```
LDR r0, =0x12345678
```

A: 4
B: 6
C: 8
D: 12
E: 16