# CS321: Computer Architecture

## Introduction

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# Books to be followed

- Computer Organization and Design: The Hardware/Software Interface (MIPS Edition) – David A. Patterson, John L. Hennessy
- Computer Organization and Architecture – William Stallings
- Computer Architecture: A Quantitative Approach – David A. Patterson, John L. Hennessy
- Computer Systems: A Programmer’s Perspective – Randal E. Bryant, David R. O’Hallaron

# Class information

- Monday — 0900-1000
- Tuesday — 1000-1100
- Wednesday — 1100-12000
- Room No — 301

# Evaluation

- **2 class tests - 20%**
- **Midsem — 30%**
- **Endsem — 50%**

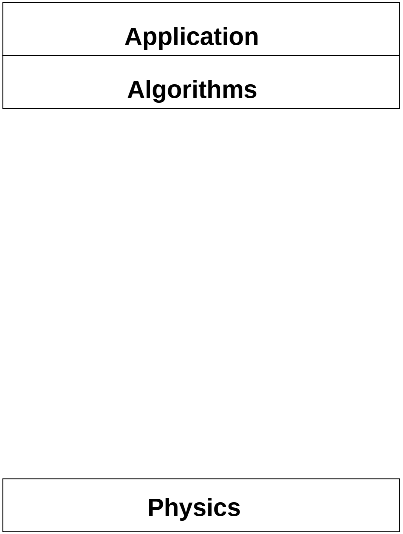
# Introduction

# Abstraction of computing systems

Application

Physics

# Abstraction of computing systems



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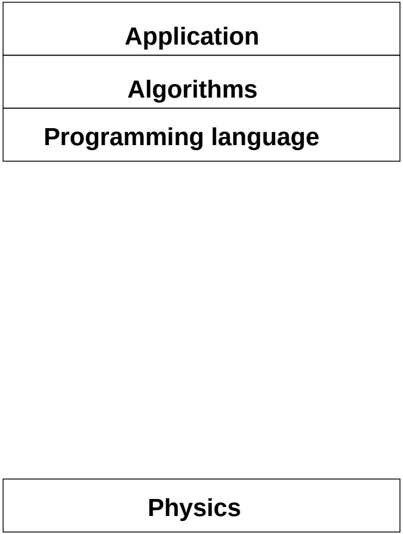

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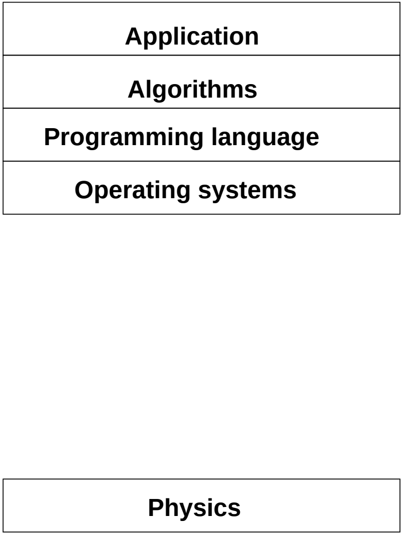

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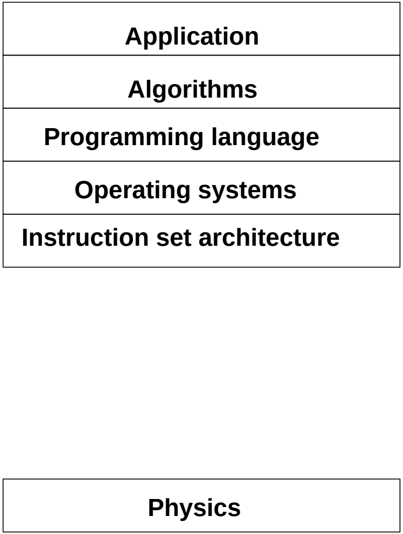

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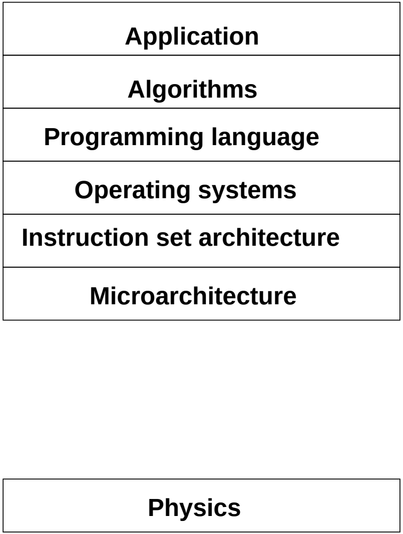

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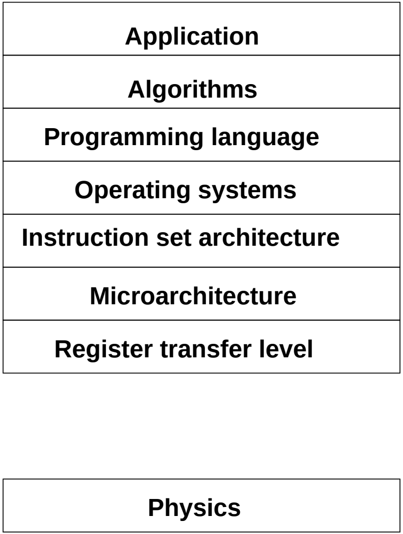

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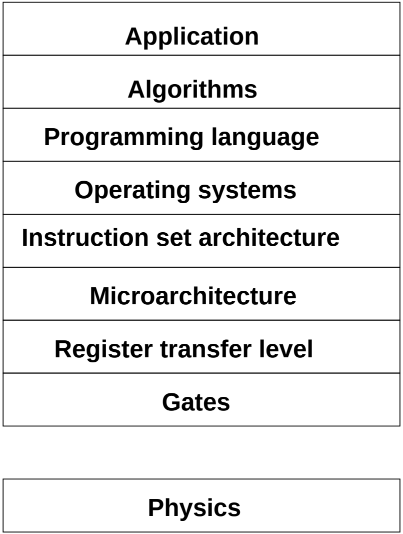

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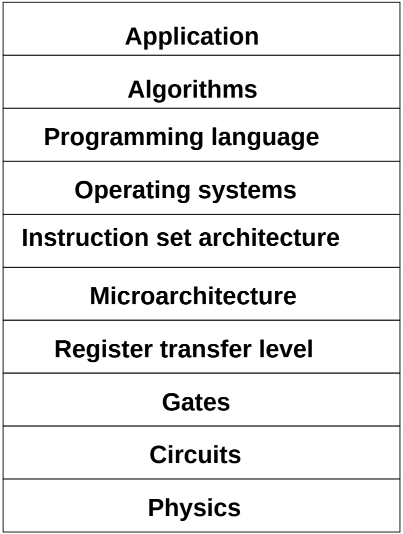

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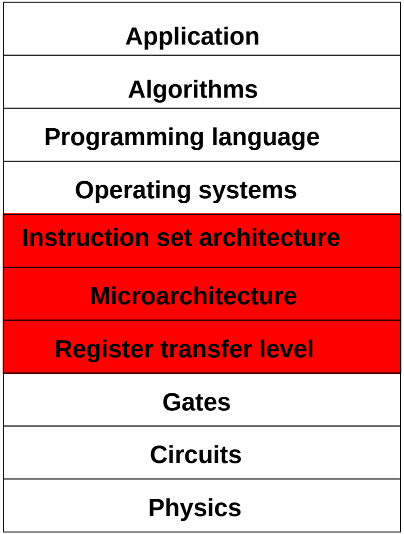

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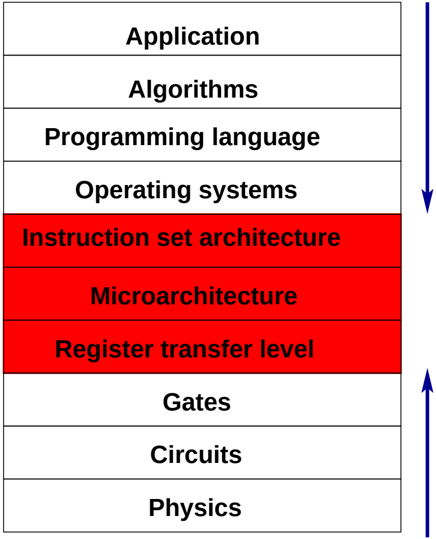

- **Application Requirements:**
  - **Suggest how to improve architecture**
  - **Provide revenue to fund development**
- **Architecture provides feedback to guide application and technology research directions**
- **Technology Constraints:**
  - **Restrict what can be done efficiently**
  - **New technologies make new arch possible**

# Abstraction

- Abstraction helps us to deal with complexity
  - Hide lower level details
- Instruction set architecture
  - Hardware/Software interface
- Application binary interface
  - ISA plus system software
- Implementation
  - The details underlying and interface

# Components of a Computer

- Same components for all kind of computers
  - Server, Desktop, Embedded systems

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  - Storage devices – Hard disk, CD/DVD, Flash
  - Network adapters for communicating with others

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- Input-Output support
  - User interface devices – Keyboard, mouse, display
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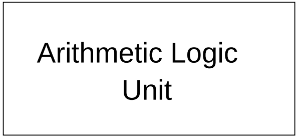
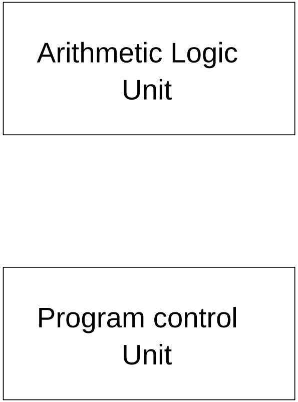
  - Network adapters for communicating with others
- Inside the computer
  - Arithmetic logic unit (ALU)
  - Program control unit
  - Memory
  - Datapath

# IAS Computer



Arithmetic Logic Unit

# IAS Computer



Arithmetic Logic Unit

Program control Unit

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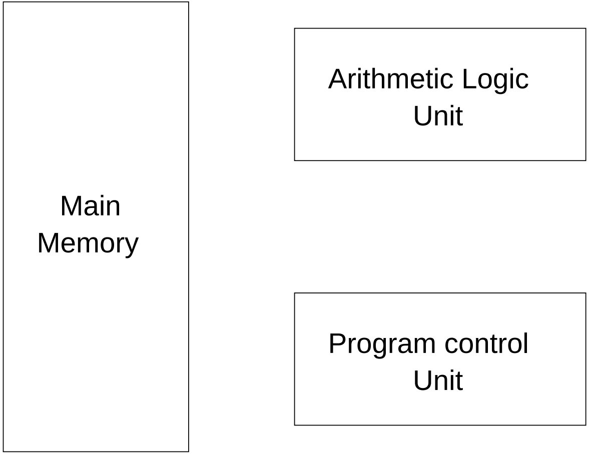

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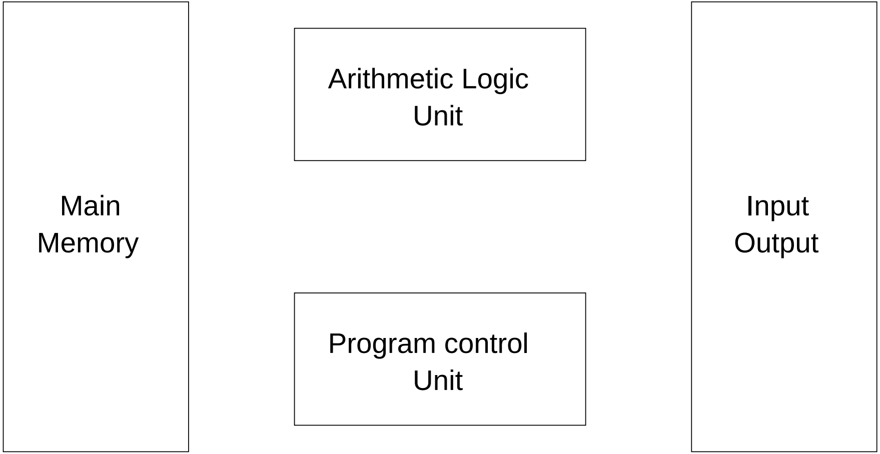


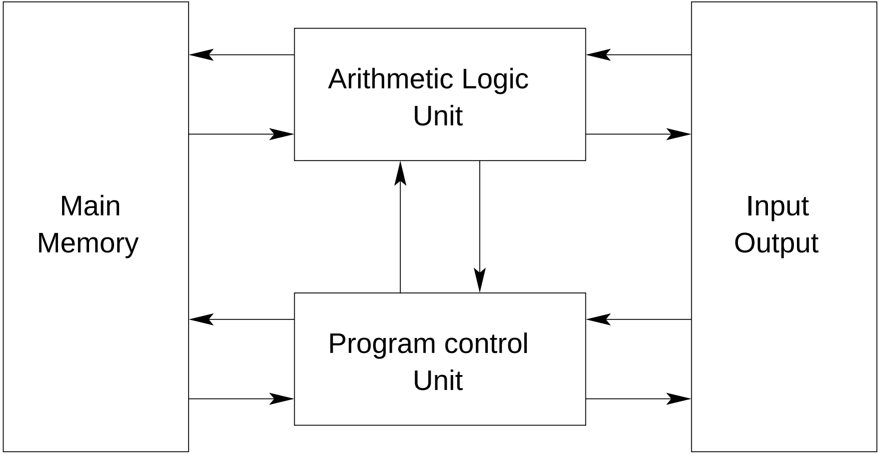
Main Memory

Arithmetic Logic Unit

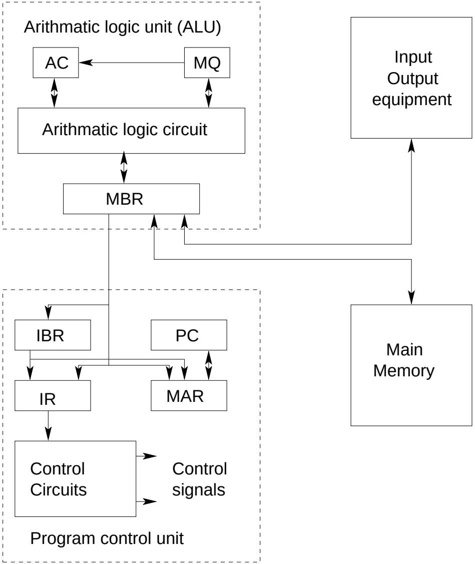
Program control Unit

Input Output

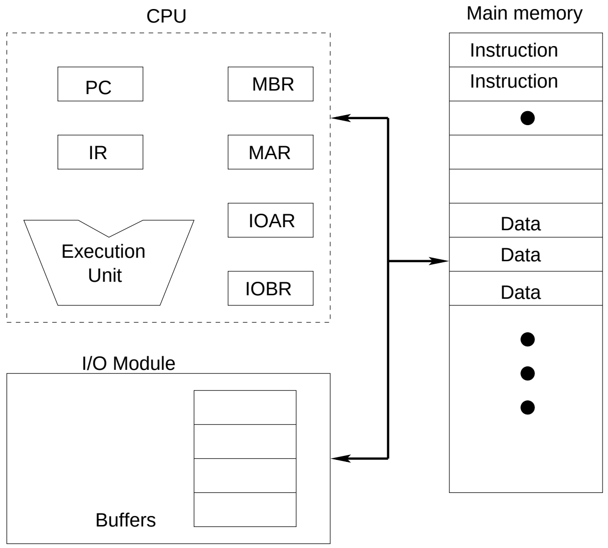
# IAS Computer



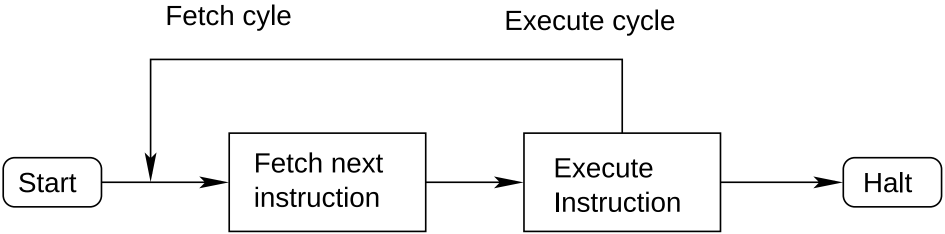
# Expanded structure of IAS Computer



# Top level view of computer



# Basic instruction cycle



# Levels of Program Code

```
g = h * i ;
k = j + i ;
g = h[1] ;
```

- High level language
  - Easy to code & debug
  - Close to problem domain
  - Provides productivity

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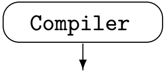

Compiler

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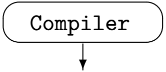

Compiler

```
MUL R0, R1, R2 ;
ADD R3, R4, R2
LDR R3, [R0,#4]
```

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- Assembly language
  - Textual representation of instructions

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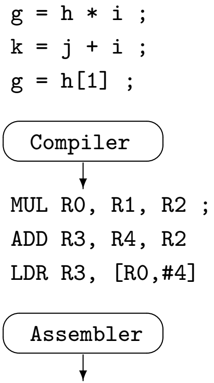

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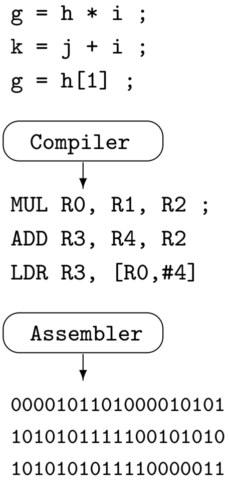

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MUL R0, R1, R2 ;
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```

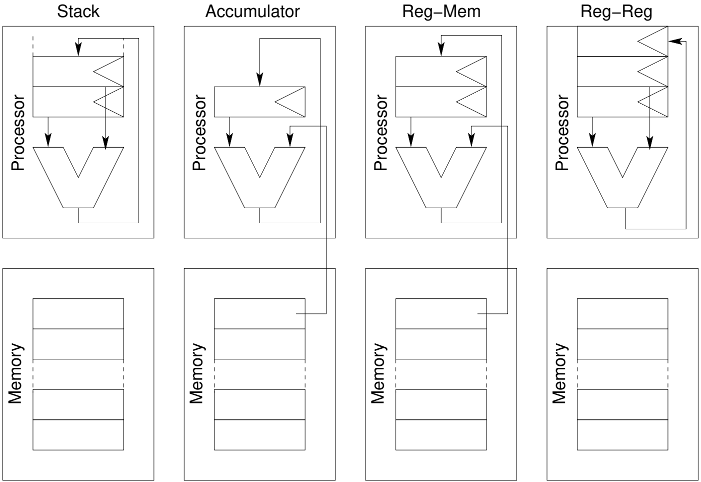
```
0000101101000010101
1010101111100101010
1010101011110000011
```

- **High level language**
  - **Easy to code & debug**
  - **Close to problem domain**
  - **Provides productivity**

- **Assembly language**
  - **Textual representation of instructions**

- **Hardware language**
  - **Binary data**
  - **Encoded instruction and data**

# Machine Model



```
push A
push B
add
pop C
```

```
load A
add B
store C
```

```
load r1, A
add  r3,r1, B
store r3, C
```

```
load r1,A
load r2,B
add r3,r2,r1
store r3,c
```

# Understanding Performance

- Algorithms
  - Determines number of operation executed
- Programing language, compiler, architecture
  - Determine number of machine instructions is executed per operation
- Processor and memory systems
  - Determines how fast instructions are executed
- I/O systems
  - Determines how fast I/O operations are performed

# Performance

- Response time
  - How long it takes to finish a task
- Throughput
  - Total workdone per unit time (eg. task/transaction/per hour)
- Dependency of response time and throughput
  - Replacing the processor with a faster version?
  - Adding more processors?

# Relative performance

- Performance is defined as 1/Execution time
- X is n times faster than Y
  - Performance$_X$/Performance$_Y$ = Execution time$_Y$/Execution time$_X$ = n
- Example: Time taken to run a program
  - 10ns in machine X and 15ns in machine Y
  - Execution time$_Y$/Execution time$_X$ = 15/10 = 1.5
  - So, X is 1.5 times faster than Y

# Measuring performance

- Elapsed time (Wall clock time)
  - Total time to complete a task including I/O, memory access, disk access, OS overhead, etc.
- CPU time
  - The time the CPU spends computing this task
  - Does not include I/O time, other jobs' share
  - Can be further subdivided – *user* CPU time and *system* CPU time
- Different programs are affected differently by CPU and system performance

# CPU clocking

- Operation is controlled by a constant rate clock
  - Clock period is duration of clock cycle. (eg. $300$ns = $300 \times 10^{-9}$s)
  - Clock frequency is cycles per second. (eg. $4$GHz = $4 \times 10^{9}$Hz)
  - Clock period = 1/Clock frequency

# CPU Time

- CPU time = CPU clock cycles × Clock period = $\dfrac{\text{CPU clock cycle}}{\text{Clock frequency}}$
- Performance can be improved by
  - Reducing number of clock cycle
  - Increasing clock frequency
  - Hardware designer must trade off clock frequency against cycle count

# Example

- Machine A: Run time 10s, Clock speed 2GHz
- Design a new machine (B say)
  - Run time is 6s
  - Faster clock require 1.2 times more clock cycles compared to A
- Clock frequency for machine B?

# Instruction count and CPI

- Clock cycles = Instruction count $\times$ Cycles per instruction
- CPU time = Instruction count $\times$ CPI $\times$ Clock period = $\dfrac{\text{Instruction count} \times \text{CPI}}{\text{Clock frequency}}$
- Instruction count for a program
  - Depends on ISA, compiler, program
- Average cycles per instruction
  - Determined by CPU hardware
  - Different instruction have different CPI
  - Average CPI is affected by instruction mix

# CPI example

- Machine A: Clock period - 250ps, CPI - 2.0
- Machine B: Clock period - 500ps, CPI - 1.2
- Same set of instructions
- Which is faster ?

# CPI in more detail

- Different instructions take different cycles
- Clock cycles = $\sum_{i=1}^{n} (\text{CPI}_i \times \text{Instruction count}_i)$
- Weighted average CPI = $\dfrac{\text{Clock cycle}}{\text{Instruction count}} = \sum_{i=1}^{n} \left(\text{CPI}_i \times \dfrac{\text{Instruction count}_i}{\text{Instruction count}}\right)$

# CPI example

| Instruction | A | B | C |
|---|---|---|---|
| CPI for instruction | 1 | 2 | 3 |
| IC in Sequence 1 | 2 | 1 | 2 |
| IC in Sequence 2 | 4 | 1 | 1 |

- **Which code sequence executes the most instructions?**
- **Compute average CPI for each sequence.**

# Performance summary

- CPU Time = $\frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{second}}{\text{Clock cycle}}$
- Performance depends on
  - Algorithm - Affects IC, possibly CPI
  - Programming language - Affects IC, CPI
  - Compiler - Affects IC, CPI
  - Instruction set architecture - Affects IC, CPI, Clock period

# Performance: Power

- Power $\propto$ Capacitive load × Voltage$^2$ × Frequency
- Suppose a new CPU has the following
  - 85% of capacitive load of old CPU
  - 15% reduction in voltage, 15% reduction in frequency
    - $\frac{P_{new}}{P_{old}} = \frac{0.85 \times C_{old} \times (V_{old} \times 0.85)^2 \times F_{old} \times 0.85}{C_{old} \times (V_{old})^2 \times F_{old}} = 0.85^4 = 0.52$
  - Constarints
    - Further reduction in voltage may not be possible
    - Dissipation of heat

# MIPS as performance metric

- MIPS: Millions of Instruction Per Second
  - Does not account for
    - Differences in ISAs in computers
    - Differences in complexity between instructions
- MIPS = $\dfrac{\text{Instruction count}}{\text{Execution time} \times 10^6} = \dfrac{\text{Instruction count}}{\frac{\text{Instruction count} \times \text{CPI}}{\text{Clock frequency}} \times 10^6} = \dfrac{\text{Clock frequency}}{\text{CPI} \times 10^6}$
- CPI varies between programs on a given CPU

# Multiprocessors

- Multicore multiprocessors
  - More than one processor per chip
- Requires explicit parallel programming
  - Instruction level parallelism
    - Hardware executes multiple instructions simultaneously
    - Hidden from programmer
  - Hard to do
    - Programming for performance
    - Load balancing
    - Optimizing communication and synchronization

# Conclusion

- Cost/performance is improving
  - Due to underlying technology development
- Hierarchical layer of abstraction
  - In both hardware and software
- Instruction set architecture
  - The Hardware/Software interface
- Execution time – measure of performance
- Power is a limiting factor
  - Use parallelism to improve performance