



Computer Architecture  
Lecture Week 3 (Part II)

# Performance Metrics

Artem Burmyakov

September 18, 2026



INNOPOLIS  
UNIVERSITY

# Sample Configurations

|                      | Config. 1 | Config. 2 | Config. 3 | Config. 4 |
|----------------------|-----------|-----------|-----------|-----------|
| Cores Number         | 1         | 2         | 4         | 4         |
| Cores Speed, GHz     | 3.5       | 2.4       | 3.5       | 2.8       |
| Memory Capacity, GB  | 32        | 16        | 32        | 32        |
| Memory Speed, GB/sec | 32        | 16        | 32        | 16        |

Performance Evaluation: **The “Best” Configuration?**

|                      | Config. 1 | Config. 2 | Config. 3 | Config. 4 |
|----------------------|-----------|-----------|-----------|-----------|
| Cores Number         | 1         | 2         | 4         | 4         |
| Cores Speed, GHz     | 3.5       | 2.4       | 3.5       | 2.8       |
| Memory Capacity, GB  | 32        | 16        | 32        | 32        |
| Memory Speed, GB/sec | 32        | 16        | 32        | 16        |

# Performance Evaluation: The “Best” Configuration?

|                      | Config. 1 | Config. 2 | Config. 3 | Config. 4 |
|----------------------|-----------|-----------|-----------|-----------|
| Cores Number         | 1         | 2         | 4         | 4         |
| Cores Speed, GHz     | 3.5       | 2.4       | 3.5       | 2.8       |
| Memory Capacity, GB  | 32        | 16        | 32        | 32        |
| Memory Speed, GB/sec | 32        | 16        | 32        | 16        |

# Performance Evaluation: The “Best” configuration in this case?

|                      | Config. 1 | Config. 2 | ... | Config. 4 |
|----------------------|-----------|-----------|-----|-----------|
| Cores Number         | 1         | 2         |     | 4         |
| Cores Speed, GHz     | 3.5       | 2.4       |     | 2.8       |
| Memory Capacity, GB  | 32        | 16        |     | 32        |
| Memory Speed, GB/sec | 32        | 16        |     | 16        |

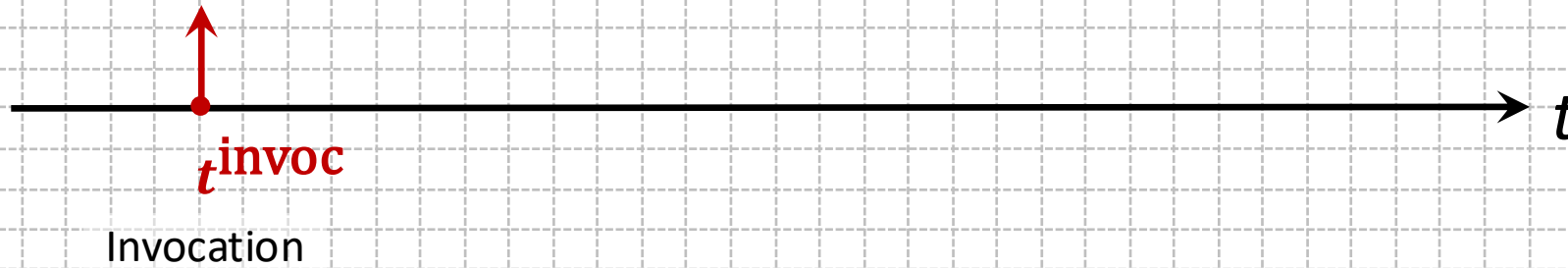
## Performance Evaluation: The “Best” configuration in this case?

|                      | Config. 1 | Config. 2 | ... | Config. 4 |
|----------------------|-----------|-----------|-----|-----------|
| Cores Number         | 1         | 2         |     | 4         |
| Cores Speed, GHz     | 3.5       | 2.4       |     | 2.8       |
| Memory Capacity, GB  | 32        | 16        |     | 32        |
| Memory Speed, GB/sec | 32        | 16        |     | 16        |

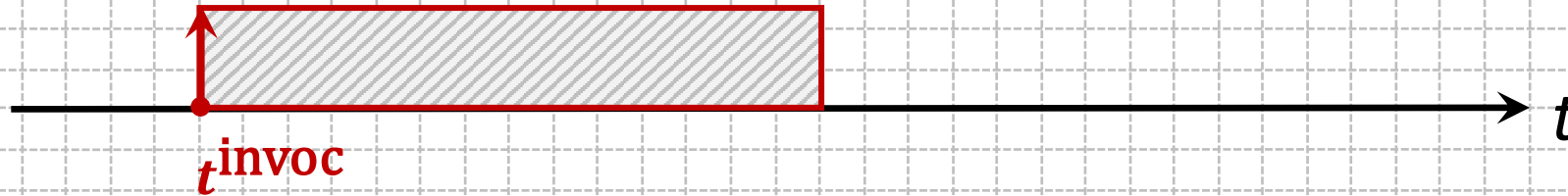
**Benchmark program** - a specialized tool used to test and measure the performance, speed, and efficiency of computer hardware or software

## Program Execution Phases

## Program Execution Phases

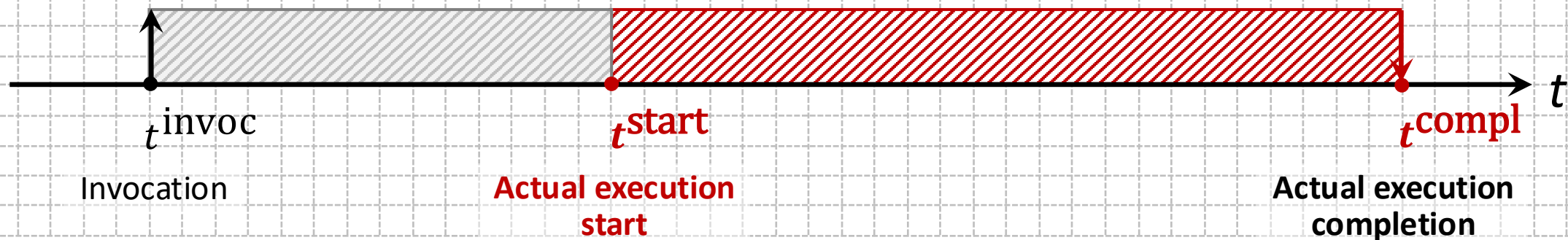


## Program Execution Phases

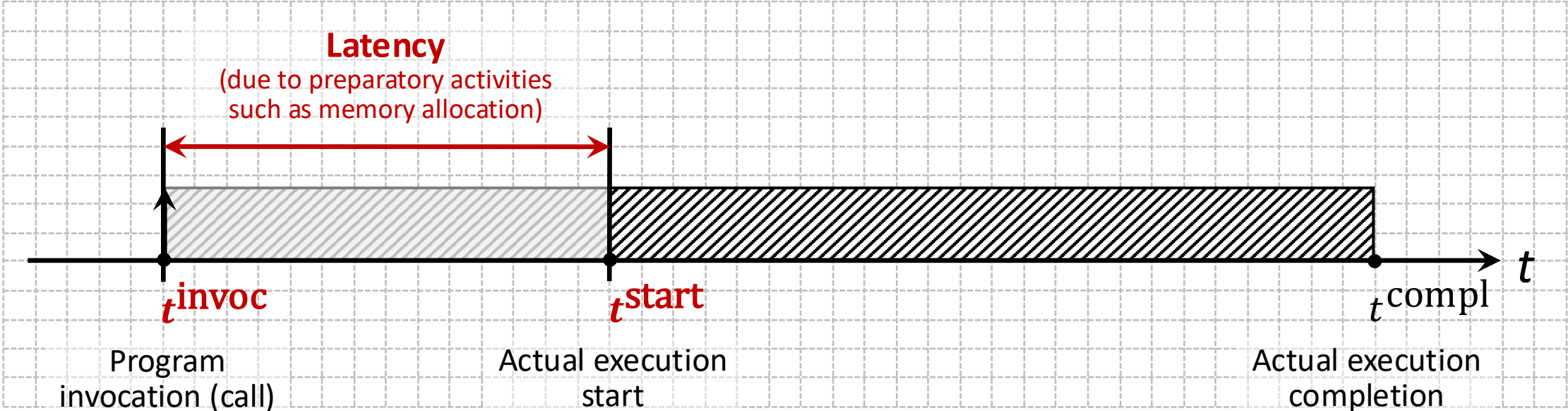


Invocation

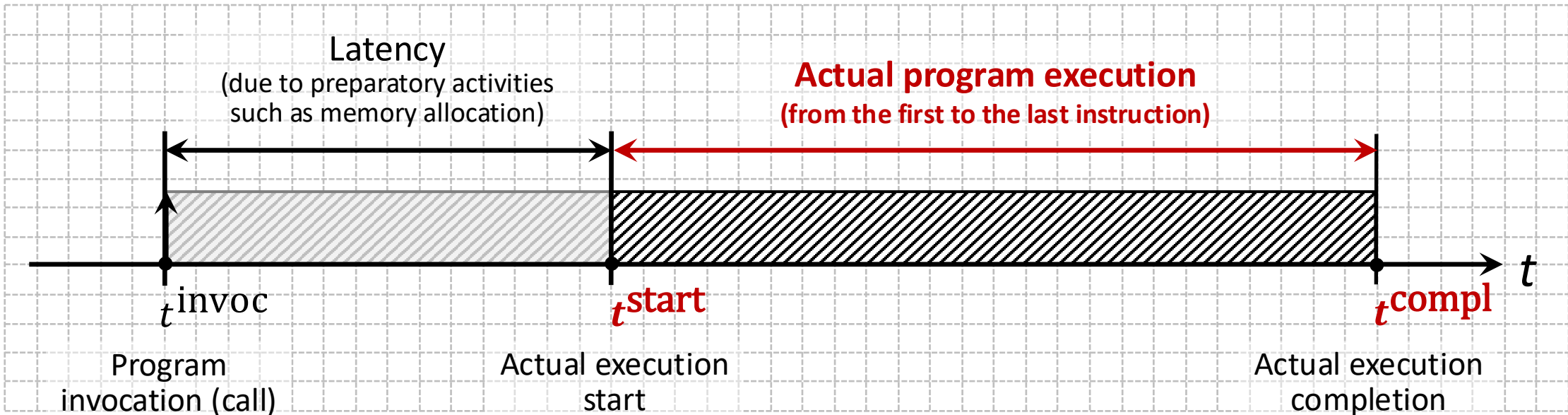
## Program Execution Phases



| Performance Metric |                | Meaning                                                                      |
|--------------------|----------------|------------------------------------------------------------------------------|
| Program            | <b>Latency</b> | Delay between a program invocation (call) and an actual execution start time |

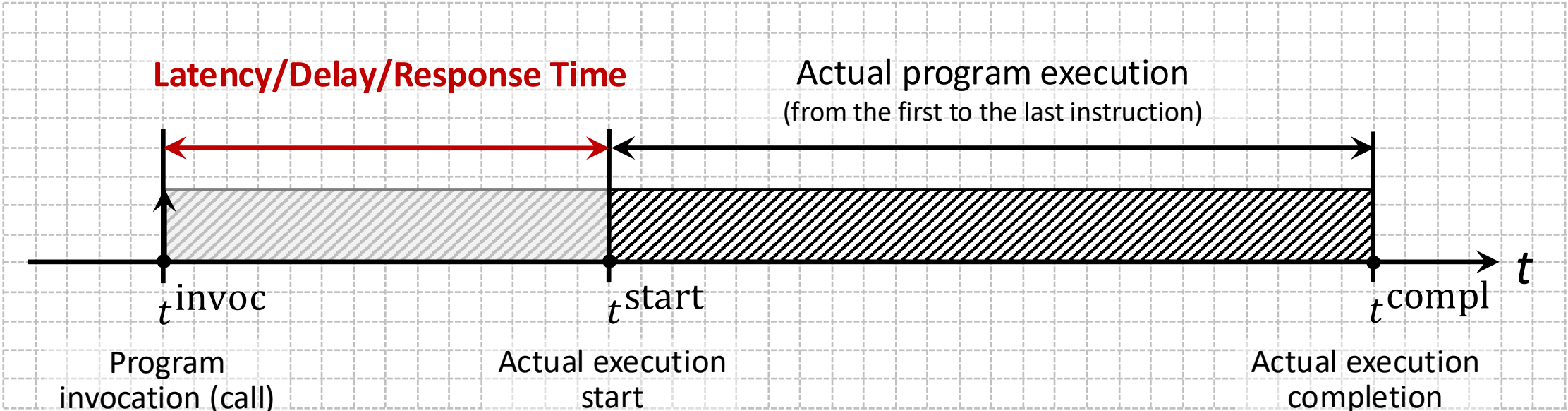


| Performance Metric |                | Meaning                                                                      |
|--------------------|----------------|------------------------------------------------------------------------------|
| Program            | <b>Latency</b> | Delay between a program invocation (call) and an actual execution start time |

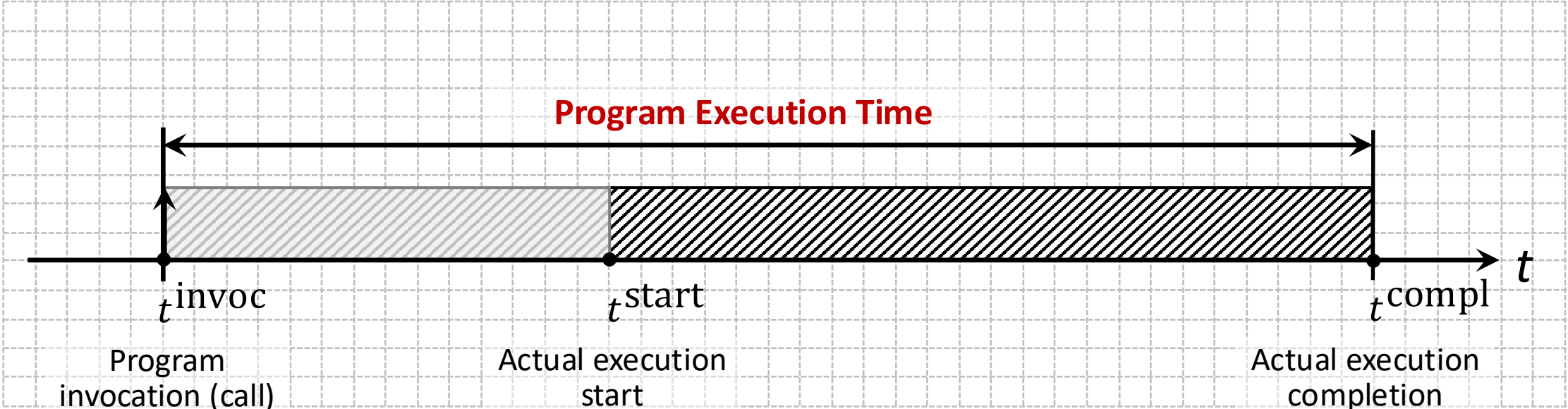


| Performance Metric |               | Meaning                                                                      |
|--------------------|---------------|------------------------------------------------------------------------------|
| Program            | Latency       | Delay between a program invocation (call) and an actual execution start time |
|                    | Delay         |                                                                              |
|                    | Response Time |                                                                              |

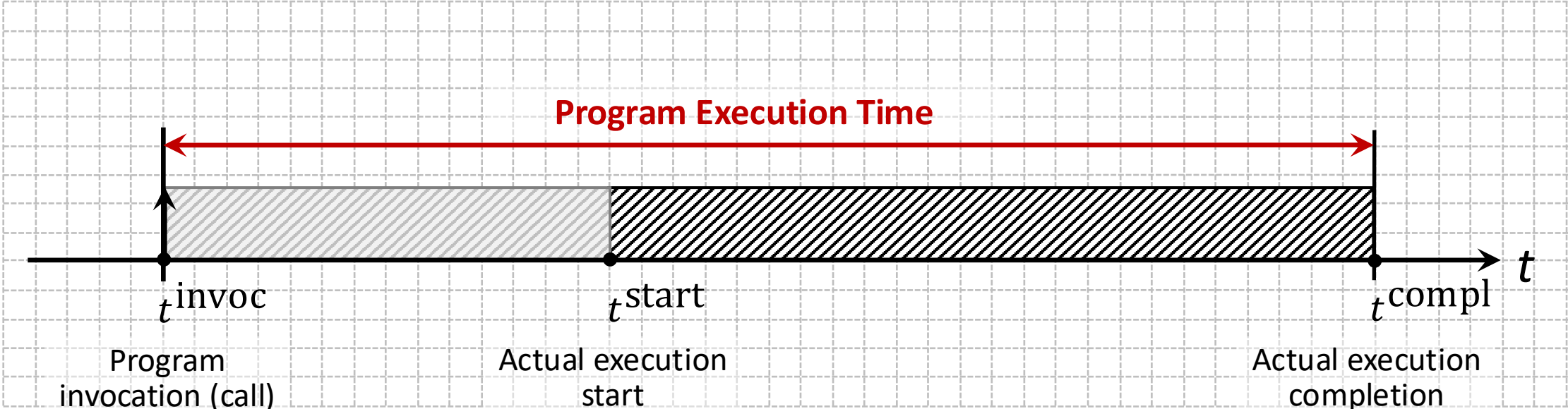
(Synonyms)



| Performance Metric |                       | Meaning                                                                      |
|--------------------|-----------------------|------------------------------------------------------------------------------|
| Program            | Latency               | Delay between a program invocation (call) and an actual execution start time |
|                    | Delay                 |                                                                              |
|                    | Response Time         |                                                                              |
|                    | <b>Execution Time</b> | <b>Time between a program invocation and its completion</b>                  |



| Performance Metric |                       | Meaning                                                                      |
|--------------------|-----------------------|------------------------------------------------------------------------------|
| Program            | Latency               | Delay between a program invocation (call) and an actual execution start time |
|                    | Delay                 |                                                                              |
|                    | Response Time         |                                                                              |
|                    | <b>Execution Time</b> | Time between a program invocation and its completion                         |



| Performance Metric       |                | Meaning                                                                      |
|--------------------------|----------------|------------------------------------------------------------------------------|
| Program                  | Latency        | Delay between a program invocation (call) and an actual execution start time |
|                          | Delay          |                                                                              |
|                          | Response Time  |                                                                              |
|                          | Execution Time | Time between a program invocation and its completion                         |
| <b>Hardware Platform</b> |                |                                                                              |

| Performance Metric |                  | Meaning                                                                        |
|--------------------|------------------|--------------------------------------------------------------------------------|
| Program            | Latency          | Delay between a program invocation (call) and an actual execution start time   |
|                    | Delay            |                                                                                |
|                    | Response Time    |                                                                                |
|                    | Execution Time   | Time between a program invocation and its completion                           |
| Hardware Platform  | <b>Bandwidth</b> | Theoretical bound on the number of jobs (instructions) to execute concurrently |

| Performance Metric |                  | Meaning                                                                        |
|--------------------|------------------|--------------------------------------------------------------------------------|
| Program            | Latency          | Delay between a program invocation (call) and an actual execution start time   |
|                    | Delay            |                                                                                |
|                    | Response Time    |                                                                                |
|                    | Execution Time   | Time between a program invocation and its completion                           |
| Hardware Platform  | <b>Bandwidth</b> | Theoretical bound on the number of jobs (instructions) to execute concurrently |

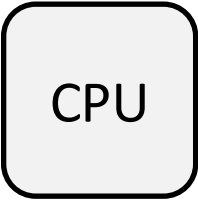
Uniprocessor with bandwidth 1:

CPU

**Not more than 1 job  
to execute at a time**

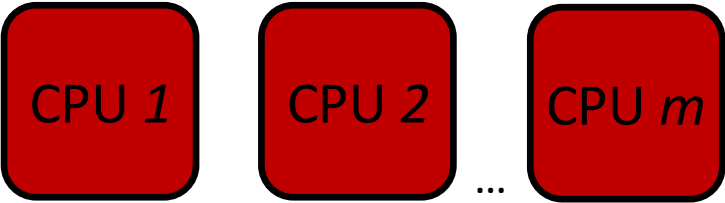
| Performance Metric |                  | Meaning                                                                        |
|--------------------|------------------|--------------------------------------------------------------------------------|
| Program            | Latency          | Delay between a program invocation (call) and an actual execution start time   |
|                    | Delay            |                                                                                |
|                    | Response Time    |                                                                                |
|                    | Execution Time   | Time between a program invocation and its completion                           |
| Hardware Platform  | <b>Bandwidth</b> | Theoretical bound on the number of jobs (instructions) to execute concurrently |

### Uniprocessor



Not more than 1 job at a time  
(bandwidth is 1 job)

### Multiprocessor with bandwidth $m$ :



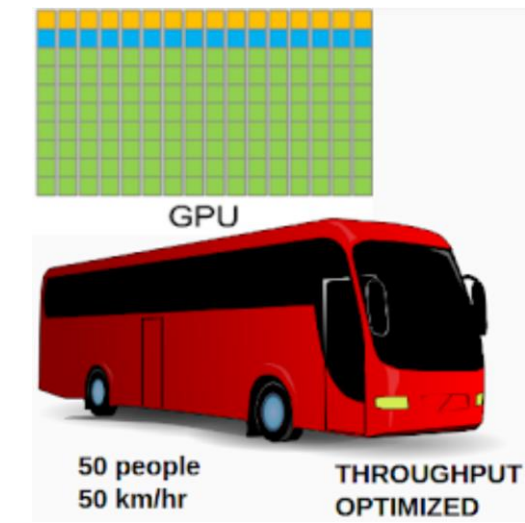
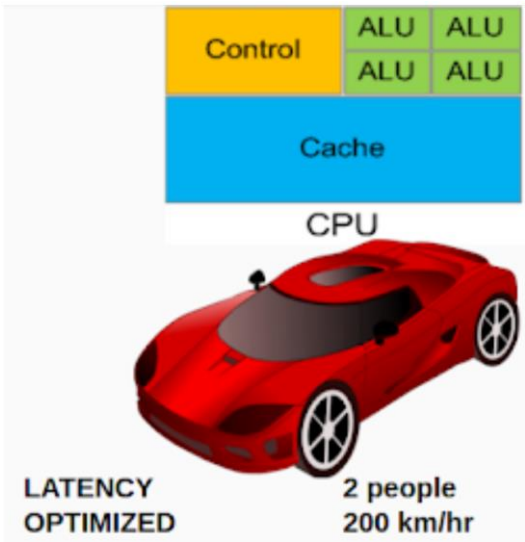
Not more than  $m$  jobs to execute concurrently

| Performance Metric |                   | Meaning                                                                            |
|--------------------|-------------------|------------------------------------------------------------------------------------|
| Program            | Latency           | Delay between a program invocation (call) and an actual execution start time       |
|                    | Delay             |                                                                                    |
|                    | Response Time     |                                                                                    |
|                    | Execution Time    | Time between a program invocation and its completion                               |
| Hardware Platform  | Bandwidth         | Theoretical bound on the number of jobs (instructions) to execute concurrently     |
|                    | <b>Throughput</b> | <b>Average number of concurrently executing jobs (instructions) over some time</b> |

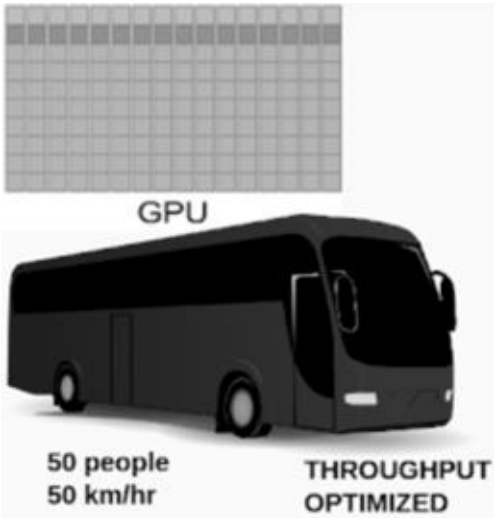
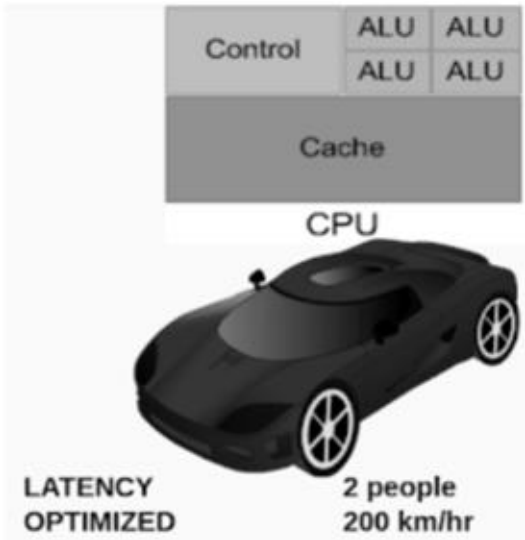
| Performance Metric |                    | Meaning                                                                        |
|--------------------|--------------------|--------------------------------------------------------------------------------|
| Program            | Latency            | Delay between a program invocation (call) and an actual execution start time   |
|                    | Delay              |                                                                                |
|                    | Response Time      |                                                                                |
|                    | Execution Time     | Time between a program invocation and its completion                           |
| Hardware Platform  | Bandwidth          | Theoretical bound on the number of jobs (instructions) to execute concurrently |
|                    | Throughput         | Average number of concurrently executing jobs (instructions) over some time    |
|                    | <b>Utilization</b> | <b>Time percentage of an effective component use</b>                           |

| Performance Metric |                | Meaning                                                                             |
|--------------------|----------------|-------------------------------------------------------------------------------------|
| Program            | Latency        | Delay between a program invocation (call) and an actual execution start time        |
|                    | Delay          |                                                                                     |
|                    | Response Time  |                                                                                     |
|                    | Execution Time | Time between a program invocation and its completion                                |
| Hardware Platform  | Bandwidth      | Theoretical bound on the number of jobs (instructions) to execute concurrently      |
|                    | Throughput     | Average number of concurrently executing jobs (instructions) over some time         |
|                    | Utilization    | Time percentage of an effective component use (e.g. <b>CPU utilization is 57%</b> ) |

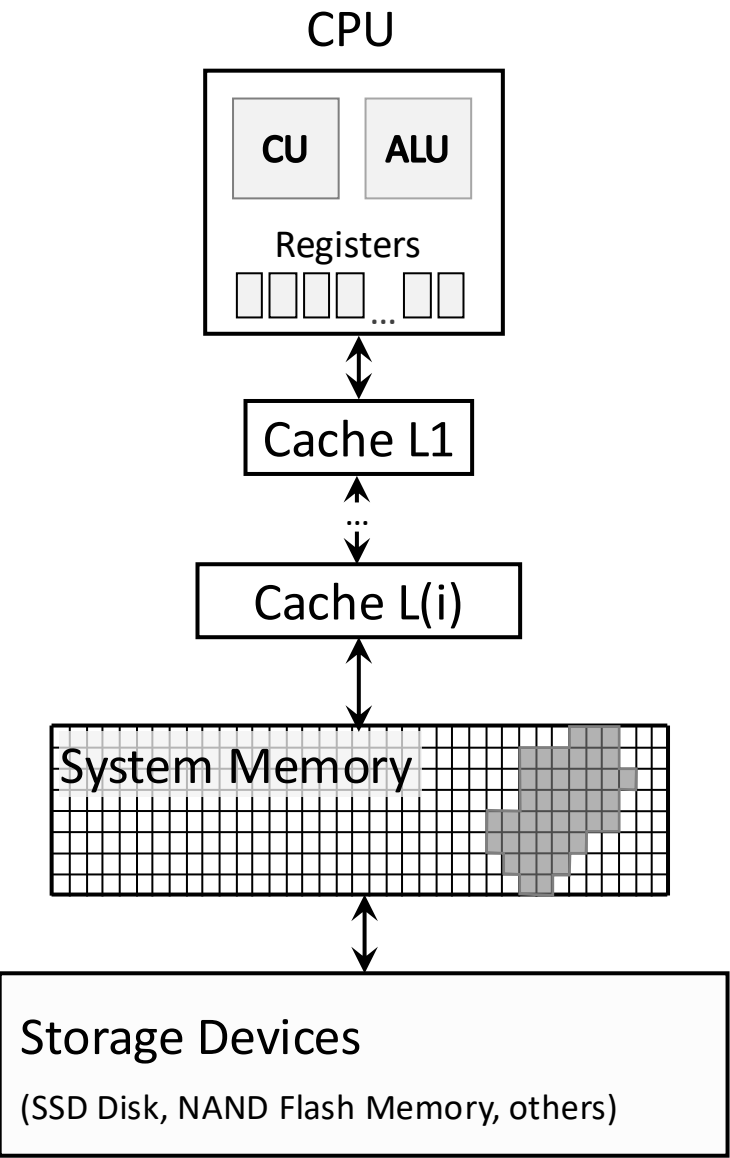
| Performance Metric |                      | Meaning                                                                        |
|--------------------|----------------------|--------------------------------------------------------------------------------|
| Program            | <b>Latency</b>       | Delay between a program invocation (call) and an actual execution start time   |
|                    | <b>Delay</b>         |                                                                                |
|                    | <b>Response Time</b> |                                                                                |
|                    | Execution Time       | Time between a program invocation and its completion                           |
| Hardware Platform  | Bandwidth            | Theoretical bound on the number of jobs (instructions) to execute concurrently |
|                    | <b>Throughput</b>    | Average number of concurrently executing jobs (instructions) over some time    |
|                    | Utilization          | Time percentage of an effective component use (e.g. CPU utilization is 57%)    |



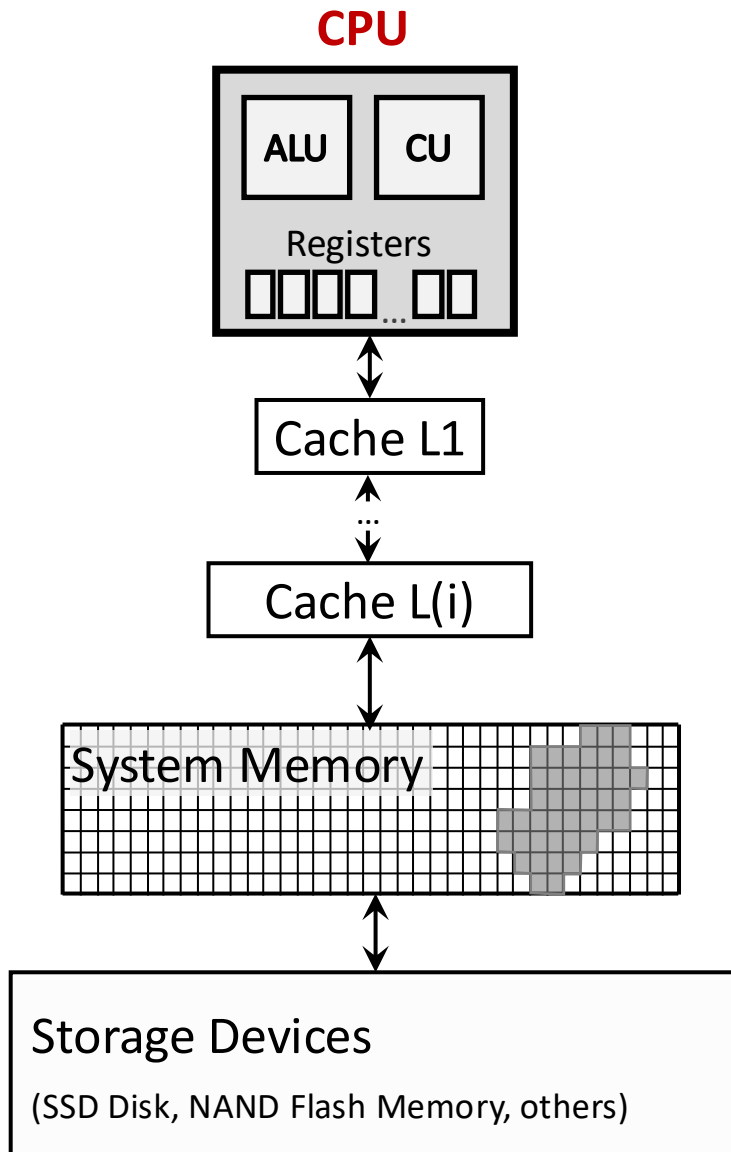
| Performance Metric |                       | Meaning                                                                        |
|--------------------|-----------------------|--------------------------------------------------------------------------------|
| Program            | <b>Latency</b>        | Delay between a program invocation (call) and an actual execution start time   |
|                    | <b>Delay</b>          |                                                                                |
|                    | <b>Response Time</b>  |                                                                                |
|                    | <b>Execution Time</b> | Time between a program invocation and its completion                           |
| Hardware Platform  | <b>Bandwidth</b>      | Theoretical bound on the number of jobs (instructions) to execute concurrently |
|                    | <b>Throughput</b>     | Average number of concurrently executing jobs (instructions) over some time    |
|                    | <b>Utilization</b>    | Time percentage of an effective component use (e.g. CPU utilization is 57%)    |



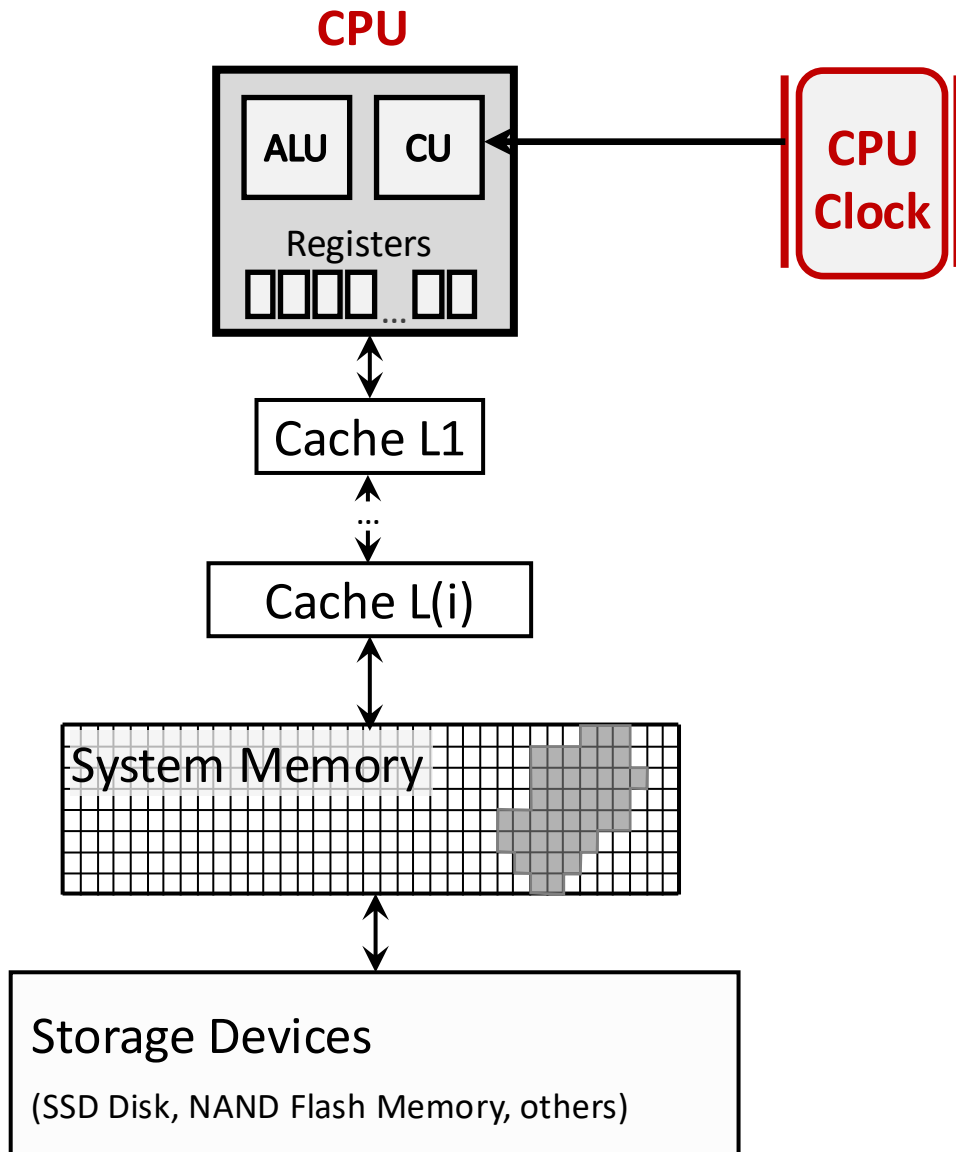
# Recap: Computer Layout



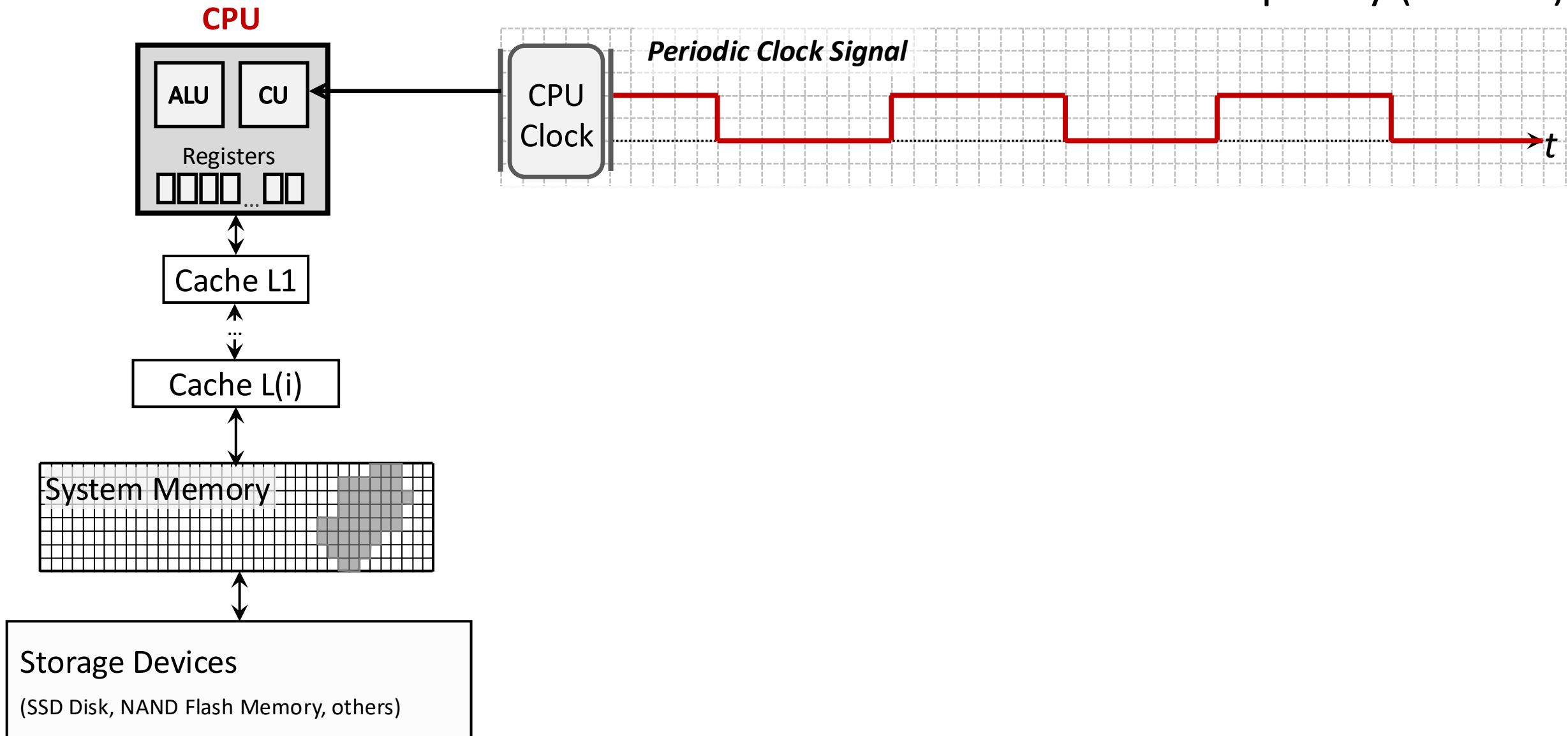
# Processor Performance Characteristics



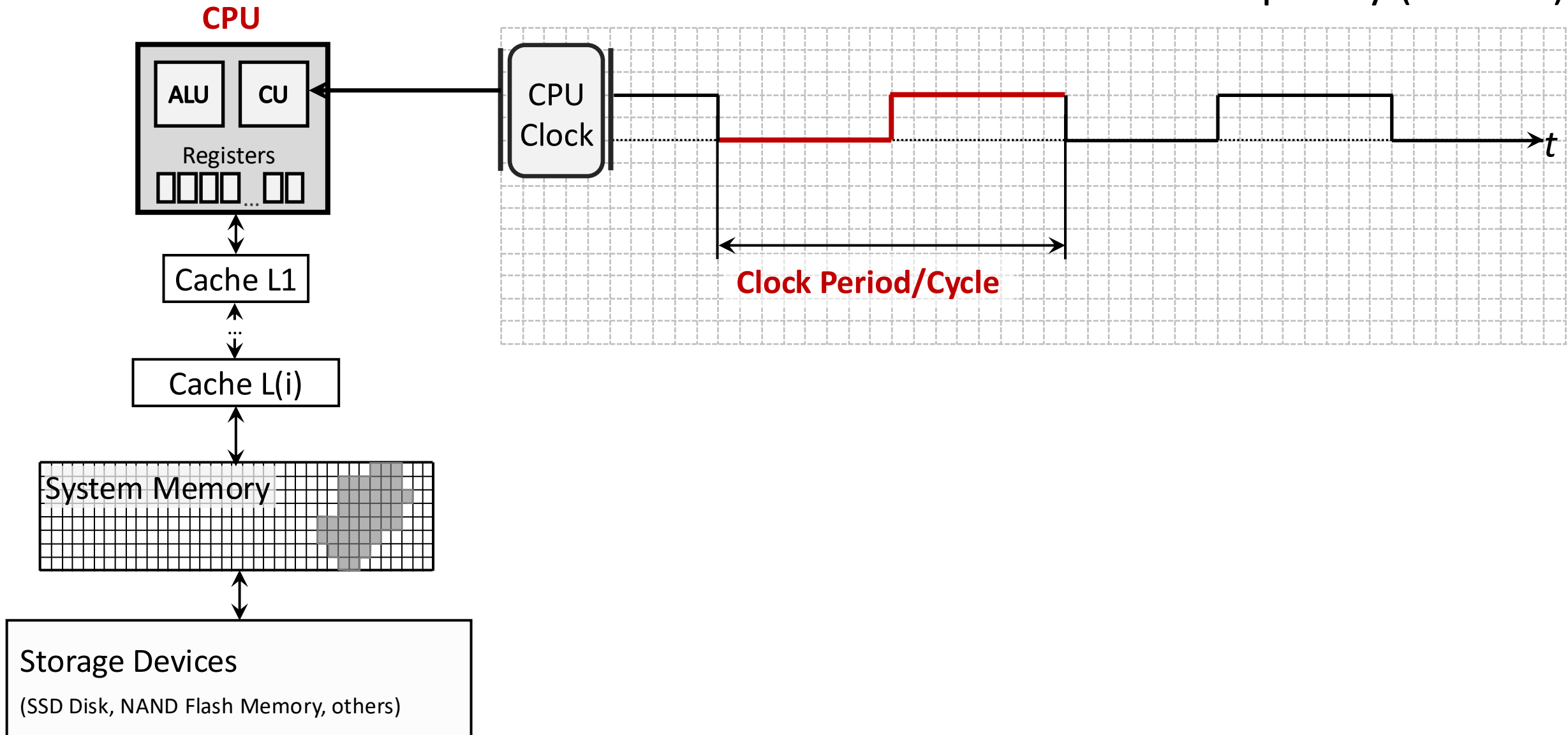
# Processor Performance: CPU Frequency (or Rate)



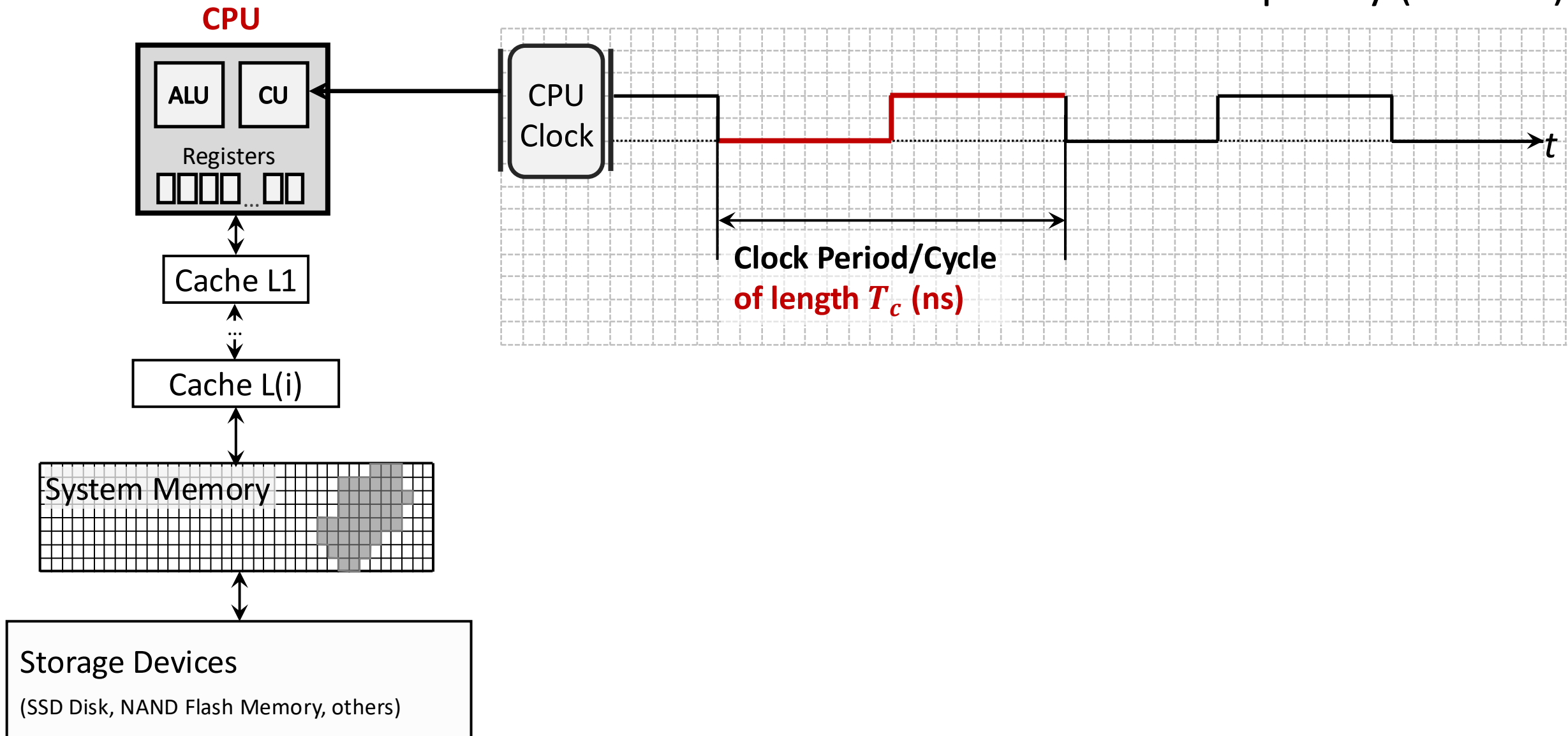
# Processor Performance: CPU Frequency (or Rate)



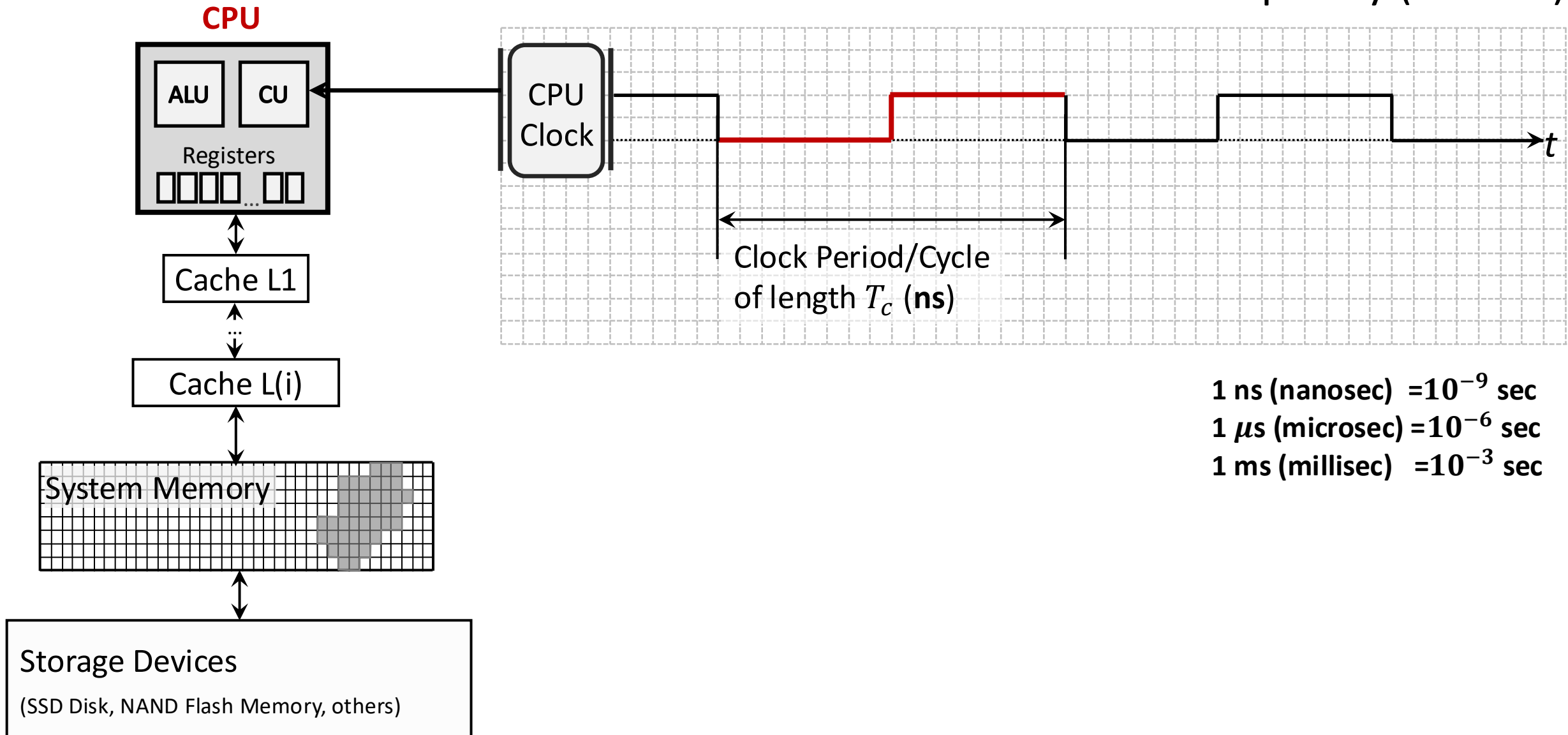
# Processor Performance: CPU Frequency (or Rate)



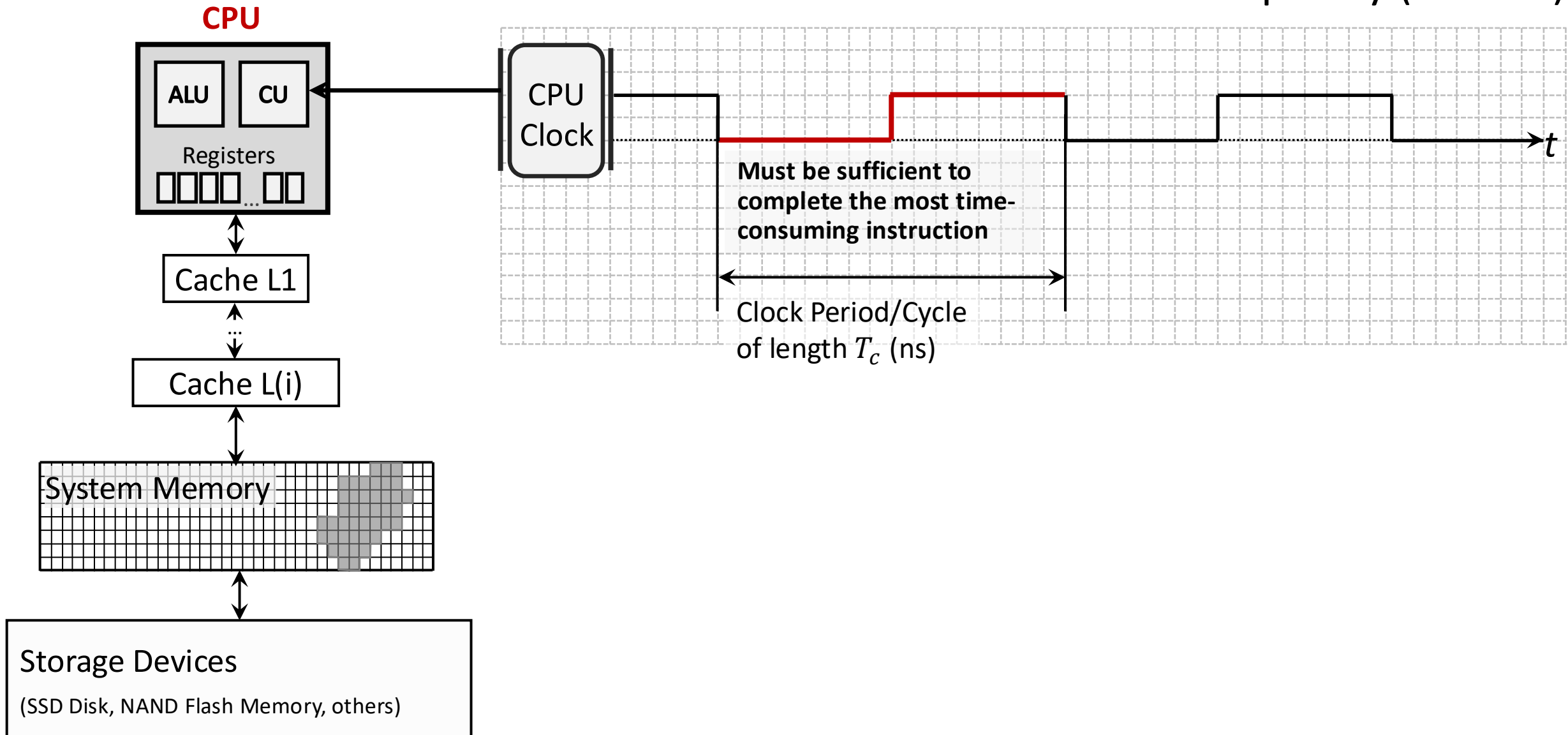
# Processor Performance: CPU Frequency (or Rate)



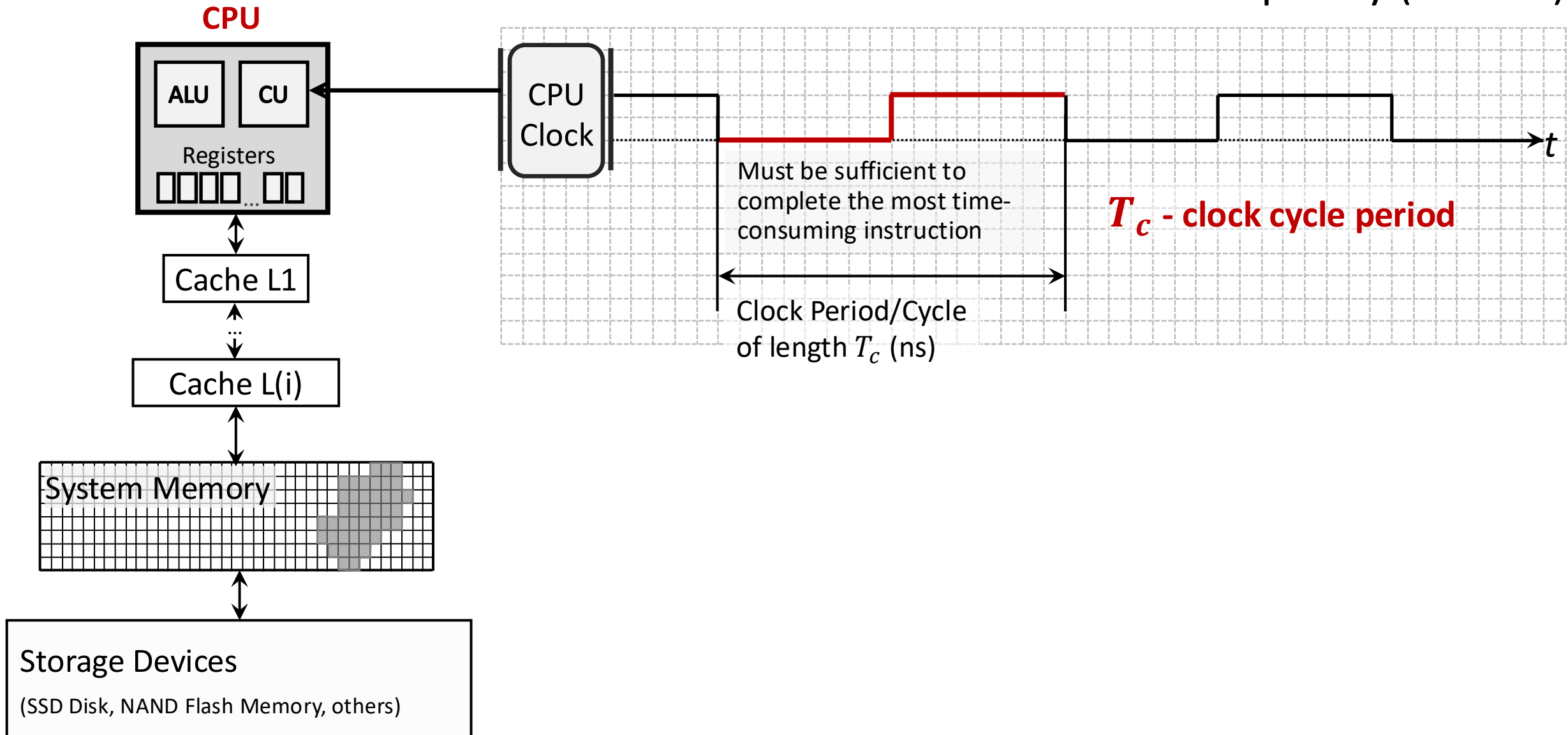
# Processor Performance: CPU Frequency (or Rate)



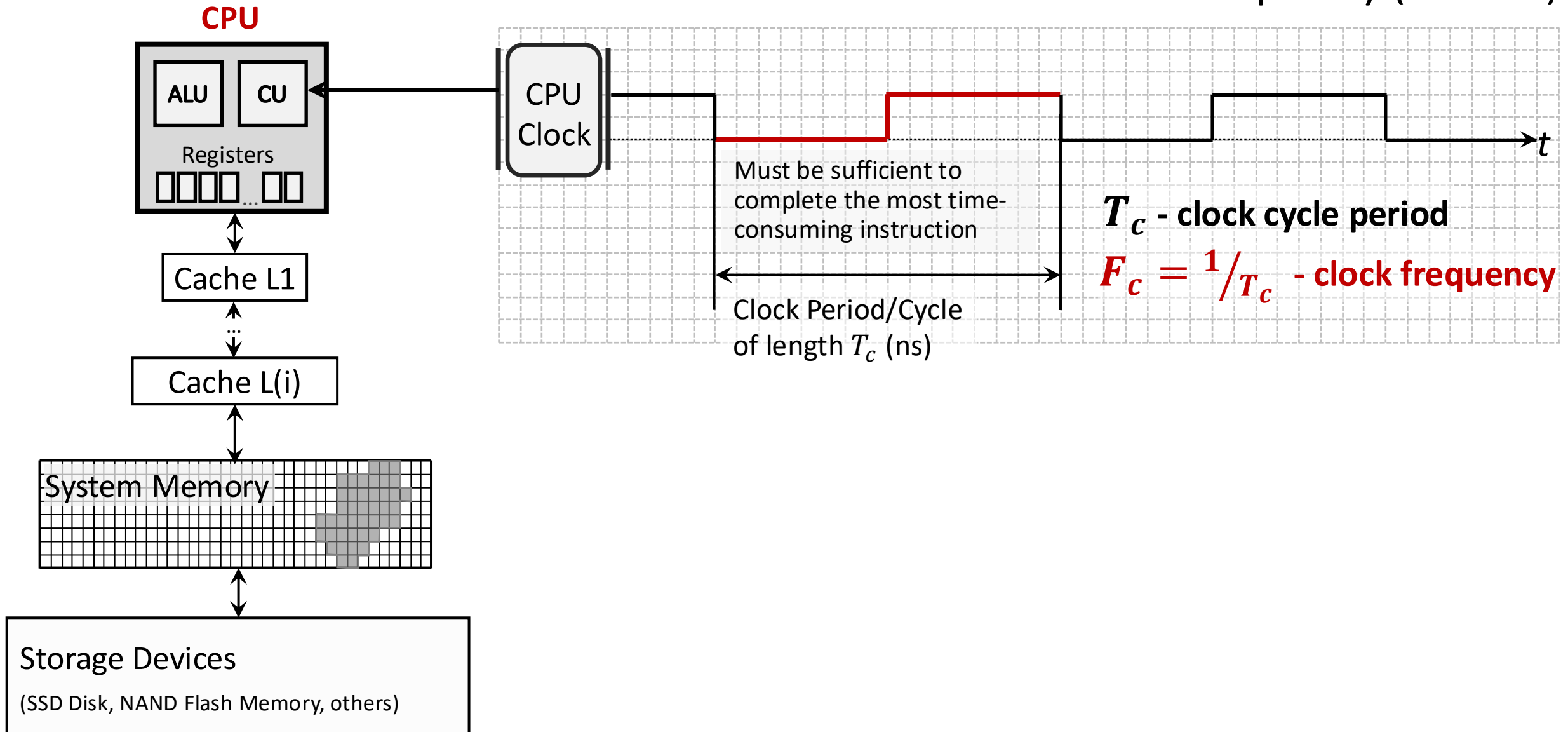
# Processor Performance: CPU Frequency (or Rate)



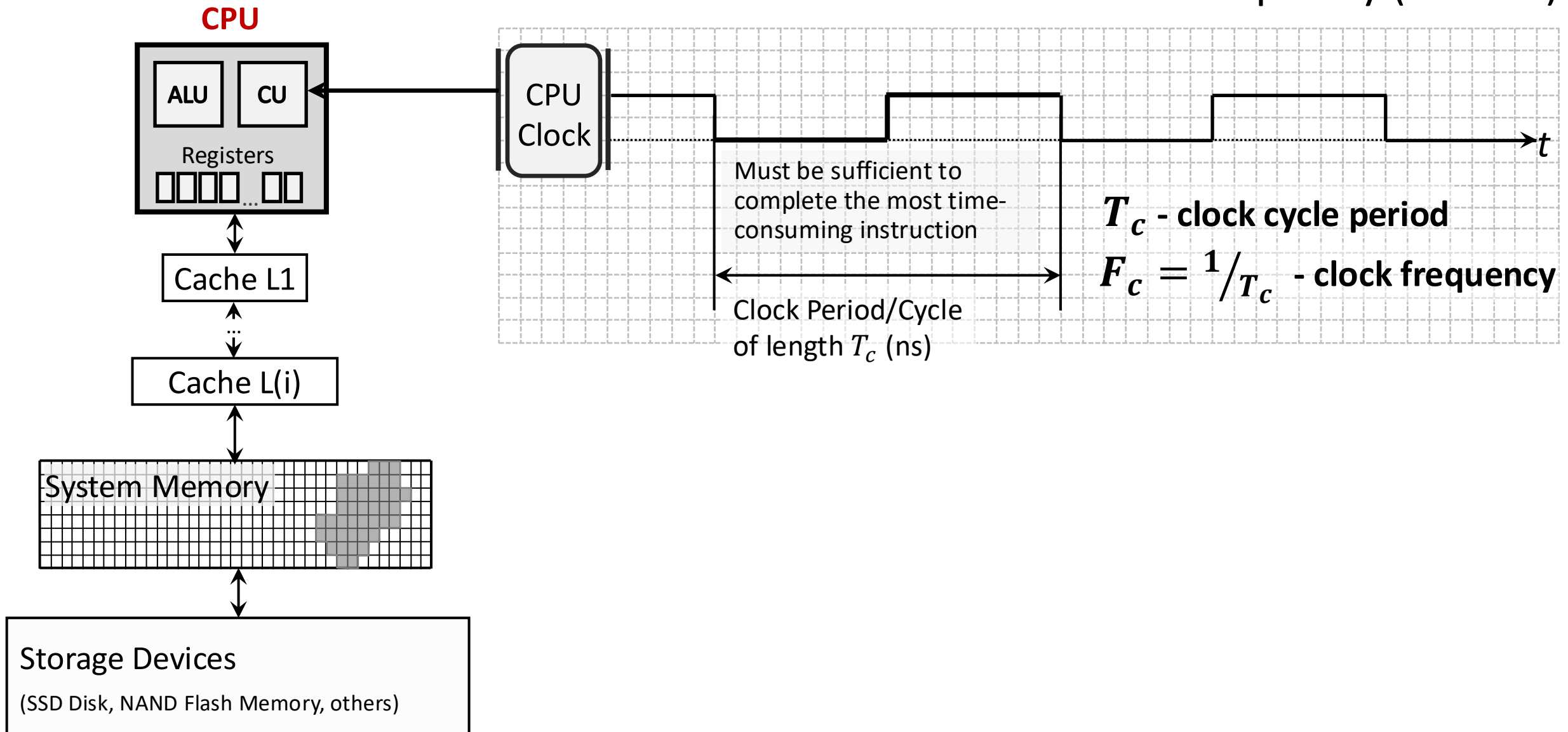
# Processor Performance: CPU Frequency (or Rate)



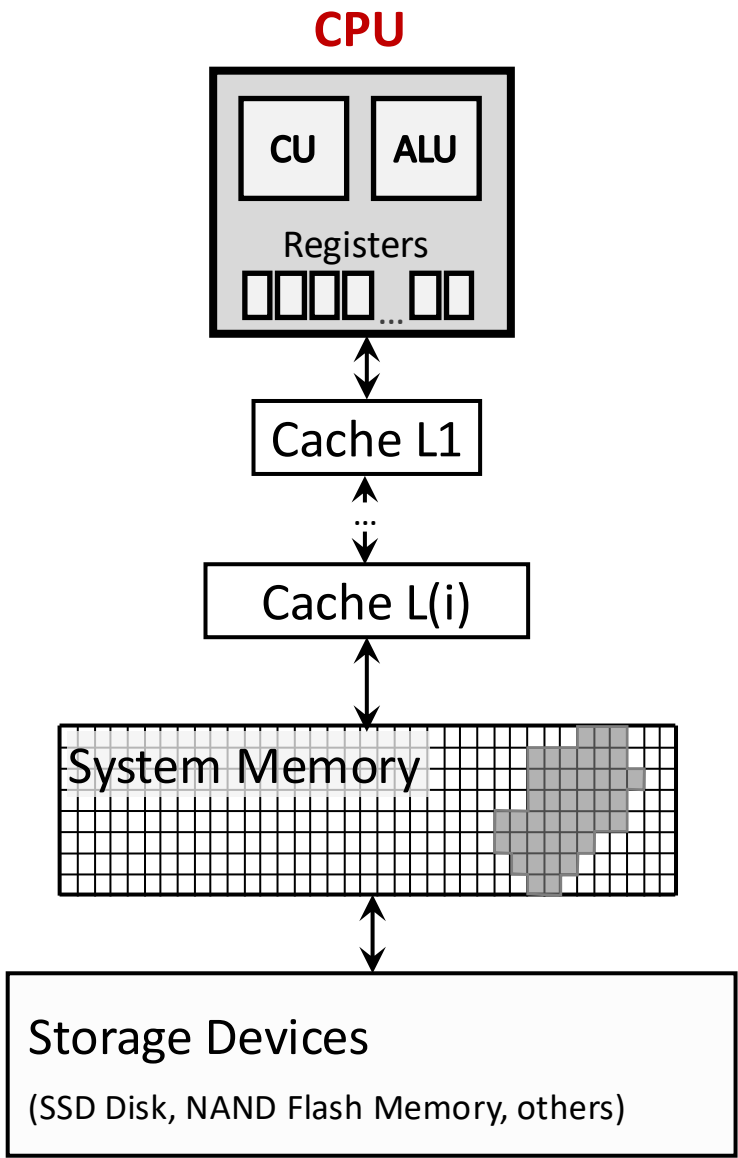
# Processor Performance: CPU Frequency (or Rate)



# Processor Performance: CPU Frequency (or Rate)

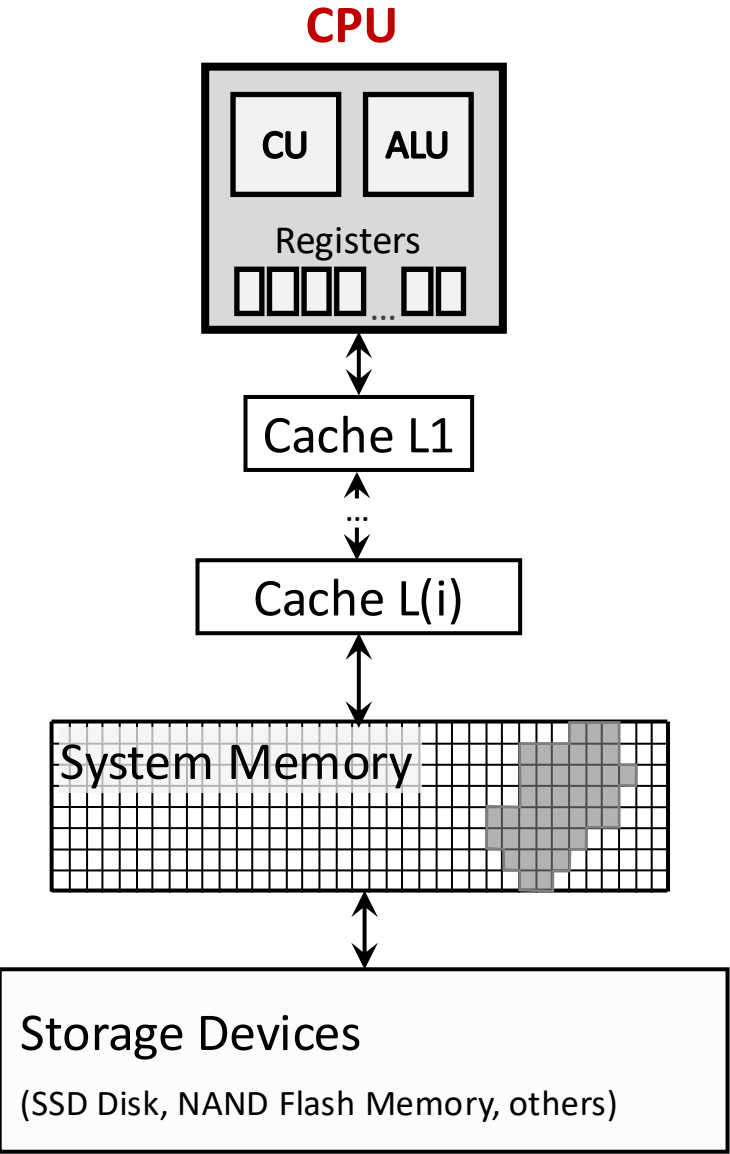


# Average Performance Characteristics: Laptop/Desktop



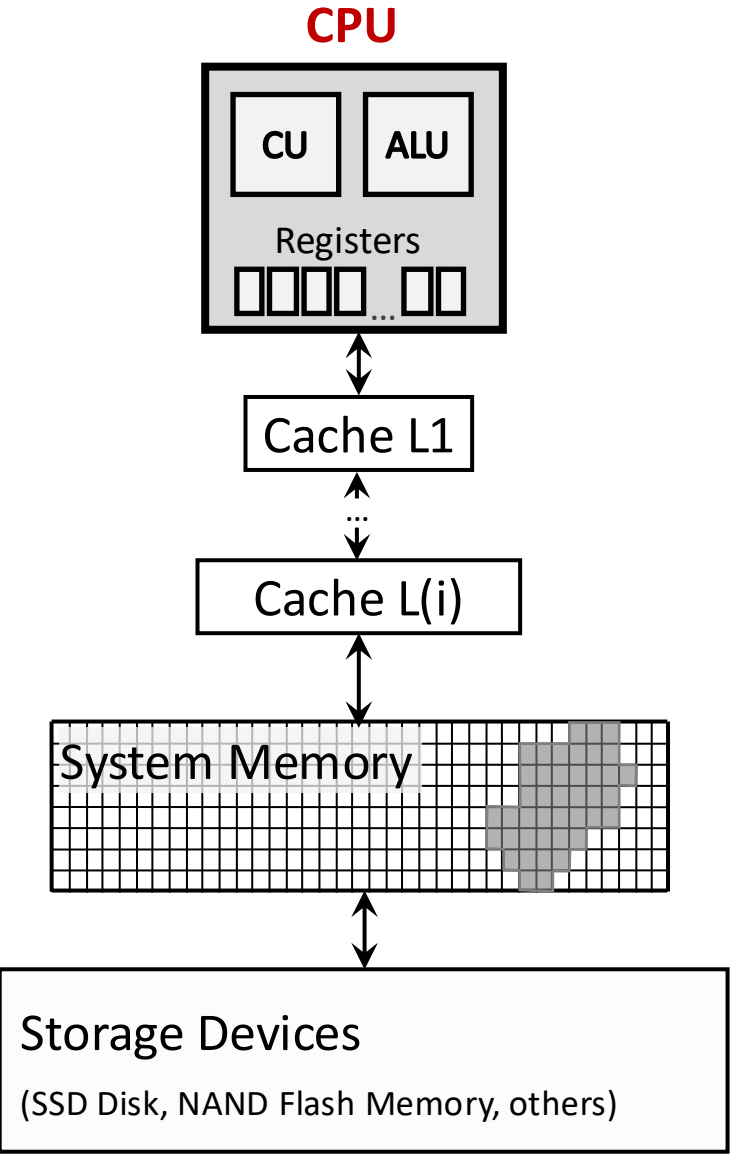
| Device     | Operation Speed | Storage Capacity |
|------------|-----------------|------------------|
| <b>CPU</b> |                 |                  |

# Average Characteristics: Laptop/Desktop



| Device                           | Operation Speed | Storage Capacity |
|----------------------------------|-----------------|------------------|
| <b>CPU</b><br><b>(4-6 cores)</b> |                 |                  |

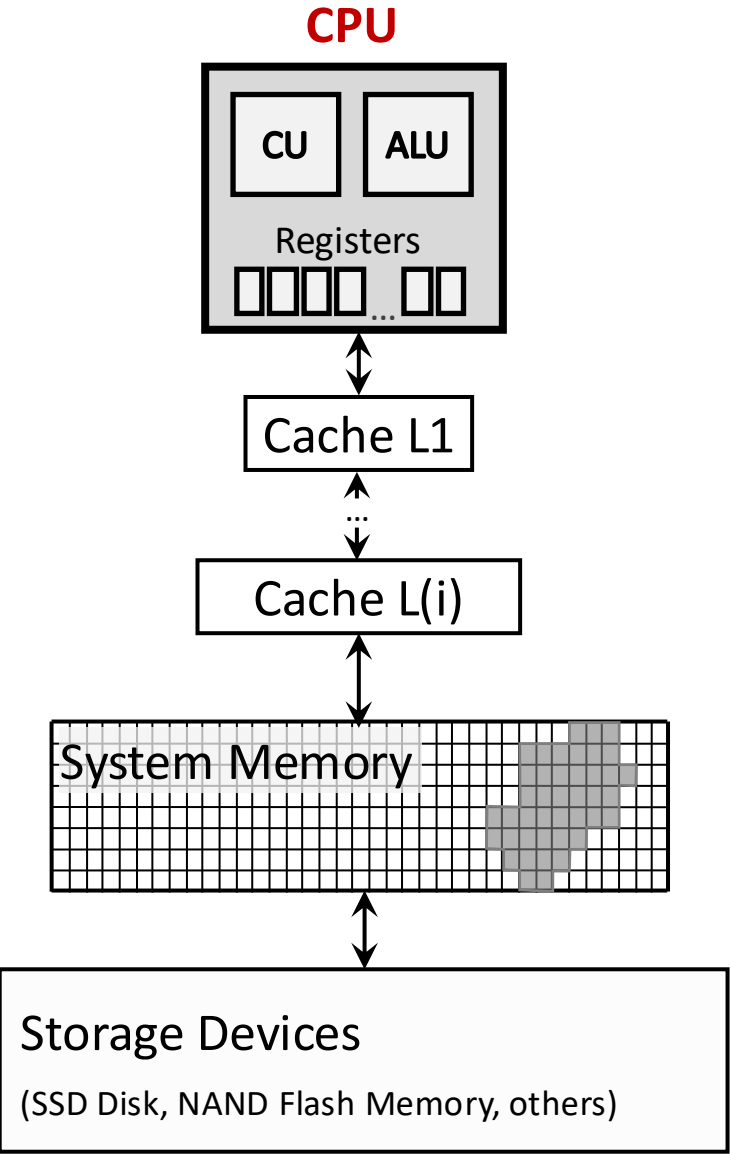
# Average Characteristics: Laptop/Desktop



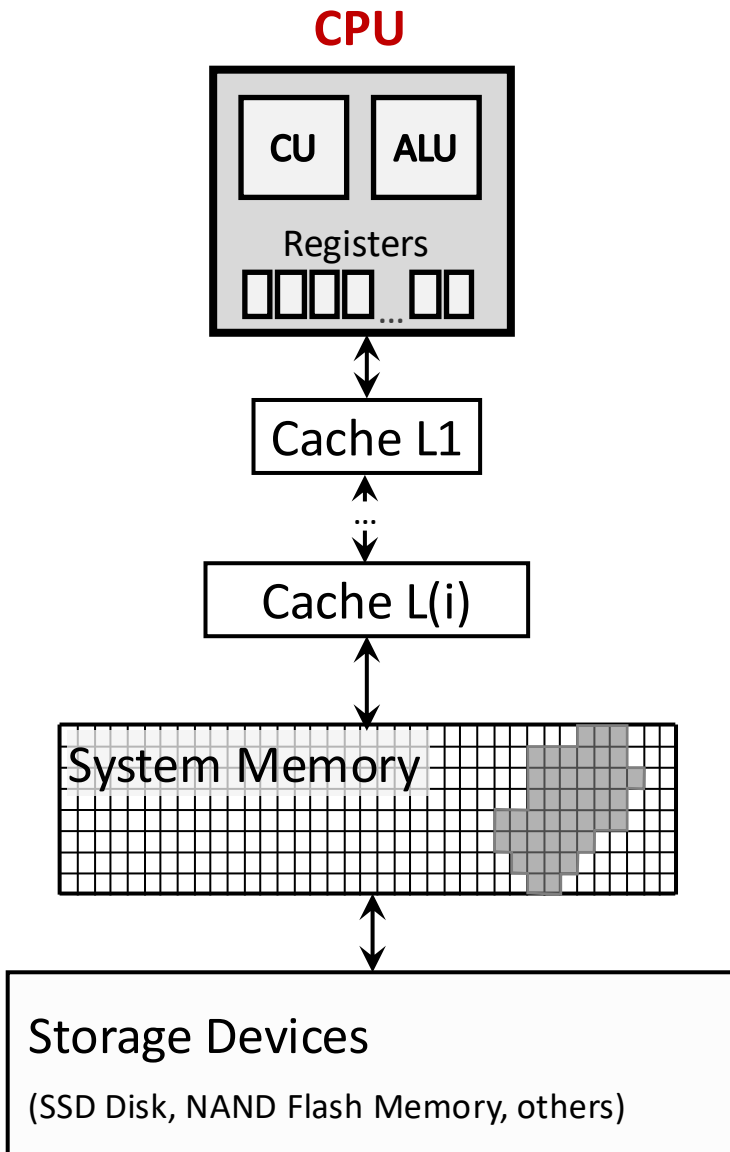
| Device             | Operation Speed | Storage Capacity |
|--------------------|-----------------|------------------|
| CPU<br>(4-6 cores) | 2.0-3.5 GHz     |                  |

# Average Characteristics: Laptop/Desktop

| Device             | Operation Speed                                  | Storage Capacity |
|--------------------|--------------------------------------------------|------------------|
| CPU<br>(4-6 cores) | <b>2.0-3.5 GHz</b><br>Up to 5.0 GHz (Turbo mode) |                  |

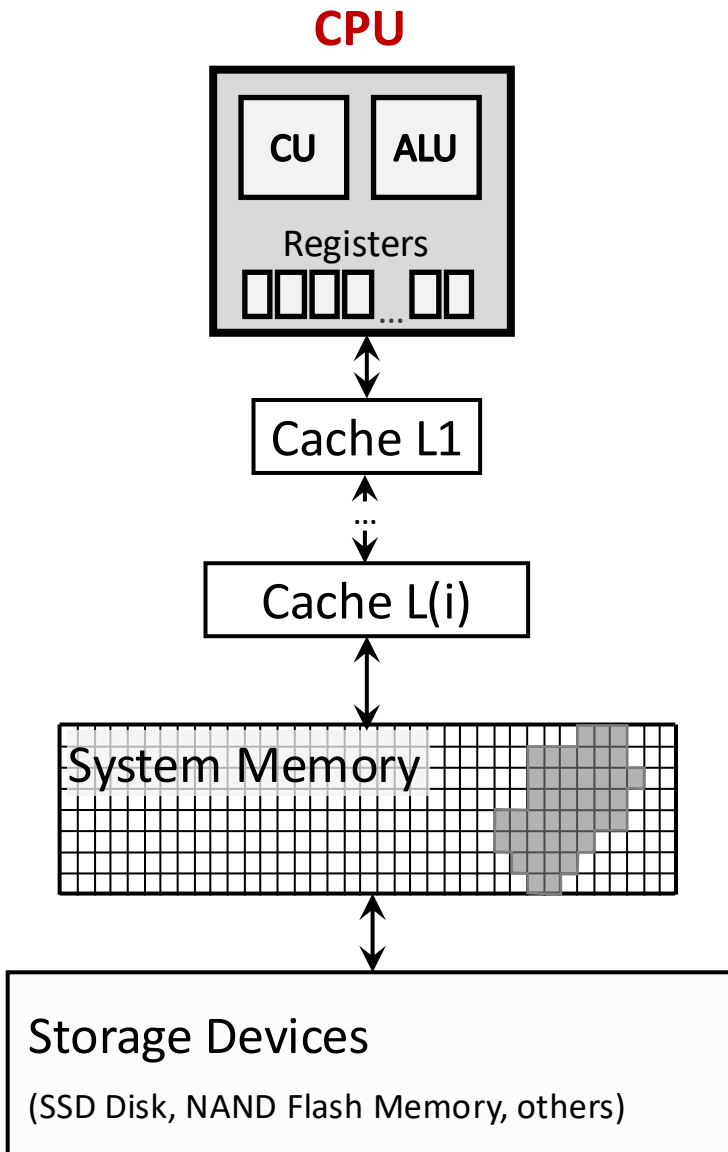


# Average Characteristics: Laptop/Desktop



| Device                    | Operation Speed                                  | Storage Capacity                            |
|---------------------------|--------------------------------------------------|---------------------------------------------|
| <b>CPU</b><br>(4-6 cores) | <b>2.0-3.5 GHz</b><br>Up to 5.0 GHz (Turbo mode) | <b>32 or 64 Bits</b><br><b>per register</b> |

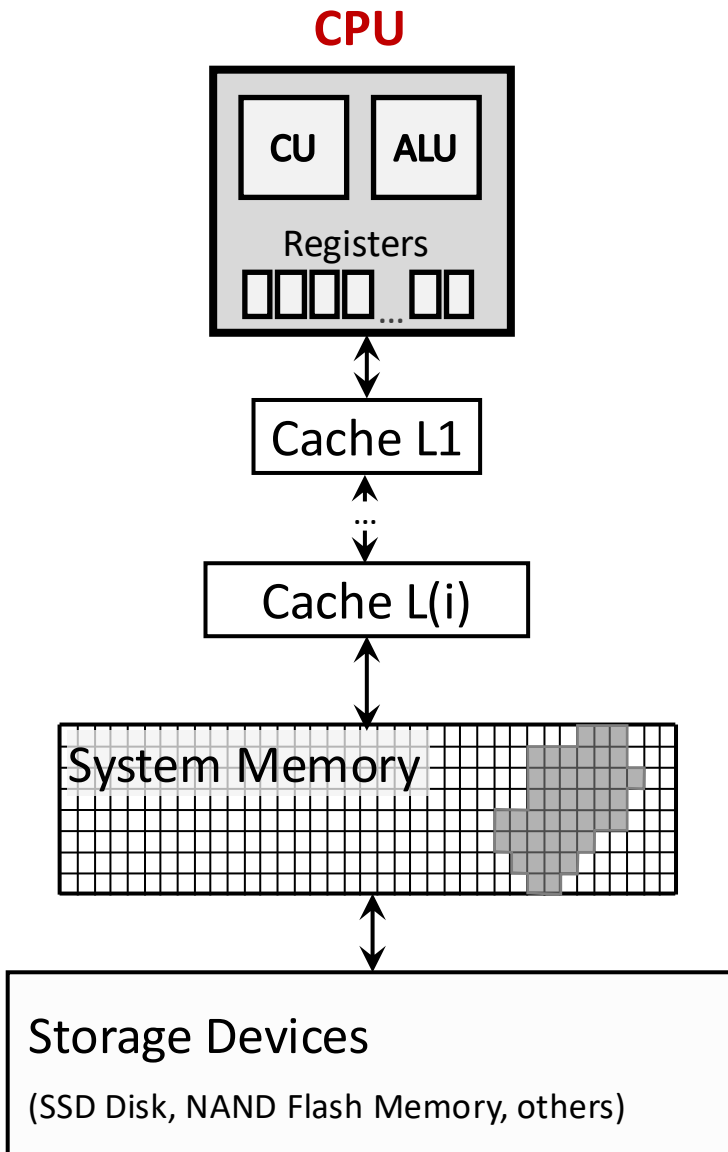
# Average Characteristics: Laptop/Desktop



| Device             | Operation Speed                                  | Storage Capacity              |
|--------------------|--------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores) | <b>2.0-3.5 GHz</b><br>Up to 5.0 GHz (Turbo mode) | 32 or 64 Bits<br>per register |

**MIPS (Millions Instructions Per Second):**  
Another metric for CPU speed

# Average Characteristics: Laptop/Desktop

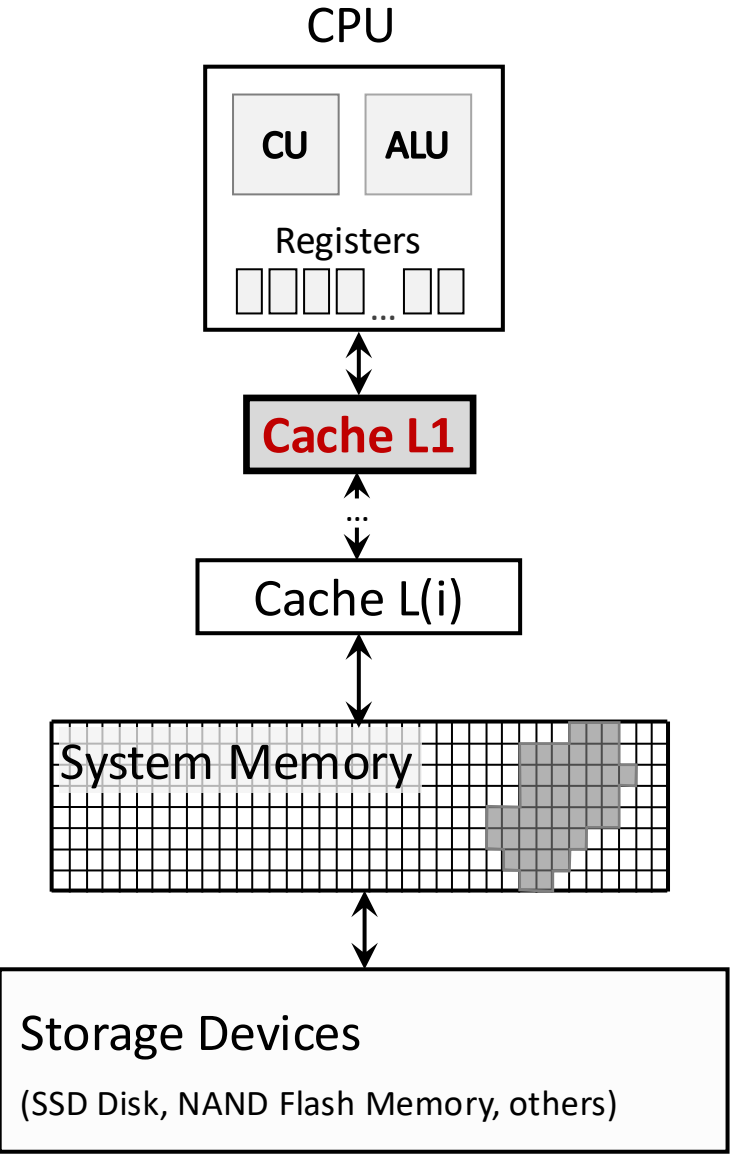


| Device             | Operation Speed                                  | Storage Capacity              |
|--------------------|--------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores) | <b>2.0-3.5 GHz</b><br>Up to 5.0 GHz (Turbo mode) | 32 or 64 Bits<br>per register |

**MIPS (Millions Instructions Per Second):**  
Another metric for CPU speed

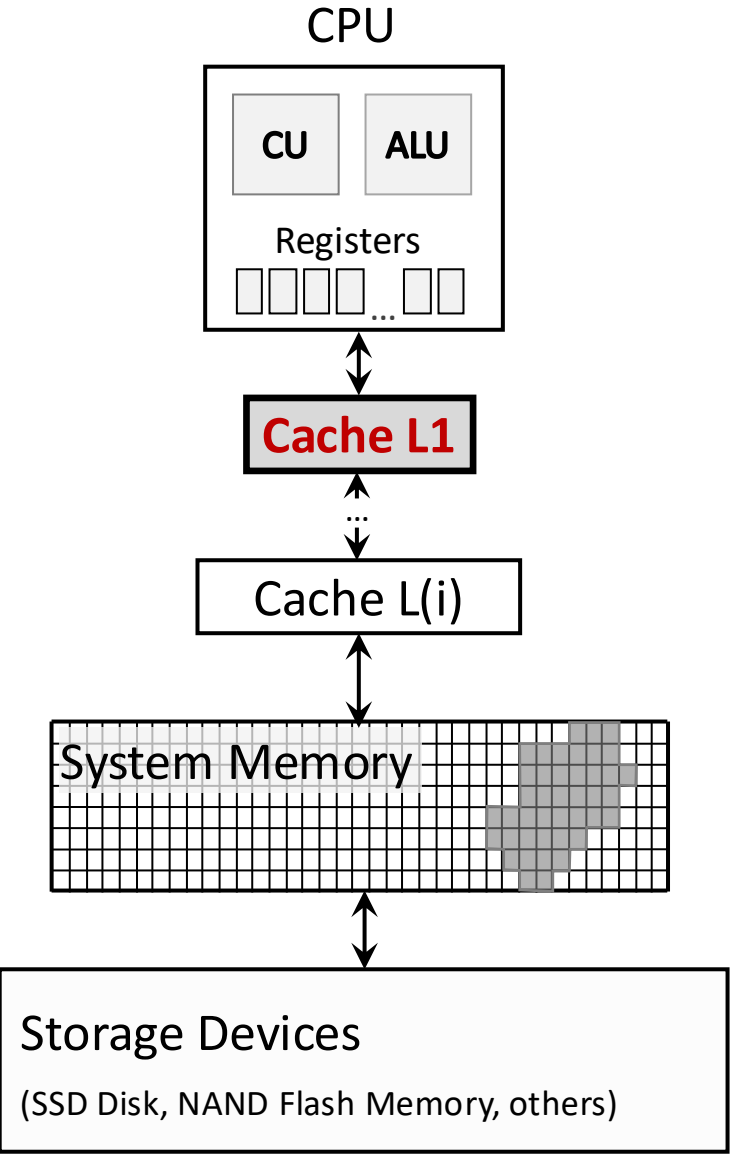
! MIPS also means the family of processors  
(Microprocessor without Interlocked Pipelined Stages)

# Average Characteristics: Laptop/Desktop



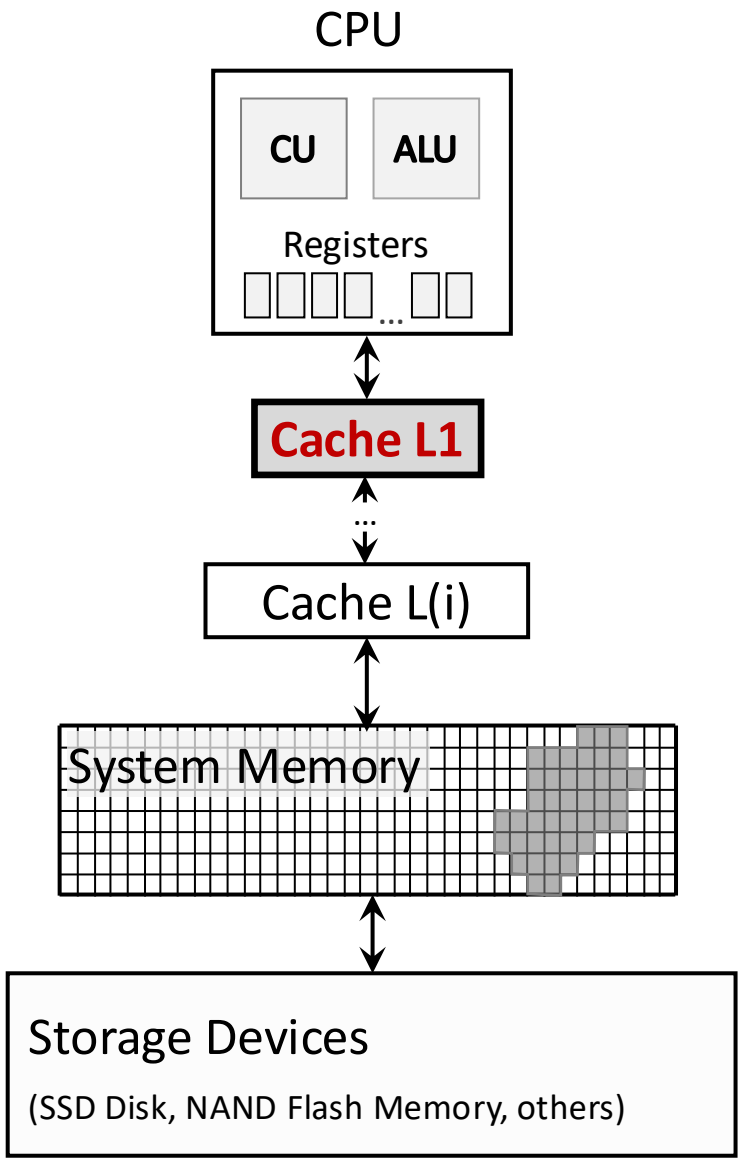
| Device                    | Operation Speed                           | Storage Capacity              |
|---------------------------|-------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode) | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           |                                           |                               |

# Average Characteristics: Laptop/Desktop



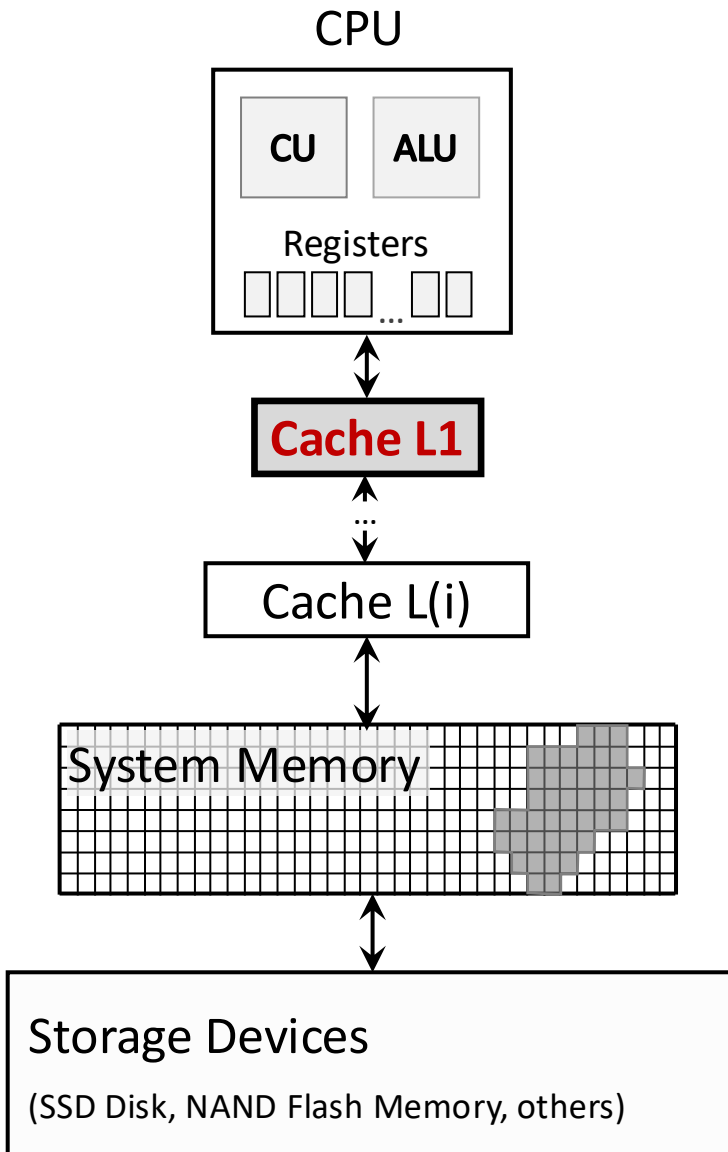
| Device                    | Operation Speed                           | Storage Capacity              |
|---------------------------|-------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode) | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | <b>The same as CPU speed;</b>             |                               |

# Average Characteristics: Laptop/Desktop



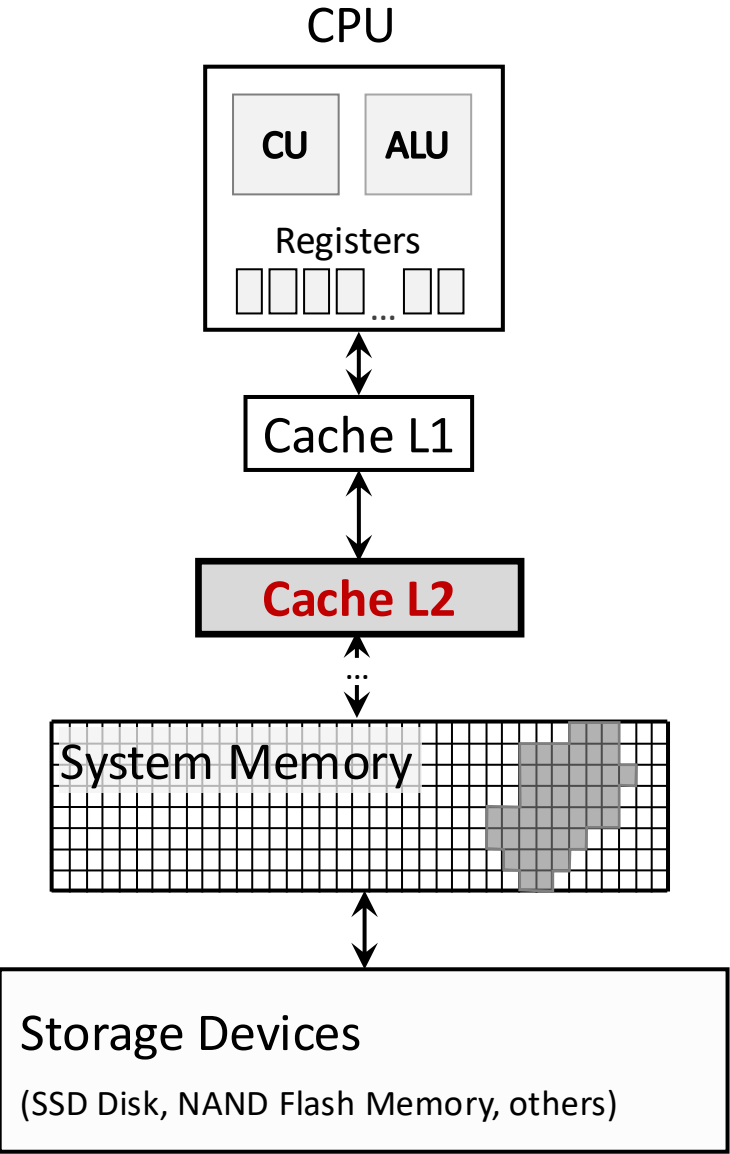
| Device                    | Operation Speed                                                    | Storage Capacity              |
|---------------------------|--------------------------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                          | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | <b>The same as CPU speed;</b><br><b>~100 times faster than RAM</b> |                               |

# Average Characteristics: Laptop/Desktop



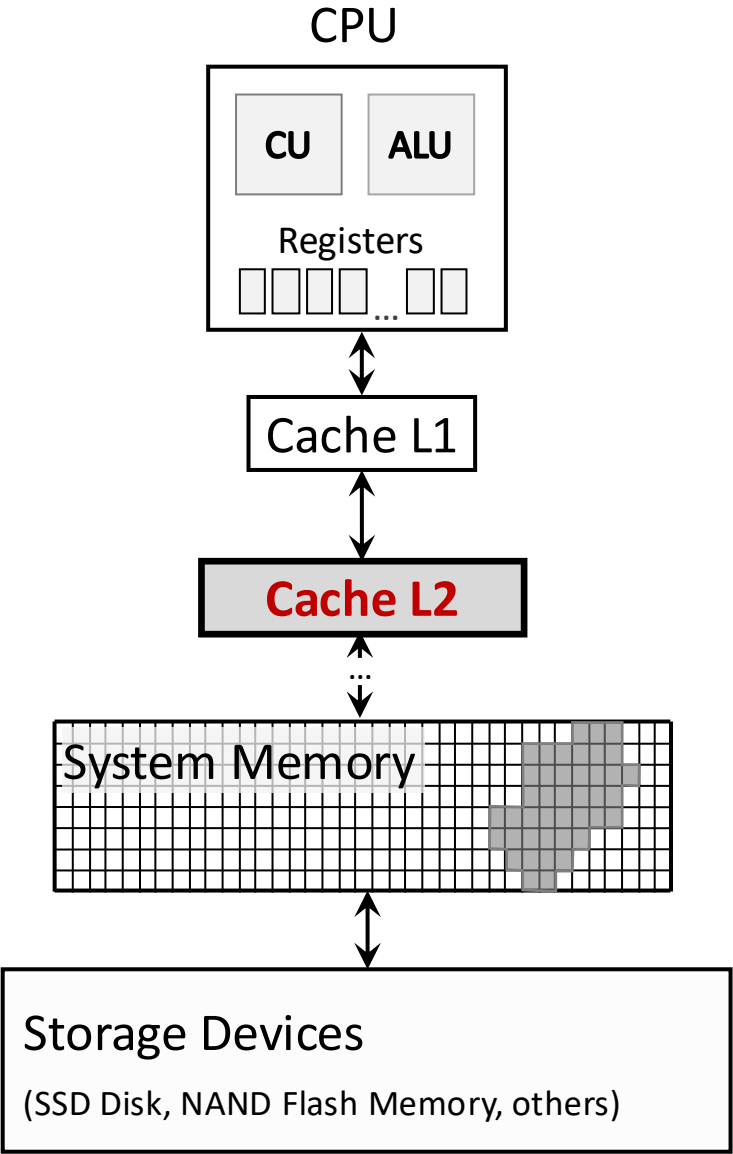
| Device                     | Operation Speed                                              | Storage Capacity              |
|----------------------------|--------------------------------------------------------------|-------------------------------|
| <b>CPU<br/>(4-6 cores)</b> | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                    | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>            | <b>The same as CPU speed;<br/>~100 times faster than RAM</b> | <b>32-128 KB</b>              |

# Average Characteristics: Laptop/Desktop



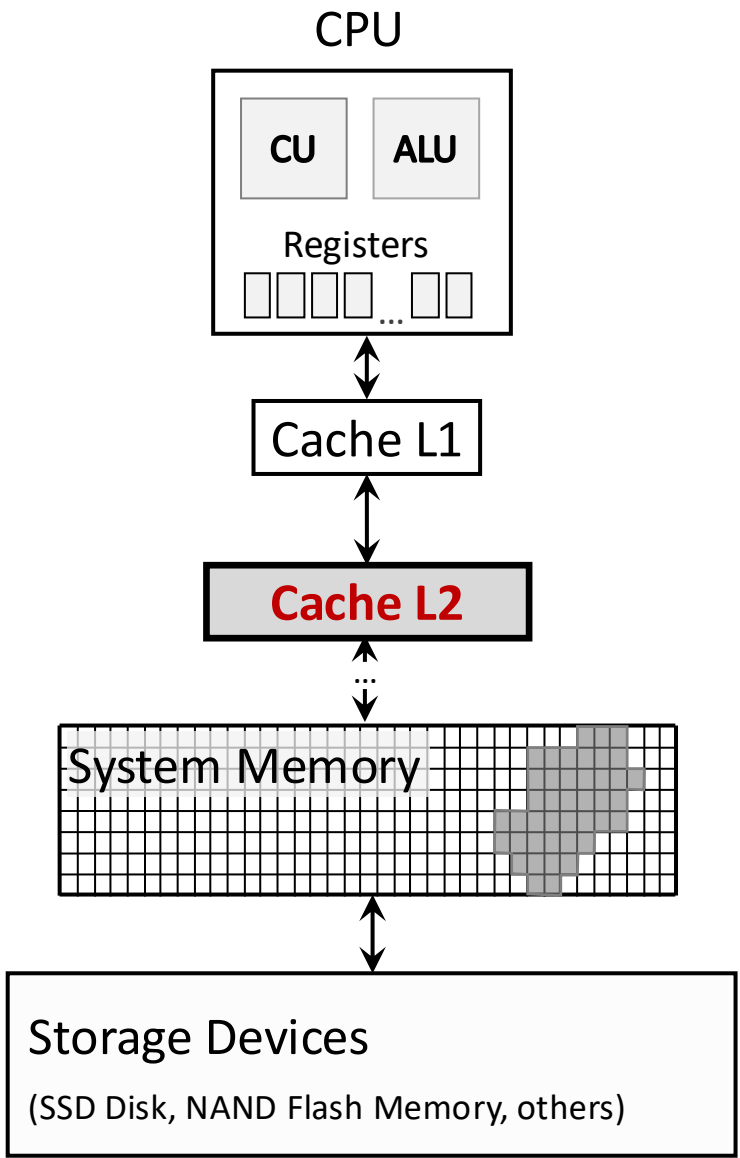
| Device                    | Operation Speed                                      | Storage Capacity              |
|---------------------------|------------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)            | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100 times faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           |                                                      |                               |

# Average Characteristics: Laptop/Desktop



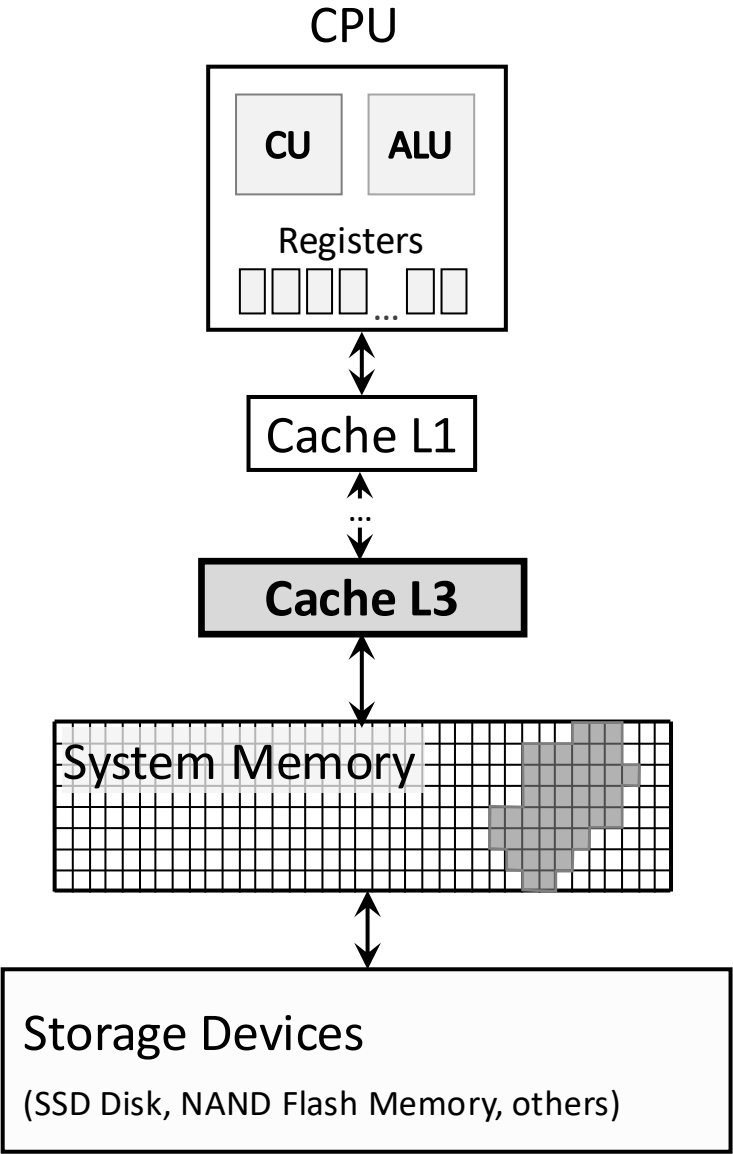
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | <b>~25x faster than RAM</b>                     |                               |

# Average Characteristics: Laptop/Desktop



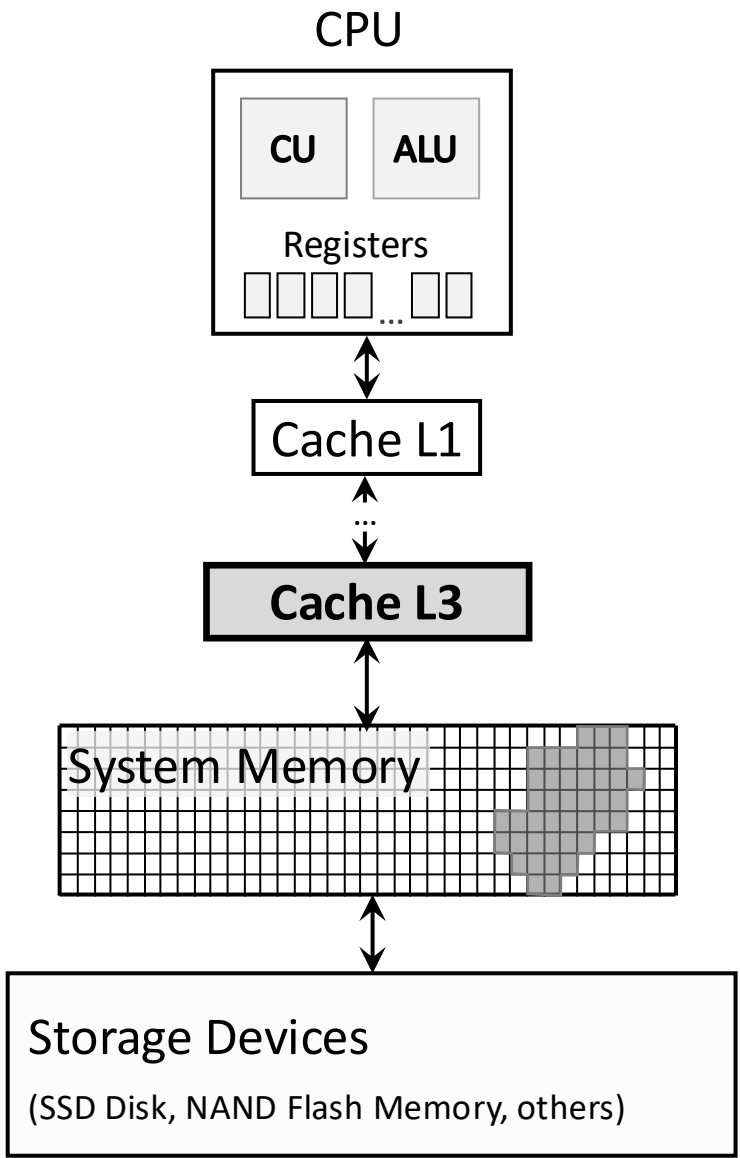
| Device                     | Operation Speed                                 | Storage Capacity              |
|----------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU<br/>(4-6 cores)</b> | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>            | <b>~25x faster than RAM</b>                     | <b>256-512 KB</b>             |

# Average Characteristics: Laptop/Desktop



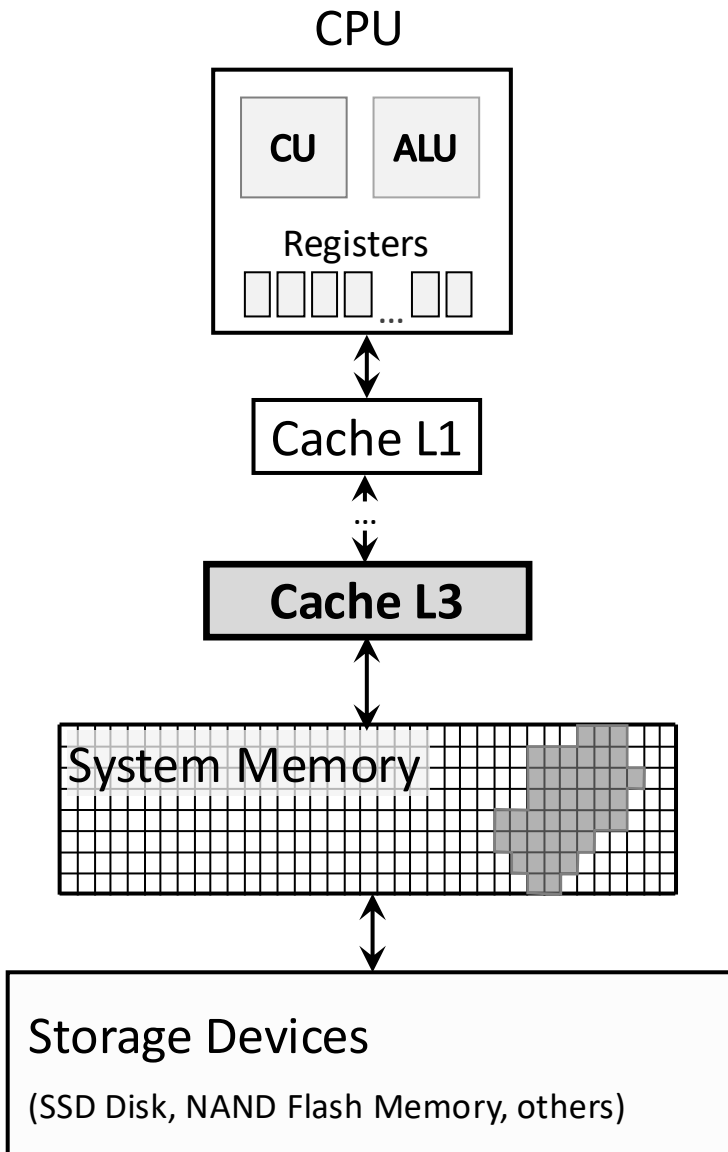
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           |                                                 |                               |

# Average Characteristics: Laptop/Desktop



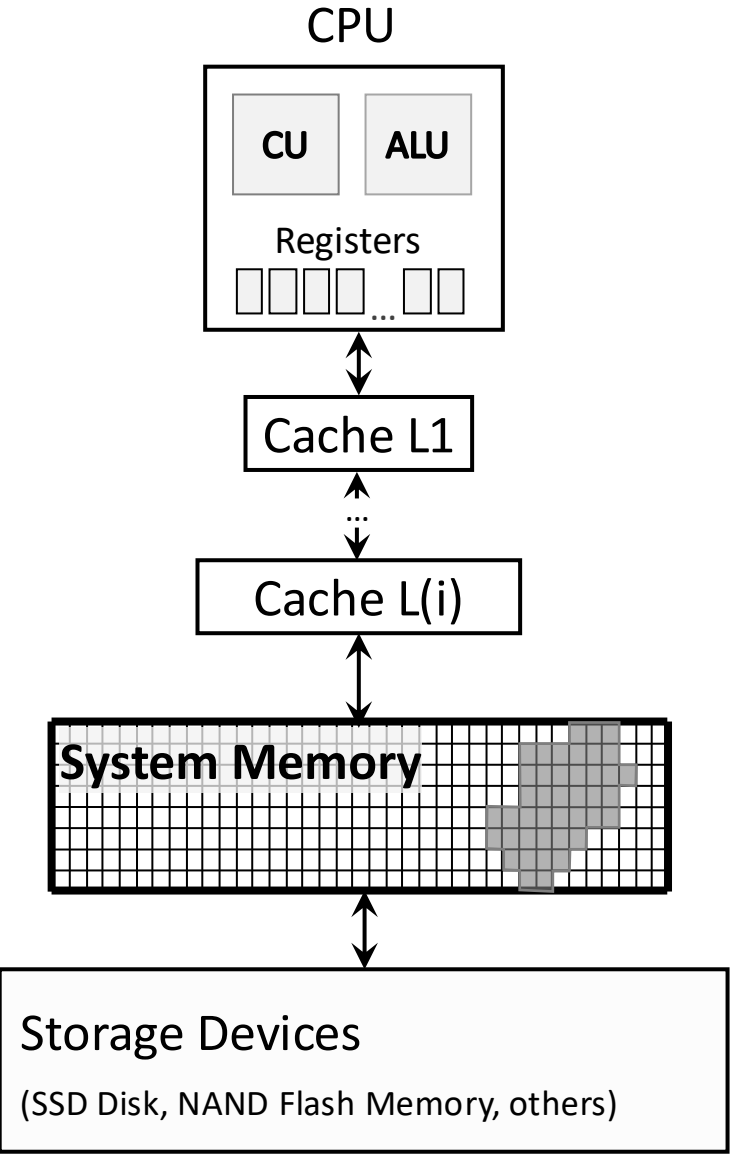
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           | <b>~2x faster than RAM</b>                      |                               |

# Average Characteristics: Laptop/Desktop



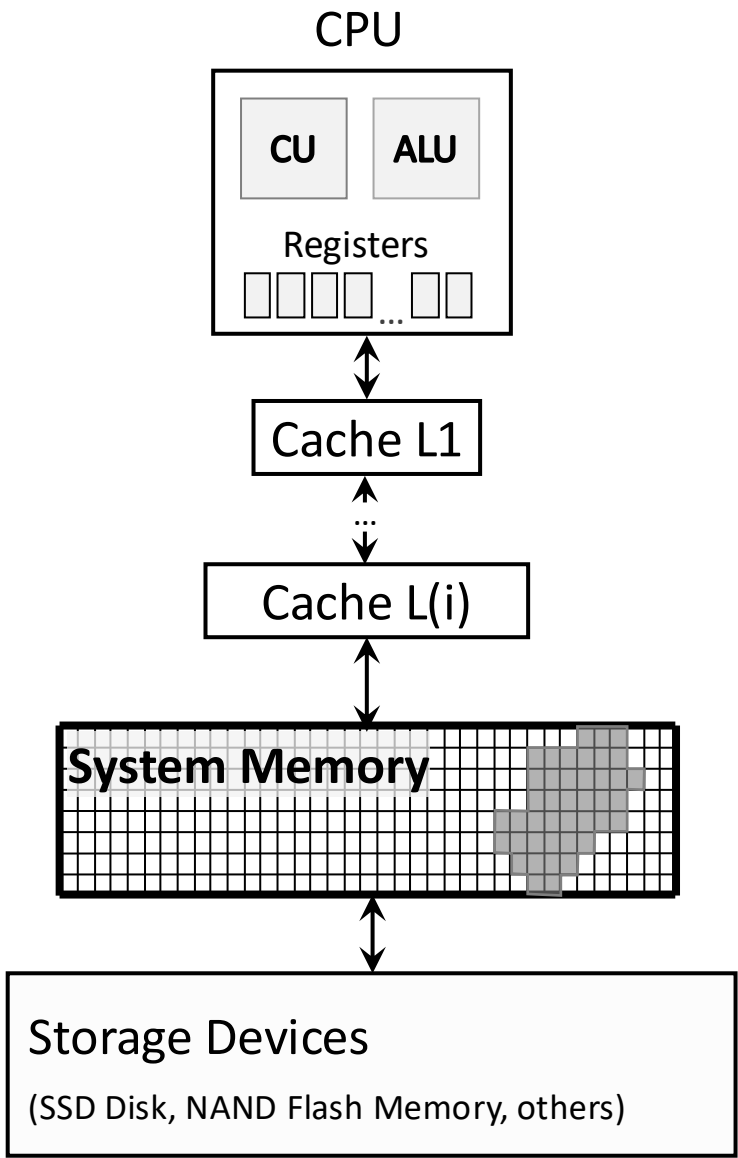
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           | <b>~2x faster than RAM</b>                      | <b>32-64 MB</b>               |

# Average Characteristics: Laptop/Desktop



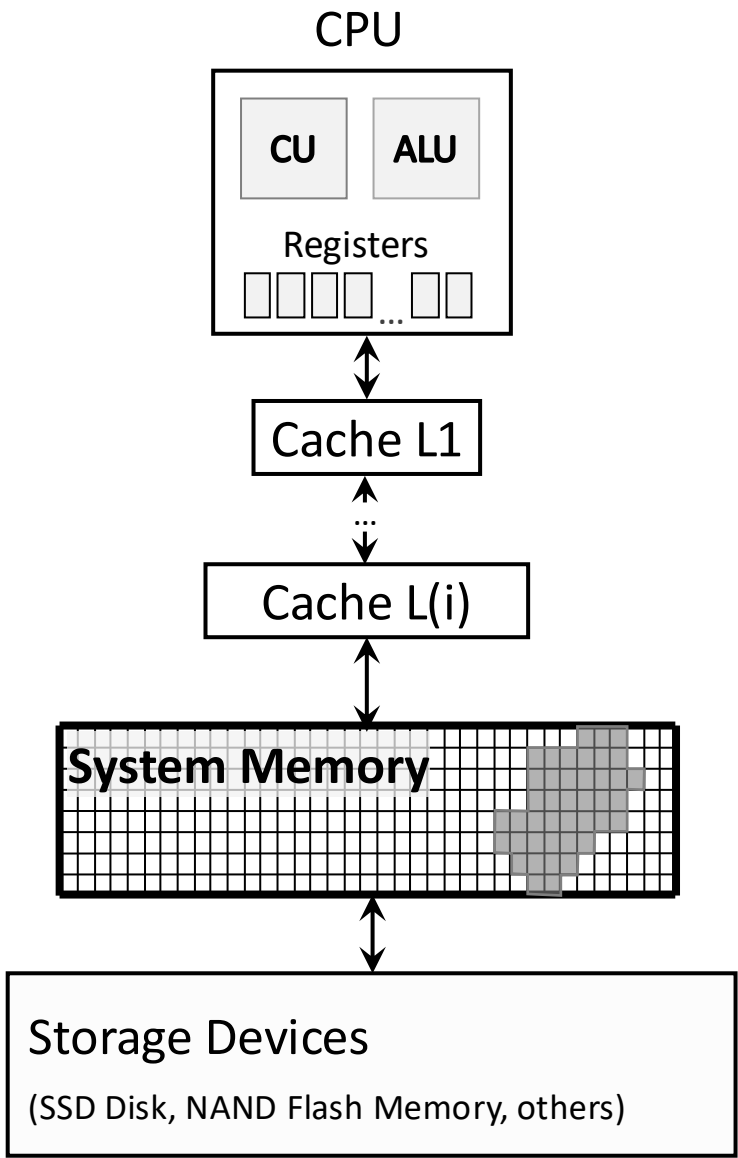
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           | ~2x faster than RAM                             | 32-64 MB                      |
| <b>System Memory</b>      |                                                 |                               |

# Average Characteristics: Laptop/Desktop



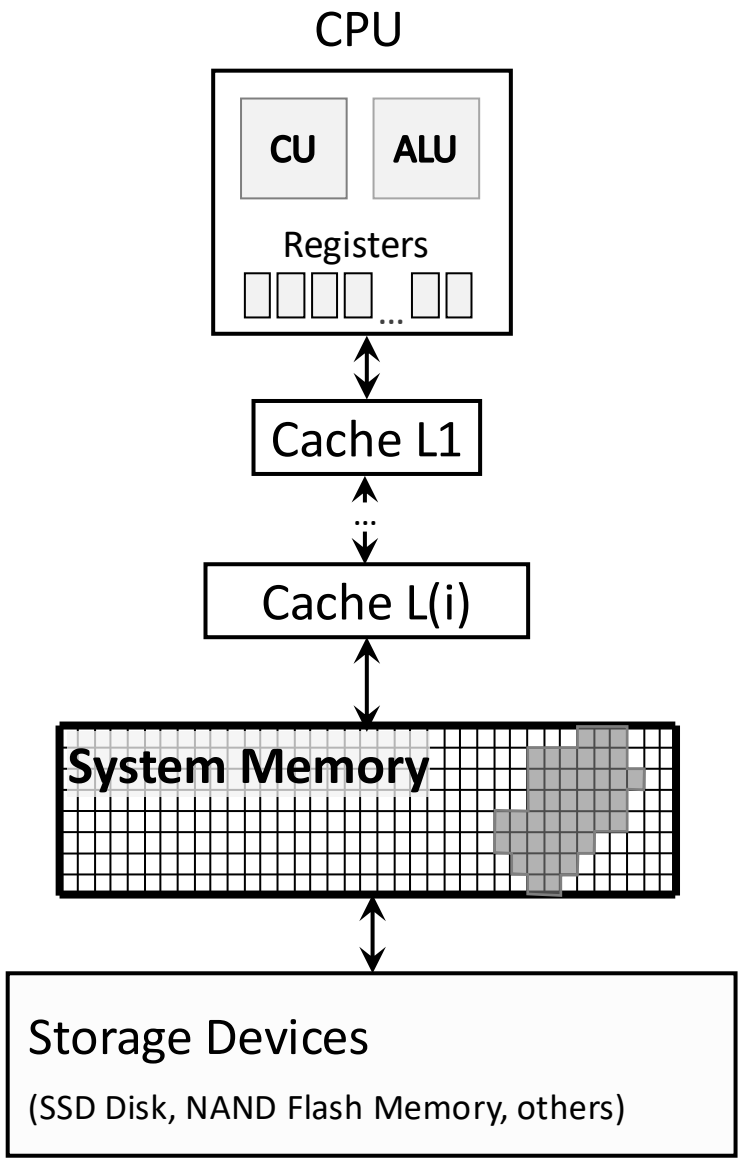
| Device                 | Operation Speed                                 | Storage Capacity           |
|------------------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   | <b>18-36 GB/sec</b>                             |                            |

# Average Characteristics: Laptop/Desktop



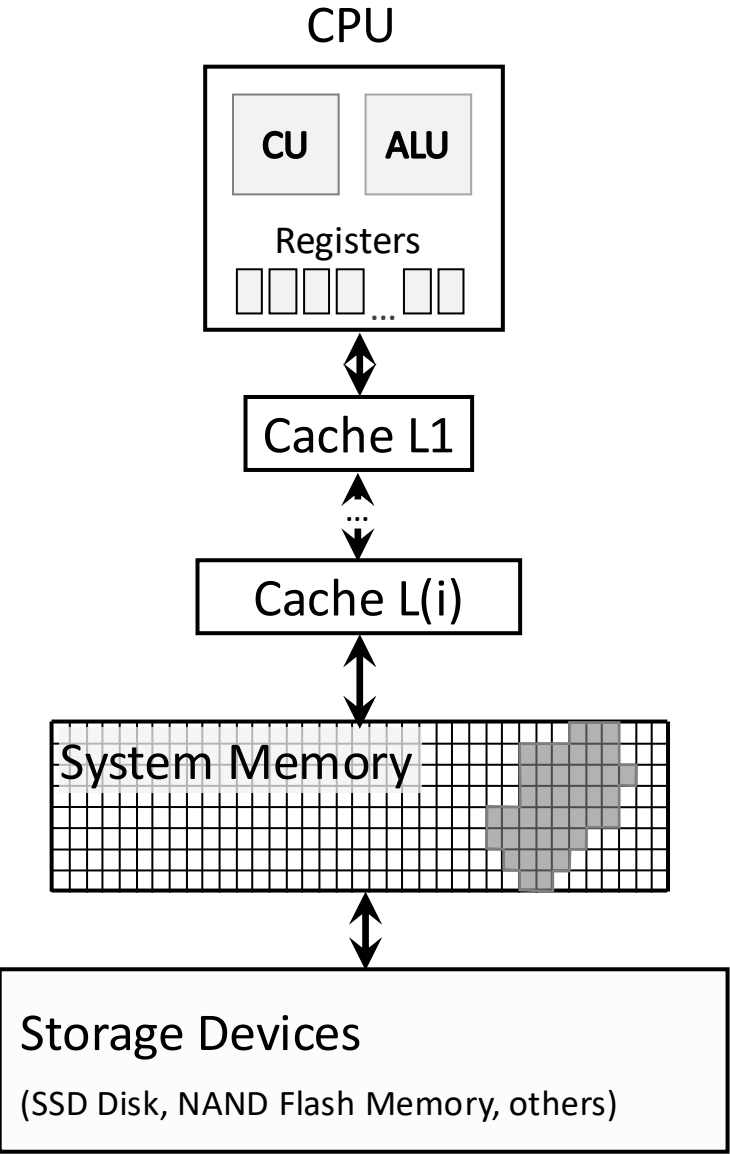
| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           | ~2x faster than RAM                             | 32-64 MB                      |
| <b>System Memory</b>      | <b>18-36 GB/sec</b>                             | <b>8-32 GB</b>                |

# Average Characteristics: Laptop/Desktop



| Device                    | Operation Speed                                 | Storage Capacity              |
|---------------------------|-------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores) | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>           | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>           | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>           | ~2x faster than RAM                             | 32-64 MB                      |
| <b>System Memory</b>      | 18-36 GB/sec                                    | 8-32 GB                       |
| <b>Communication Bus</b>  |                                                 |                               |

# Average Characteristics: Laptop/Desktop



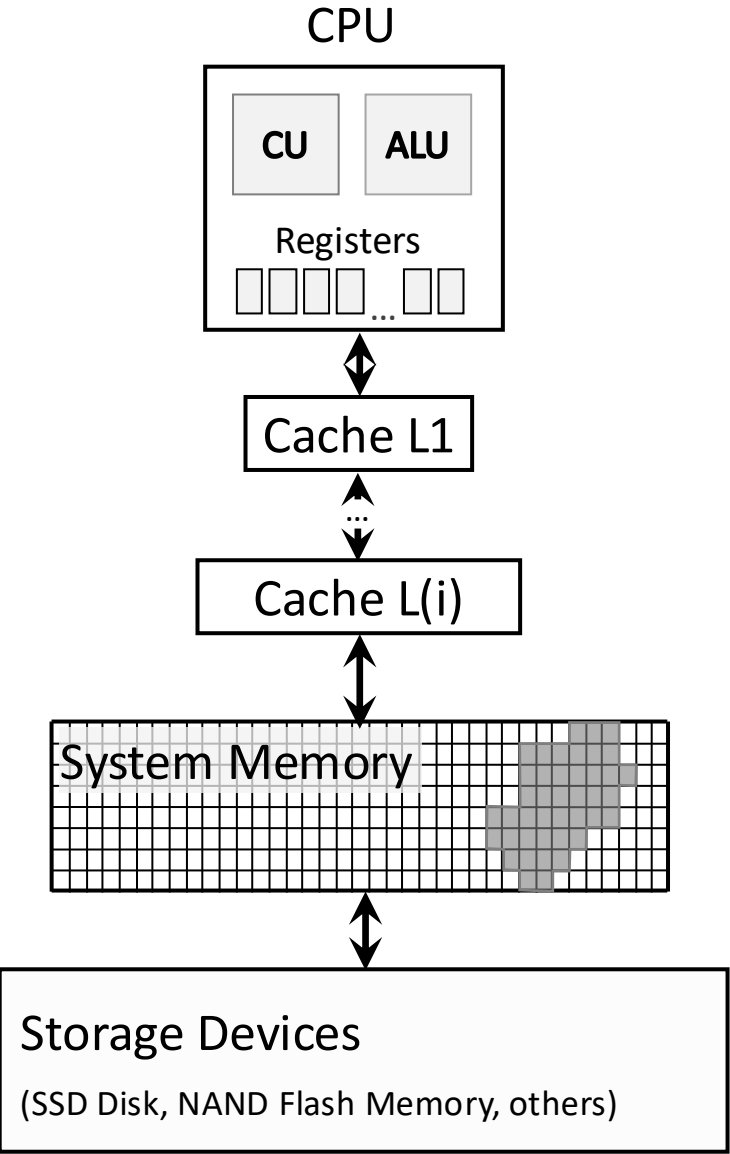
| Device                     |                   | Operation Speed                                 | Storage Capacity              |
|----------------------------|-------------------|-------------------------------------------------|-------------------------------|
| <b>CPU<br/>(4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>            |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>            |                   | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>            |                   | ~2x faster than RAM                             | 32-64 MB                      |
| <b>System Memory</b>       |                   | 18-36 GB/sec                                    | 8-32 GB                       |
| <b>Bus</b>                 | <b>RAM (DDR4)</b> |                                                 |                               |
|                            | <b>PCIe (4.0)</b> |                                                 |                               |
|                            | <b>USB (3.0)</b>  |                                                 |                               |

RAM (Random Access Memory) – synonym for “System Memory”

PCIe: Peripheral Component Interconnect Express

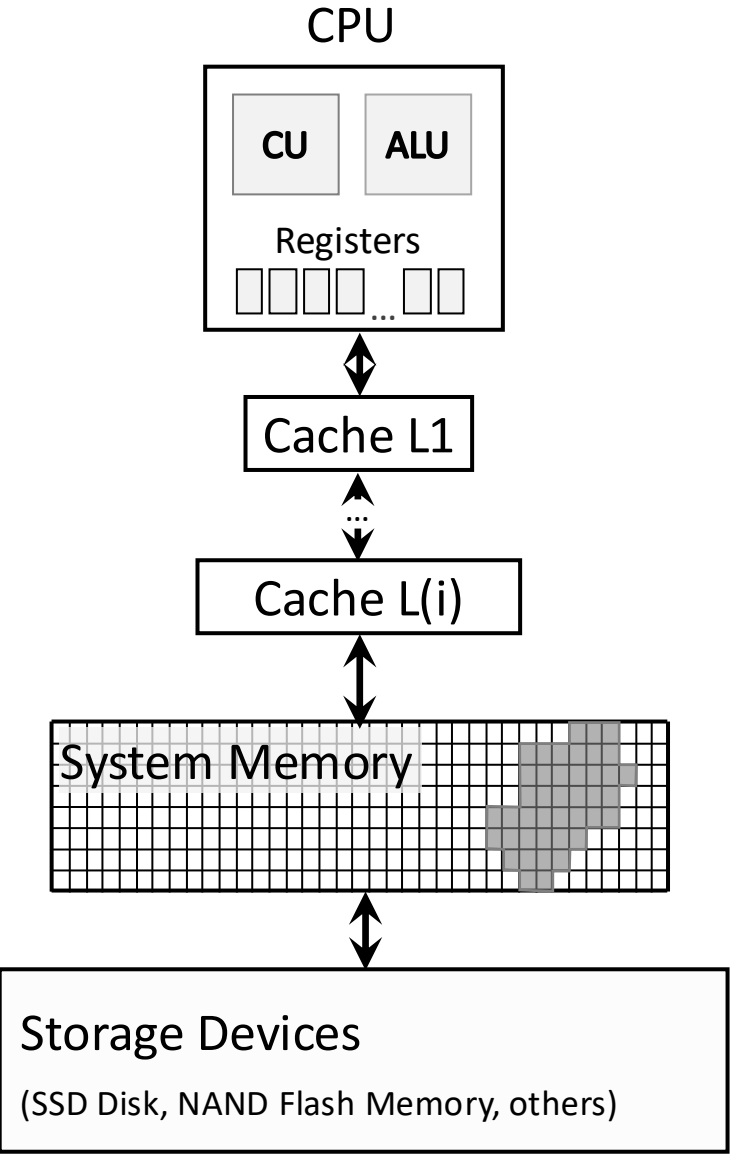
USB: Universal Serial Bus

# Average Characteristics: Laptop/Desktop



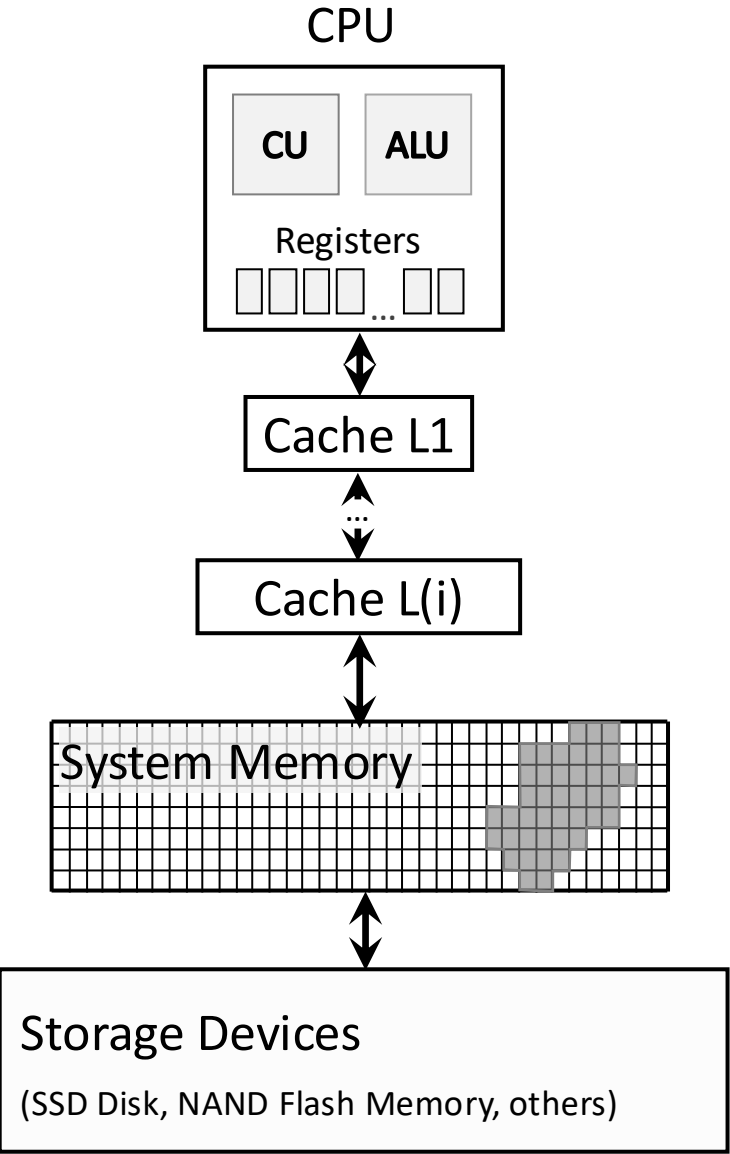
| Device                 |                   | Operation Speed                                 | Storage Capacity           |
|------------------------|-------------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |                   | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |                   | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |                   | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | <b>RAM (DDR4)</b> | <b>18-36 GB/sec (64 lines)</b>                  |                            |
|                        | <b>PCIe (4.0)</b> |                                                 |                            |
|                        | <b>USB (3.0)</b>  |                                                 |                            |

# Average Characteristics: Laptop/Desktop



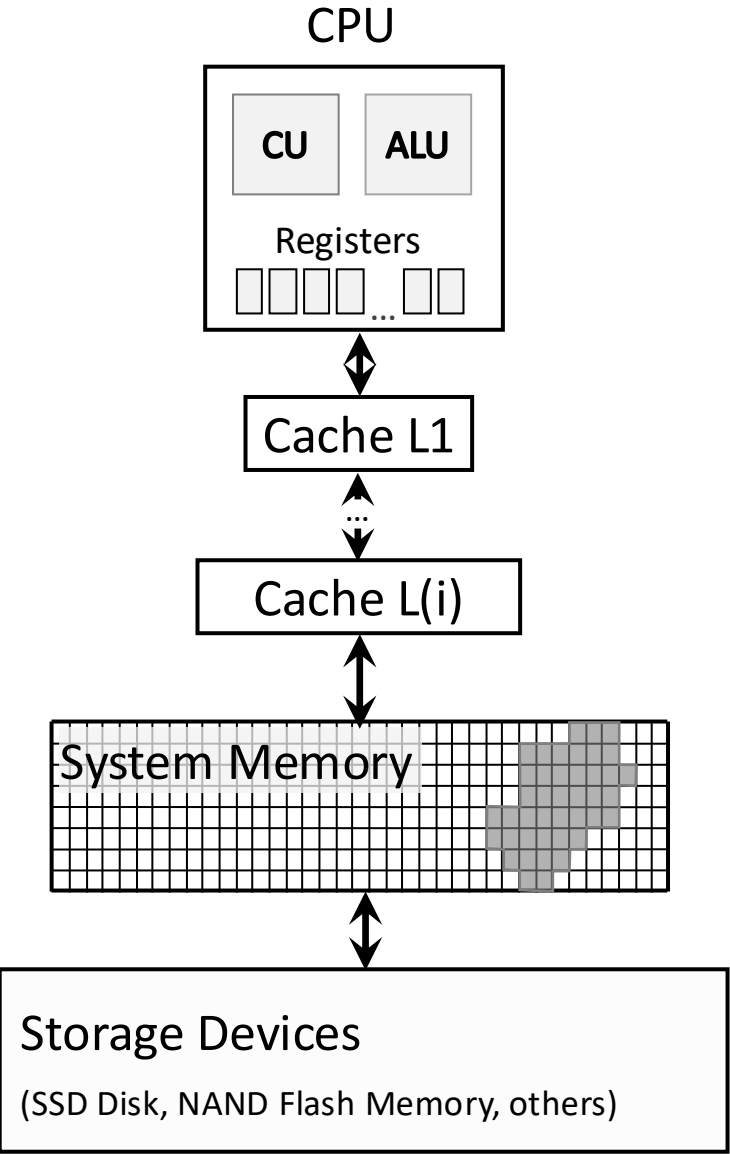
| Device                 |                   | Operation Speed                                 | Storage Capacity                                                           |
|------------------------|-------------------|-------------------------------------------------|----------------------------------------------------------------------------|
| <b>CPU (4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register                                                 |
| <b>L1 Cache</b>        |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                                                                  |
| <b>L2 Cache</b>        |                   | ~25x faster than RAM                            | 256-512 KB                                                                 |
| <b>L3 Cache</b>        |                   | ~2x faster than RAM                             | 32-64 MB                                                                   |
| <b>System Memory</b>   |                   | 18-36 GB/sec                                    | 8-32 GB                                                                    |
| <b>Bus</b>             | <b>RAM (DDR4)</b> | 18-36 GB/sec <b>(64 lines)</b>                  | The number of lines reflects the number of simultaneously transferred bits |
|                        | <b>PCIe (4.0)</b> |                                                 |                                                                            |
|                        | <b>USB (3.0)</b>  |                                                 |                                                                            |

# Average Characteristics: Laptop/Desktop



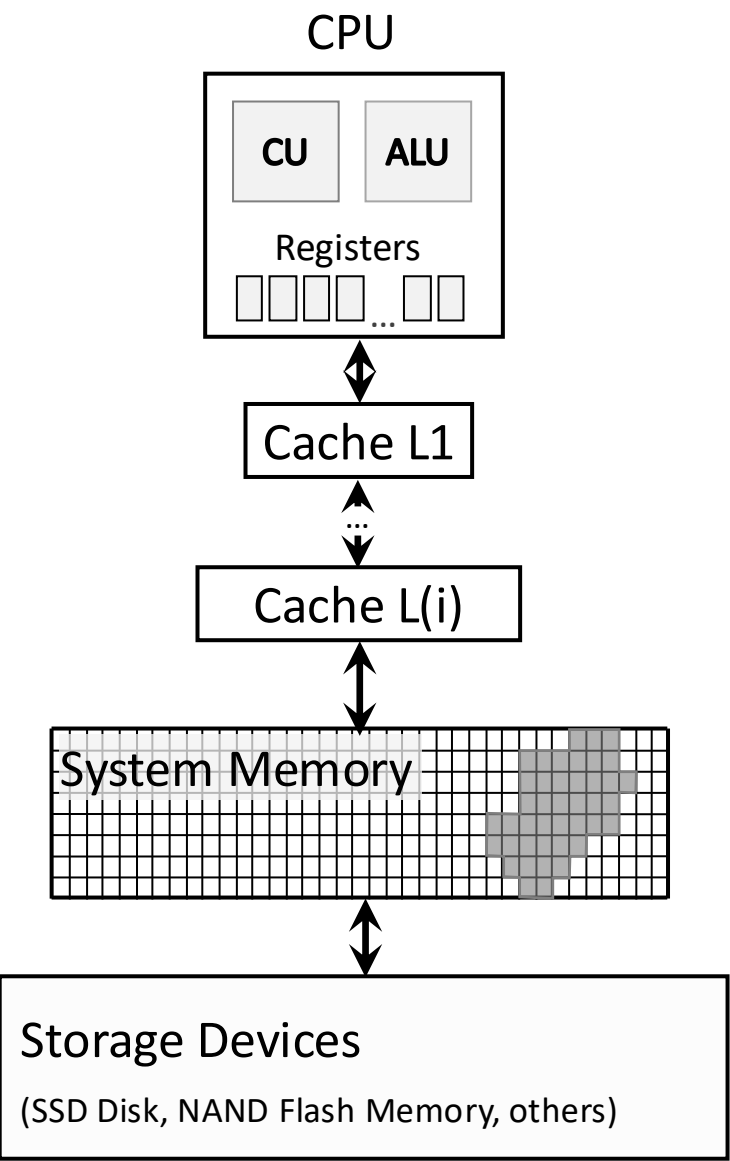
| Device                 |                   | Operation Speed                                 | Storage Capacity           |
|------------------------|-------------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |                   | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |                   | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |                   | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | <b>RAM (DDR4)</b> | 18-36 GB/sec (64 lines)                         |                            |
|                        | <b>PCIe (4.0)</b> | 8 GB/sec (4 lines)                              |                            |
|                        | <b>USB (3.0)</b>  |                                                 |                            |

# Average Characteristics: Laptop/Desktop



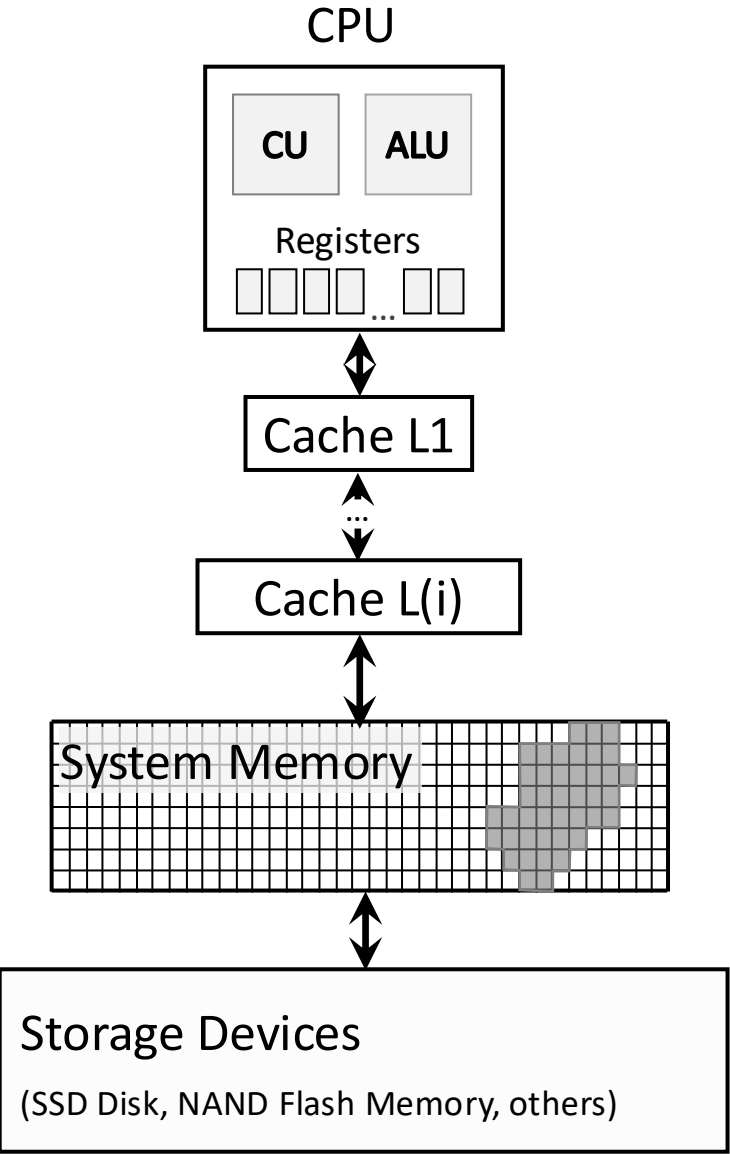
| Device                 |                   | Operation Speed                                 | Storage Capacity           |
|------------------------|-------------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |                   | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |                   | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |                   | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | <b>RAM (DDR4)</b> | 18-36 GB/sec (64 lines)                         |                            |
|                        | <b>PCIe (4.0)</b> | 8 GB/sec (4 lines)                              |                            |
|                        | <b>USB (3.0)</b>  | 0.5 GB/sec (1 line)                             |                            |

# Average Characteristics: Laptop/Desktop



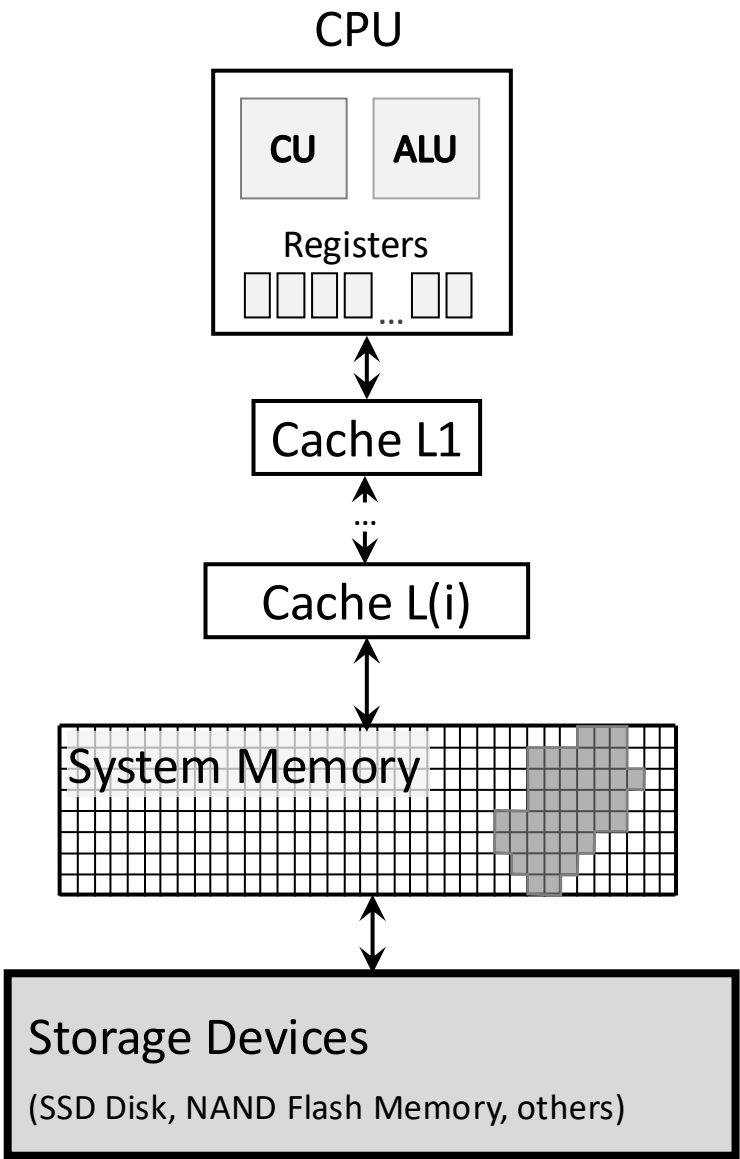
| Device                 |                   | Operation Speed                                 | Storage Capacity           |
|------------------------|-------------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |                   | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |                   | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |                   | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |                   | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | <b>RAM (DDR4)</b> | 18-36 GB/sec (64 lines)                         | <b>N/A</b>                 |
|                        | <b>PCIe (4.0)</b> | 8 GB/sec (4 lines)                              |                            |
|                        | <b>USB (3.0)</b>  | 0.5 GB/sec (1 line)                             |                            |

# Average Characteristics: Laptop/Desktop



| Device                     |            | Operation Speed                                 | Storage Capacity              |
|----------------------------|------------|-------------------------------------------------|-------------------------------|
| <b>CPU<br/>(4-6 cores)</b> |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| <b>L1 Cache</b>            |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| <b>L2 Cache</b>            |            | ~25x faster than RAM                            | 256-512 KB                    |
| <b>L3 Cache</b>            |            | ~2x faster than RAM                             | 32-64 MB                      |
| <b>System Memory</b>       |            | 18-36 GB/sec                                    | 8-32 GB                       |
| <b>Bus</b>                 | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                           |
|                            | PCIe (4.0) | 8 GB/sec (4 lines)                              |                               |
|                            | USB (3.0)  | 0.5 GB/sec (1 line)                             |                               |
| <b>Storage Device</b>      |            |                                                 |                               |

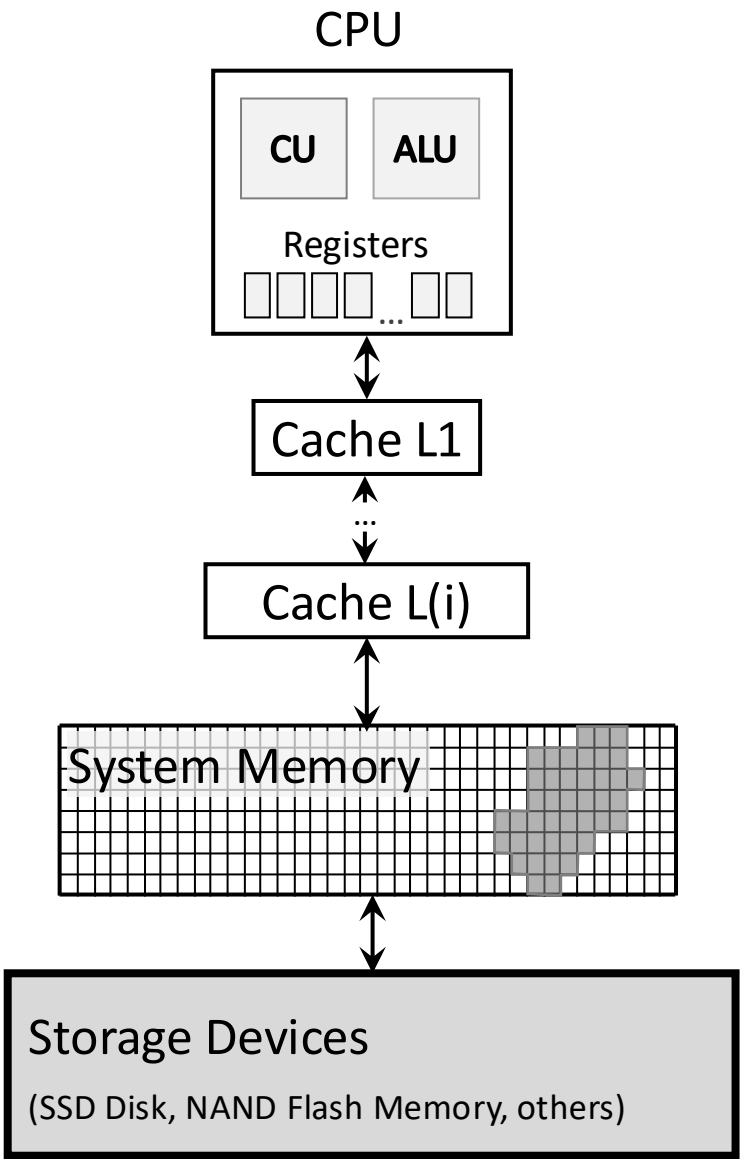
# Average Characteristics: Laptop/Desktop



| Device             |            | Operation Speed                                 | Storage Capacity              |
|--------------------|------------|-------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores) |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| L1 Cache           |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| L2 Cache           |            | ~25x faster than RAM                            | 256-512 KB                    |
| L3 Cache           |            | ~2x faster than RAM                             | 32-64 MB                      |
| System Memory      |            | 18-36 GB/sec                                    | 8-32 GB                       |
| Bus                | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                           |
|                    | PCIe (4.0) | 8 GB/sec (4 lines)                              |                               |
|                    | USB (3.0)  | 0.5 GB/sec (1 line)                             |                               |
| Storage            | SSD        |                                                 |                               |
|                    | HDD        |                                                 |                               |

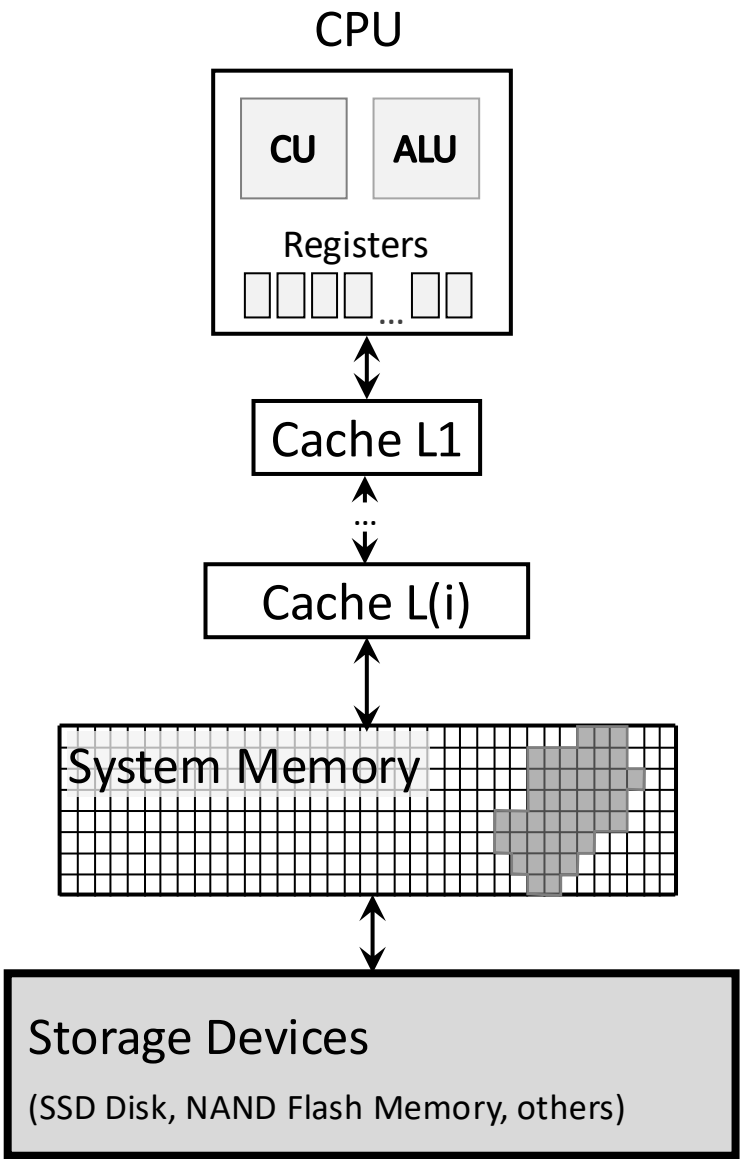
SSD: Solid State Drive; HDD: Hard Disk Drive

# Average Characteristics: Laptop/Desktop



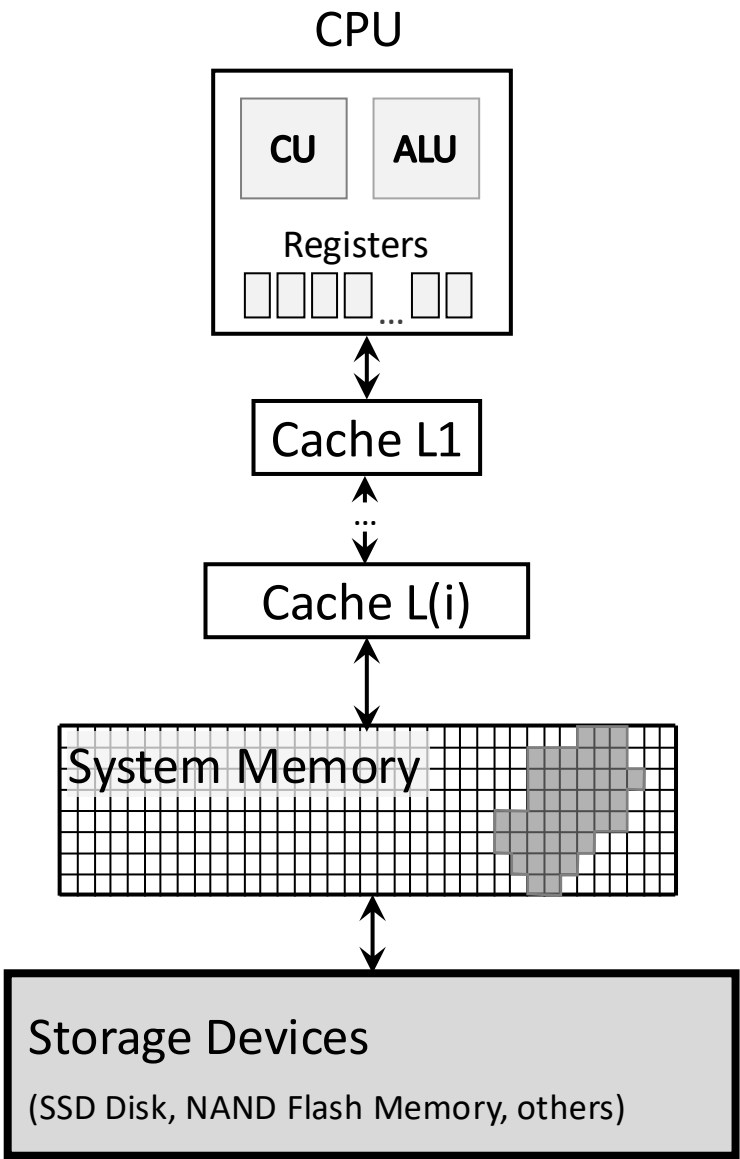
| Device                 |            | Operation Speed                                 | Storage Capacity           |
|------------------------|------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |            | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |            | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |            | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                        |
|                        | PCIe (4.0) | 8 GB/sec (4 lines)                              |                            |
|                        | USB (3.0)  | 0.5 GB/sec (1 line)                             |                            |
| <b>Storage</b>         | <b>SSD</b> | <b>0.5-2 GB/sec</b>                             |                            |
|                        | <b>HDD</b> |                                                 |                            |

# Average Characteristics: Laptop/Desktop



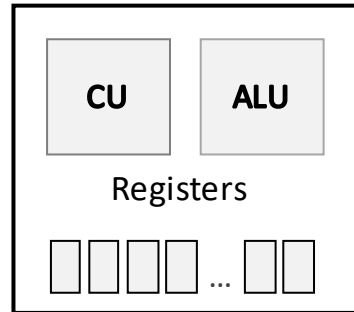
| Device                 |            | Operation Speed                                 | Storage Capacity           |
|------------------------|------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |            | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |            | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |            | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                        |
|                        | PCIe (4.0) | 8 GB/sec (4 lines)                              |                            |
|                        | USB (3.0)  | 0.5 GB/sec (1 line)                             |                            |
| <b>Storage</b>         | <b>SSD</b> | 0.5-2 GB/sec                                    |                            |
|                        | <b>HDD</b> | 0.1-0.15 GB/sec                                 |                            |

# Average Characteristics: Laptop/Desktop



| Device                 |            | Operation Speed                                 | Storage Capacity           |
|------------------------|------------|-------------------------------------------------|----------------------------|
| <b>CPU (4-6 cores)</b> |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits per register |
| <b>L1 Cache</b>        |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                  |
| <b>L2 Cache</b>        |            | ~25x faster than RAM                            | 256-512 KB                 |
| <b>L3 Cache</b>        |            | ~2x faster than RAM                             | 32-64 MB                   |
| <b>System Memory</b>   |            | 18-36 GB/sec                                    | 8-32 GB                    |
| <b>Bus</b>             | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                        |
|                        | PCIe (4.0) | 8 GB/sec (4 lines)                              |                            |
|                        | USB (3.0)  | 0.5 GB/sec (1 line)                             |                            |
| <b>Storage</b>         | <b>SSD</b> | 0.5-2 GB/sec                                    | <b>250-500 GB</b>          |
|                        | <b>HDD</b> | 0.1-0.15 GB/sec                                 | <b>100-150 GB</b>          |

## CPU



Cache L1

...

Cache L(i)

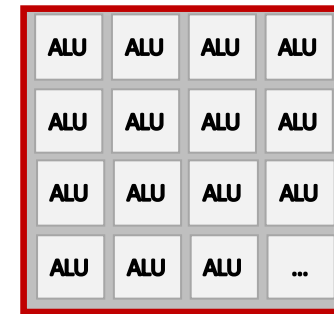
System Memory

Storage Devices

(SSD Disk, NAND Flash Memory, others)

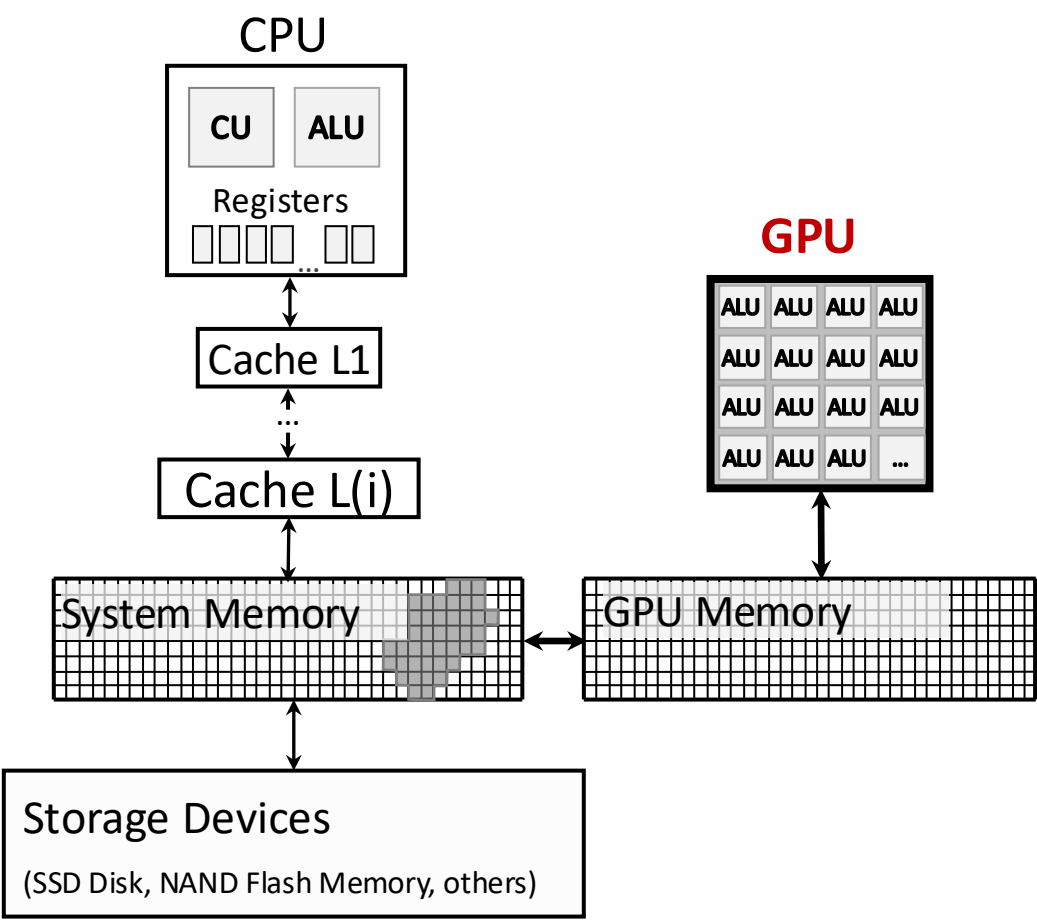
## GPU (Graphics Processing Unit) Subsystem

### GPU



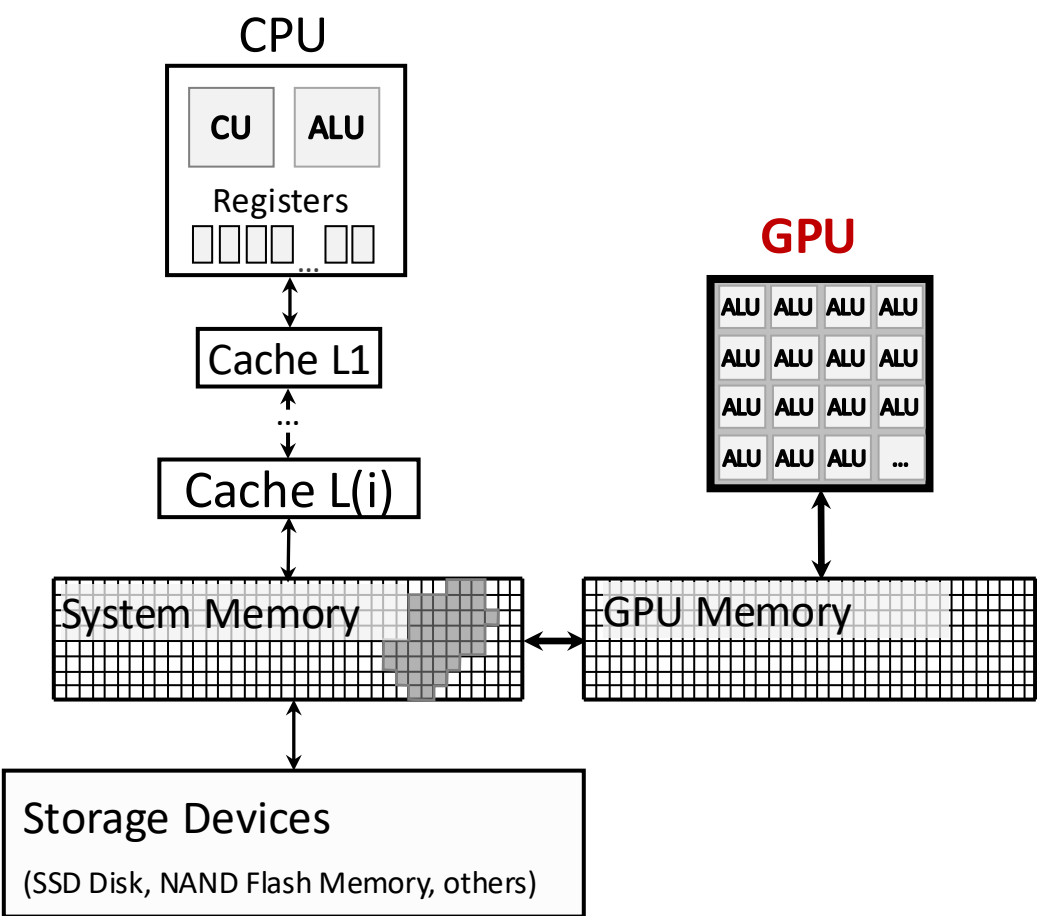
GPU Memory

# Average Characteristics: Laptop/Desktop



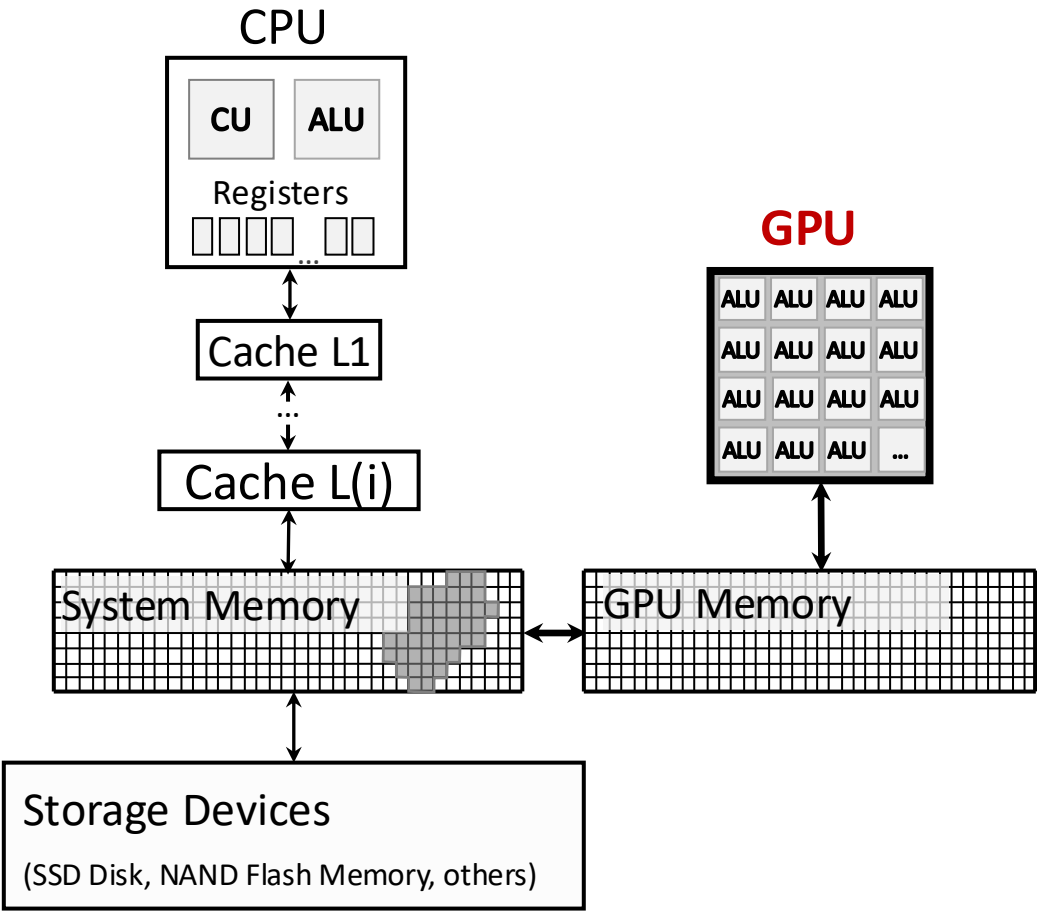
| Device                  |            | Operation Speed                                 | Storage Capacity              |
|-------------------------|------------|-------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            |                                                 |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                            | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                             | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                    | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                              |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                             |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                    | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                 | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



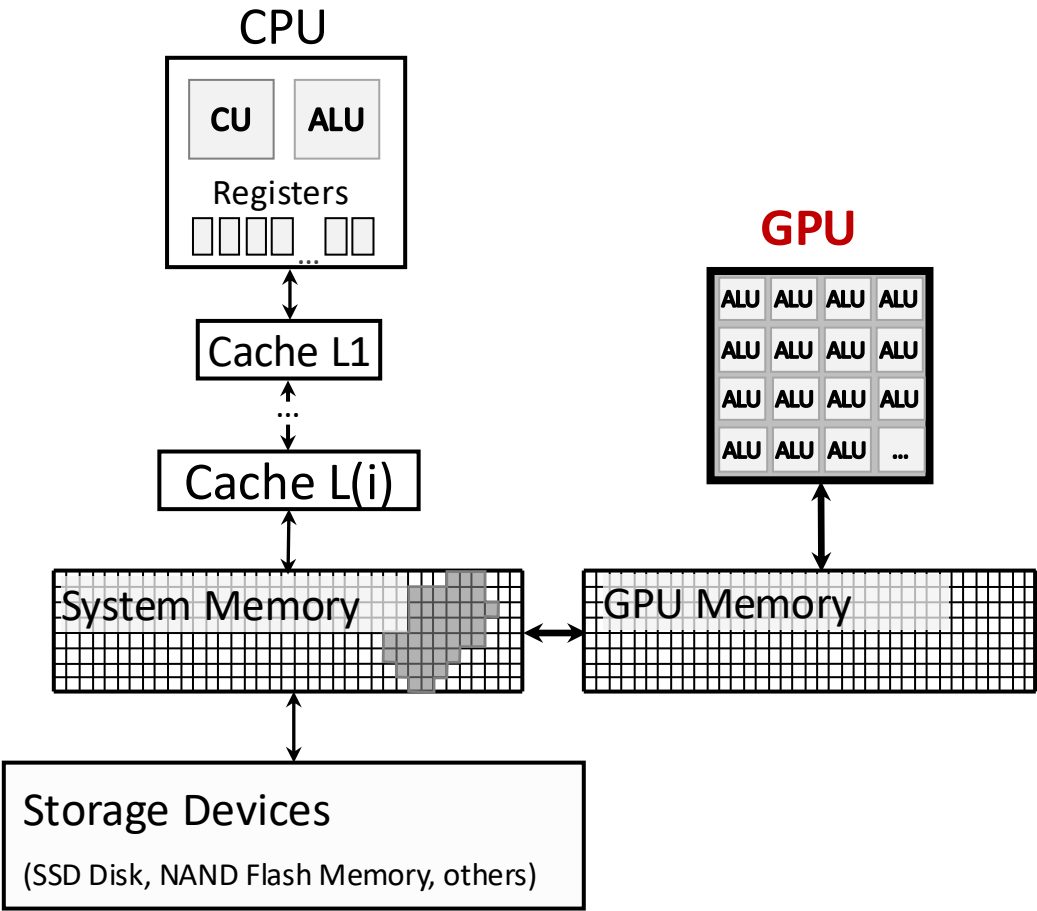
| Device                  |            | Operation Speed                                 | Storage Capacity              |
|-------------------------|------------|-------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)       | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz                                     |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                            | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                             | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                    | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                         | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                              |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                             |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                    | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                 | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



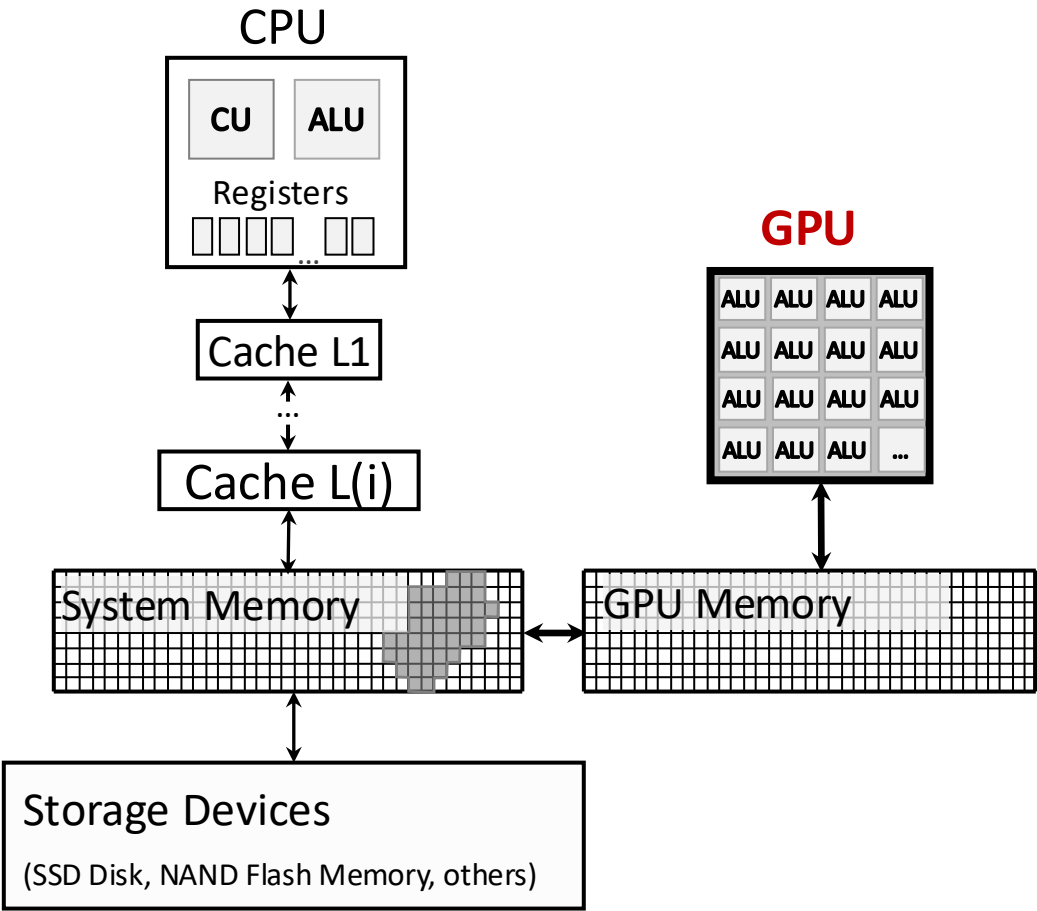
| Device                  |            | Operation Speed                                         | Storage Capacity              |
|-------------------------|------------|---------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)               | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple Instruction Set (IS)<br>supported |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM         | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                    | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                     | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                            | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                 | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                      |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                     |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                            | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                         | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



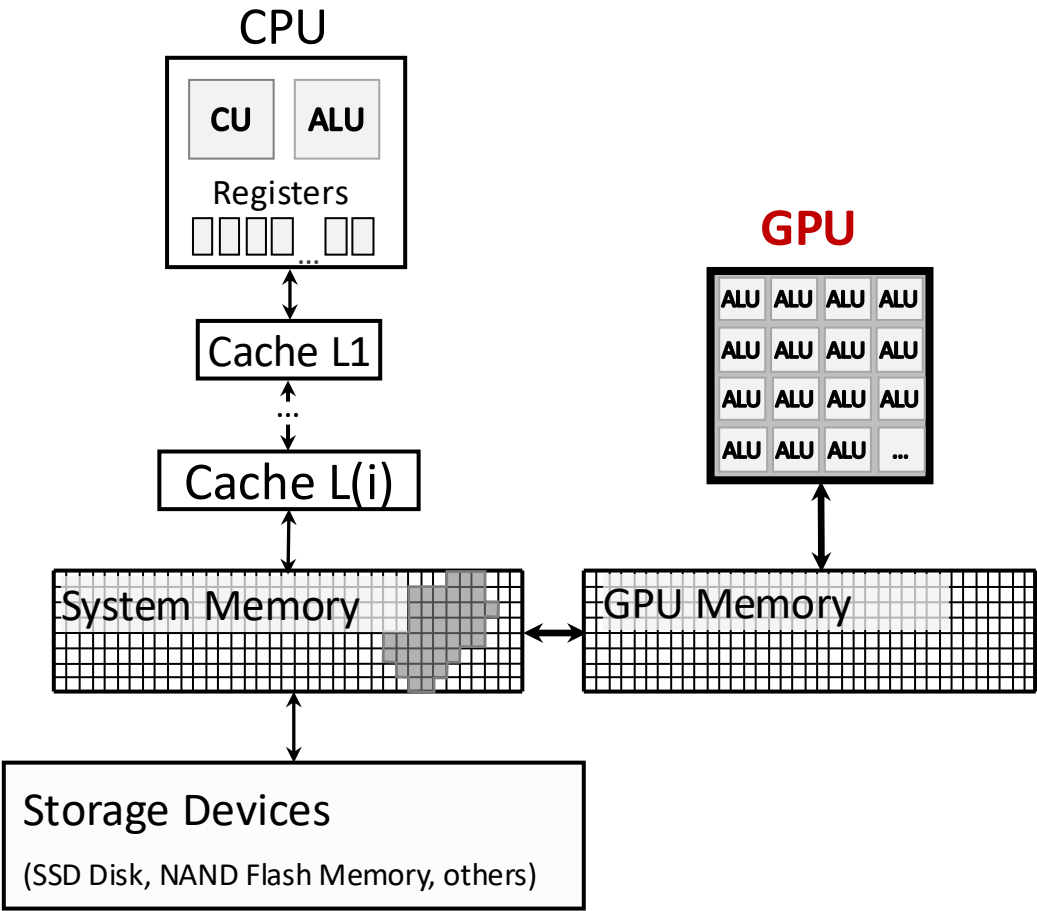
| Device                  |            | Operation Speed                                        | Storage Capacity              |
|-------------------------|------------|--------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)              | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS;<br>Parallel execution (SIMD) |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM        | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                   | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                    | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                           | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                     |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                    |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                           | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                        | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



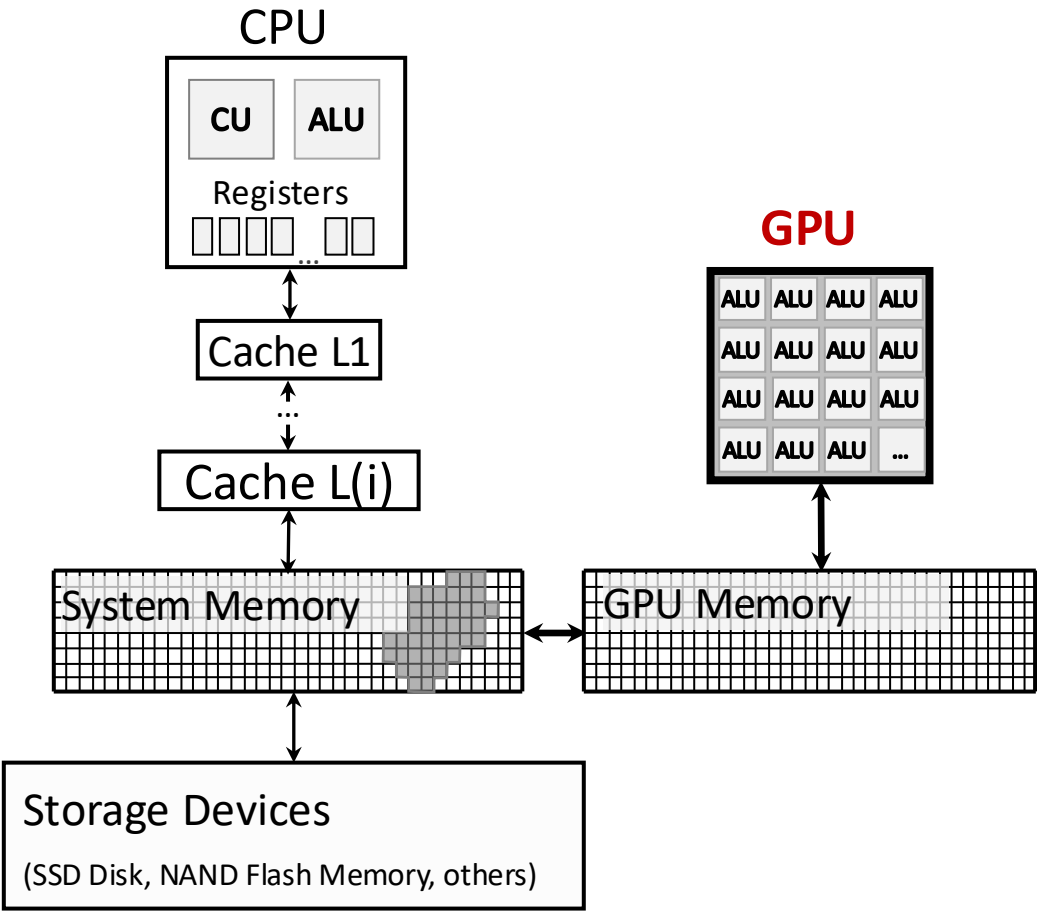
| Device                  |            | Operation Speed                                                            | Storage Capacity              |
|-------------------------|------------|----------------------------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                                  | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100 times faster than CPU |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                            | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                                       | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                                        | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                                               | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                                    | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                         |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                        |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                                               | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                                            | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



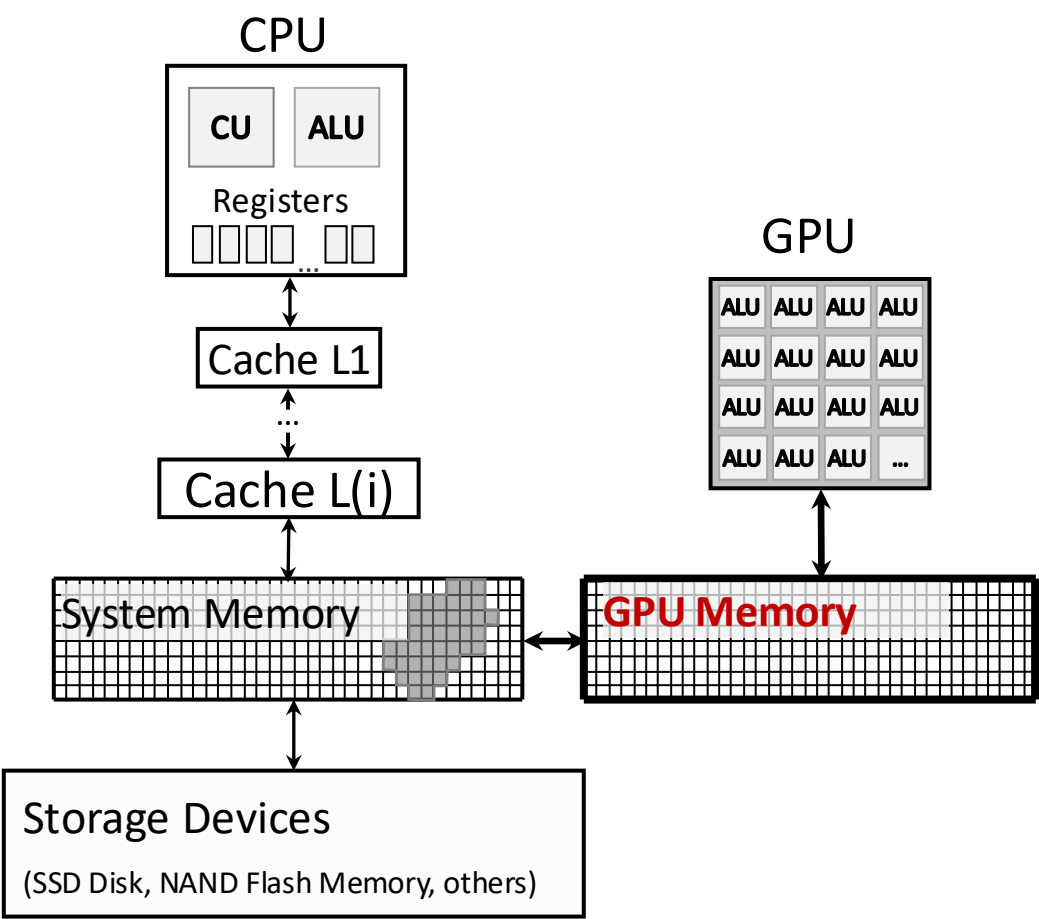
| Device                  |            | Operation Speed                                                                          | Storage Capacity              |
|-------------------------|------------|------------------------------------------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                                                | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br><b>Simple IS; parallel execution</b><br><b>~100 times faster than CPU</b> |                               |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                                          | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                                                     | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                                                      | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                                                             | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                                                  | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                                       |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                                      |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                                                             | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                                                          | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



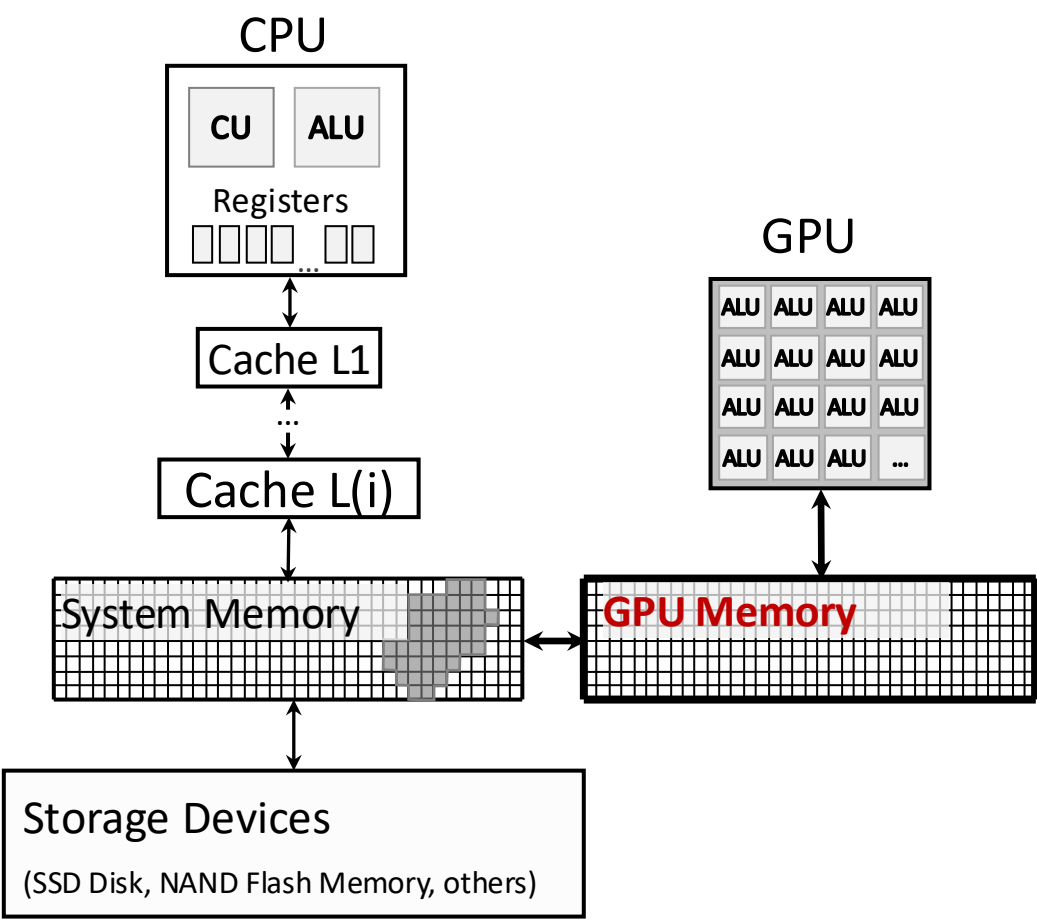
| Device                  |            | Operation Speed                                                       | Storage Capacity              |
|-------------------------|------------|-----------------------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits<br>per register       |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                                  | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                                   | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                                          | 8-32 GB                       |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                               | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                    |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                   |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                                          | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                                       | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



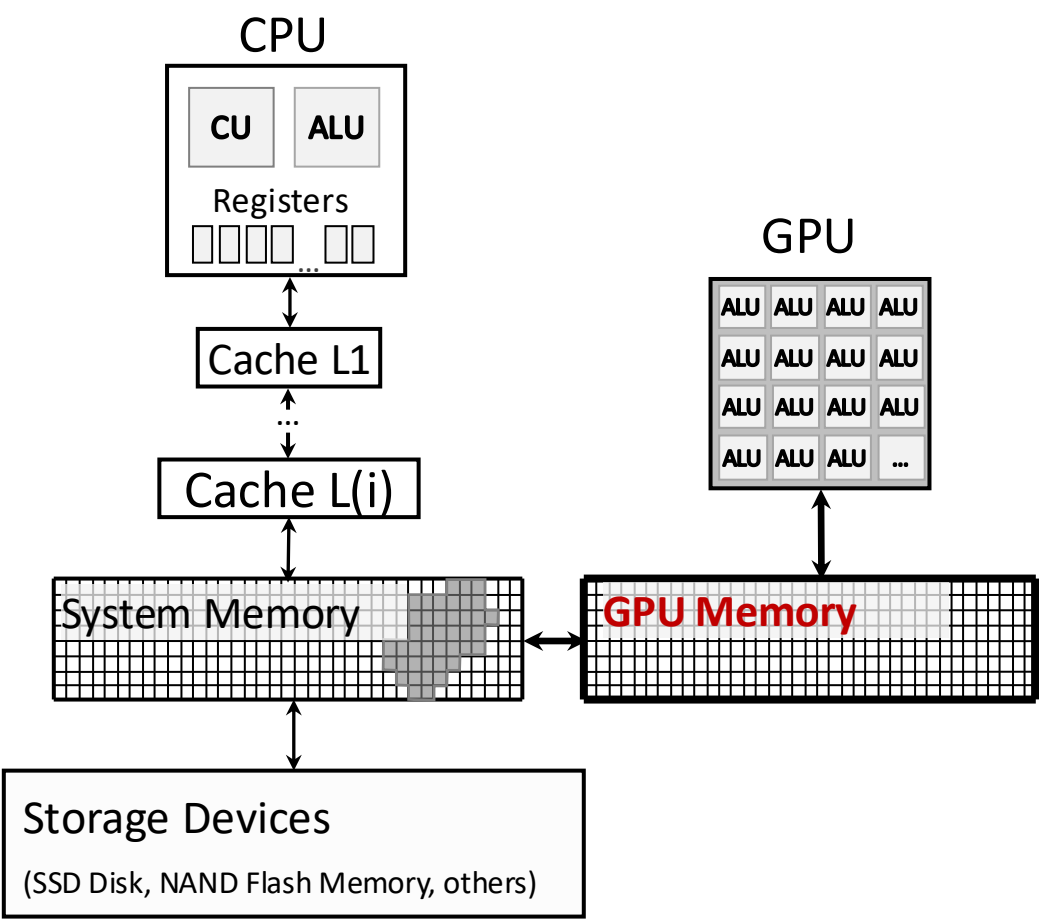
| Device                  |            | Operation Speed                                                       | Storage Capacity              |
|-------------------------|------------|-----------------------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits<br>per register       |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                                  | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                                   | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                                          | 8-32 GB                       |
| GPU Memory              |            |                                                                       |                               |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                               | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                    |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                   |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                                          | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                                       | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



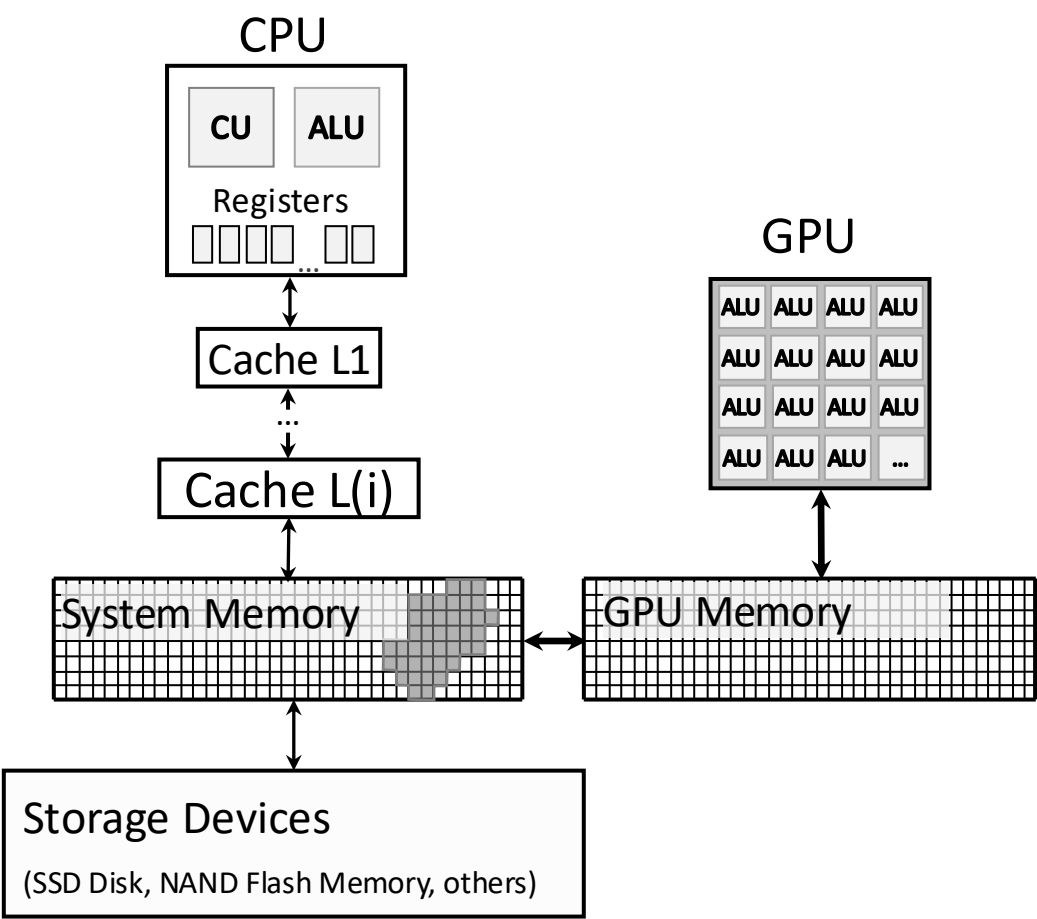
| Device                  |            | Operation Speed                                                       | Storage Capacity           |
|-------------------------|------------|-----------------------------------------------------------------------|----------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits per register       |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                  |
| L2 Cache                |            | ~25x faster than RAM                                                  | 256-512 KB                 |
| L3 Cache                |            | ~2x faster than RAM                                                   | 32-64 MB                   |
| System Memory           |            | 18-36 GB/sec                                                          | 8-32 GB                    |
| GPU Memory              |            | 300-500 GB/sec<br>(due to high throughput)                            |                            |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                               | N/A                        |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                    |                            |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                   |                            |
| Storage                 | SSD        | 0.5-2 GB/sec                                                          | 250-500 GB                 |
|                         | HDD        | 0.1-0.15 GB/sec                                                       | 100-150 GB                 |

# Average Characteristics: Laptop/Desktop



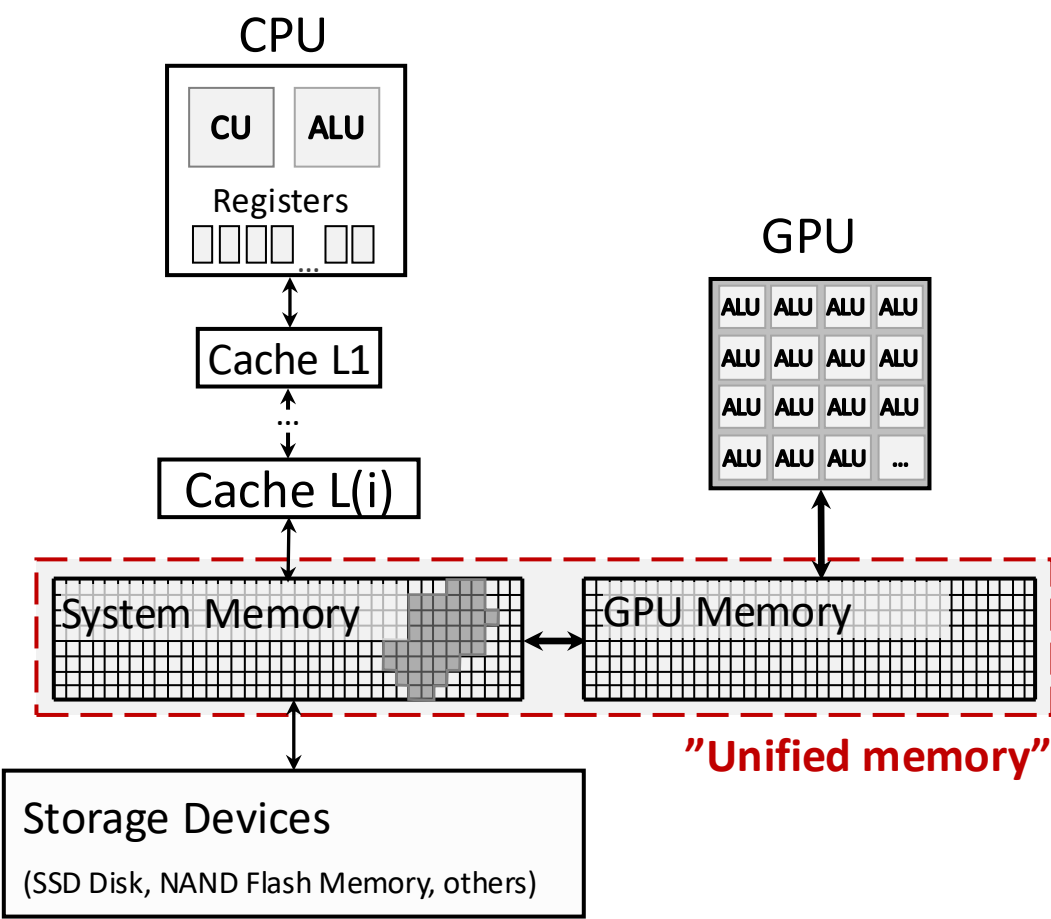
| Device                  |            | Operation Speed                                                       | Storage Capacity              |
|-------------------------|------------|-----------------------------------------------------------------------|-------------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits<br>per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits<br>per register       |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                     |
| L2 Cache                |            | ~25x faster than RAM                                                  | 256-512 KB                    |
| L3 Cache                |            | ~2x faster than RAM                                                   | 32-64 MB                      |
| System Memory           |            | 18-36 GB/sec                                                          | 8-32 GB                       |
| GPU Memory              |            | <b>300-500 GB/sec</b><br>(due to high throughput)                     | <b>8-16 GB</b>                |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                               | N/A                           |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                    |                               |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                   |                               |
| Storage                 | SSD        | 0.5-2 GB/sec                                                          | 250-500 GB                    |
|                         | HDD        | 0.1-0.15 GB/sec                                                       | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



| Device                         |                   | Operation Speed                                                       | Storage Capacity              |
|--------------------------------|-------------------|-----------------------------------------------------------------------|-------------------------------|
| <b>CPU</b><br>(4-6 cores)      |                   | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits<br>per register |
| <b>GPU</b><br>(700-2000 cores) |                   | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits<br>per register       |
| <b>L1 Cache</b>                |                   | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                     |
| <b>L2 Cache</b>                |                   | ~25x faster than RAM                                                  | 256-512 KB                    |
| <b>L3 Cache</b>                |                   | ~2x faster than RAM                                                   | 32-64 MB                      |
| <b>System Memory</b>           |                   | 18-36 GB/sec                                                          | 8-32 GB                       |
| <b>GPU Memory</b>              |                   | 300-500 GB/sec<br>(due to high throughput)                            | 8-16 GB                       |
| <b>Bus</b>                     | <b>RAM (DDR4)</b> | 18-36 GB/sec (64 lines)                                               | N/A                           |
|                                | <b>PCIe (4.0)</b> | 8 GB/sec (4 lines)                                                    |                               |
|                                | <b>USB (3.0)</b>  | 0.5 GB/sec (1 line)                                                   |                               |
| <b>Storage</b>                 | <b>SSD</b>        | 0.5-2 GB/sec                                                          | 250-500 GB                    |
|                                | <b>HDD</b>        | 0.1-0.15 GB/sec                                                       | 100-150 GB                    |

# Average Characteristics: Laptop/Desktop



| Device                  |            | Operation Speed                                                       | Storage Capacity           |
|-------------------------|------------|-----------------------------------------------------------------------|----------------------------|
| CPU<br>(4-6 cores)      |            | 2.0-3.5 GHz<br>Up to 5.0 GHz (Turbo mode)                             | 32 or 64 Bits per register |
| GPU<br>(700-2000 cores) |            | 1.5-2.0 GHz<br>Simple IS; parallel execution<br>~100x faster than CPU | 32 Bits per register       |
| L1 Cache                |            | The same as CPU speed;<br>~100x faster than RAM                       | 32-128 KB                  |
| L2 Cache                |            | ~25x faster than RAM                                                  | 256-512 KB                 |
| L3 Cache                |            | ~2x faster than RAM                                                   | 32-64 MB                   |
| System Memory           |            | 18-36 GB/sec                                                          | 8-32 GB                    |
| GPU Memory              |            | 300-500 GB/sec<br>(due to high throughput)                            | 8-16 GB                    |
| Bus                     | RAM (DDR4) | 18-36 GB/sec (64 lines)                                               | N/A                        |
|                         | PCIe (4.0) | 8 GB/sec (4 lines)                                                    |                            |
|                         | USB (3.0)  | 0.5 GB/sec (1 line)                                                   |                            |
| Storage                 | SSD        | 0.5-2 GB/sec                                                          | 250-500 GB                 |
|                         | HDD        | 0.1-0.15 GB/sec                                                       | 100-150 GB                 |

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution result of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

## Question:

What is a program execution speedup if increasing the number of cores from  $1$  to  $m$ ?

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

## Question:

What is a program execution speedup if increasing the number of cores from  $1$  to  $m$ ?

## Solution?

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

## Question:

What is a program execution speedup if increasing the number of cores from  $1$  to  $m$ ?

## Solution:

- 1)  $(100 - x)\%$  can execute in parallel upon  $m$  cores**

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

## Question:

What is a program execution speedup if increasing the number of cores from  $1$  to  $m$ ?

## Solution:

- 1)  $(100 - x)\%$  can execute in parallel upon  $m$  cores;
- 2) **These  $(100 - x)\%$  execute in parallel  $m$  times faster**

# Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

## Program given:

- 1)  $x\%$  of instructions depend on the execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

## Question:

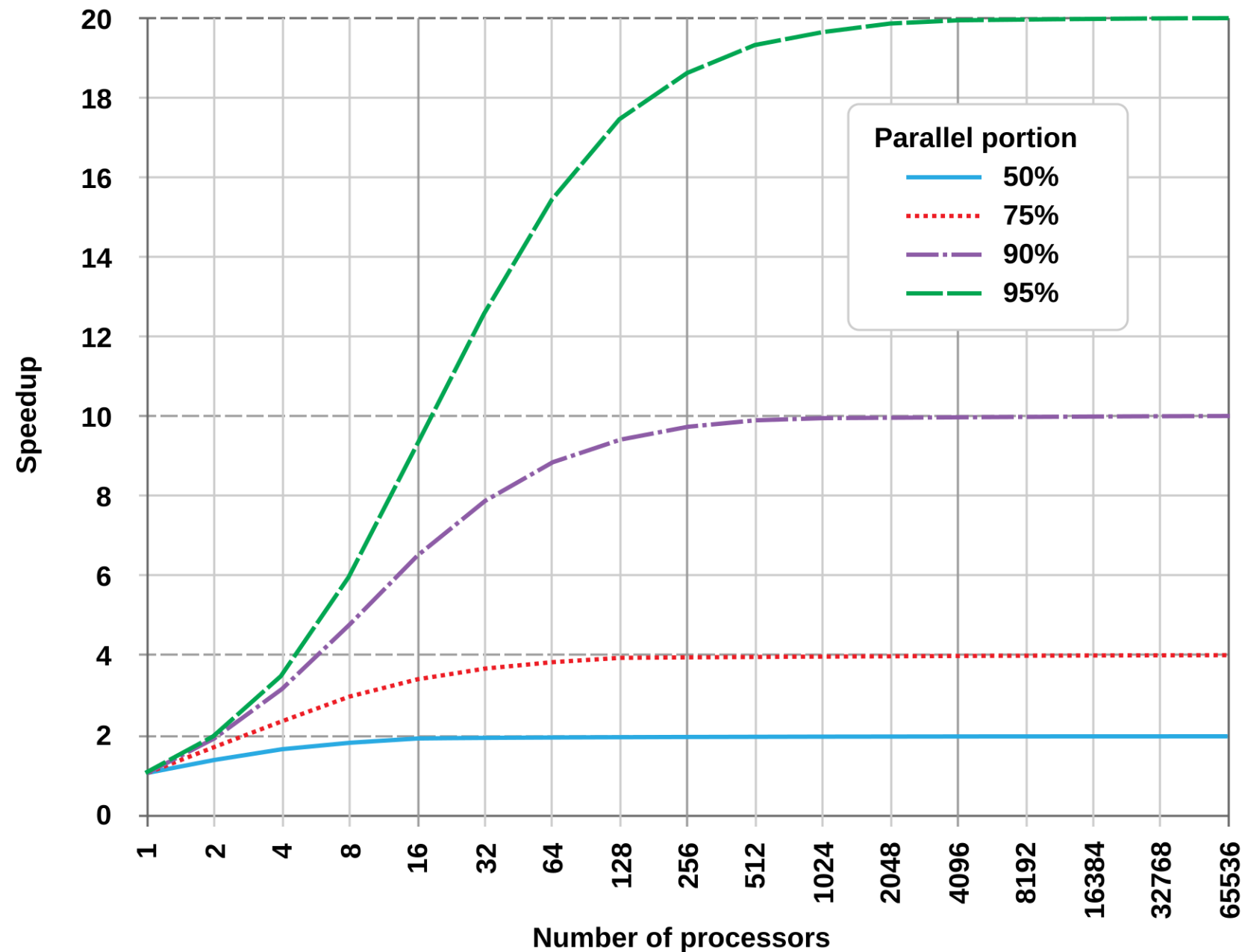
What is a program execution speedup if increasing the number of cores from  $1$  to  $m$ ?

## Solution:

- 1)  $(100 - x)\%$  can execute in parallel upon  $m$  cores;
- 2) These  $(100 - x)\%$  execute in parallel  $m$  times faster;
- 3) According to Amdahl's law, the runtime of such a program reduces according to:

$$\text{speedup} = \frac{t^{1 \text{ proc}}}{t^{m \text{ procs}}} = \frac{1}{x + \frac{1-x}{m}}$$

# Amdahl's Law



## Amdahl's Law

Provides a theoretical upper bound on the execution speedup thanks to multicores use

### Program given:

- 1)  $x\%$  of instructions depend on execution results of previous instructions;
- 2)  $(100 - x)\%$  of instructions do not depend on previous ones;

### Question:

What is a program execution speedup if increasing the number of cores from 1 to  $m$ ?

### Solution:

- 1)  $(100 - x)\%$  can execute in parallel upon  $m$  cores;
- 2) These  $(100 - x)\%$  execute in parallel  $m$  times faster;
- 3) According to Amdahl's law, the runtime of such a program reduces according to:

$$\text{speedup} = \frac{t^{1 \text{ proc}}}{t^{m \text{ procs}}} = \frac{1}{x + \frac{1-x}{m}}$$

