Introduction

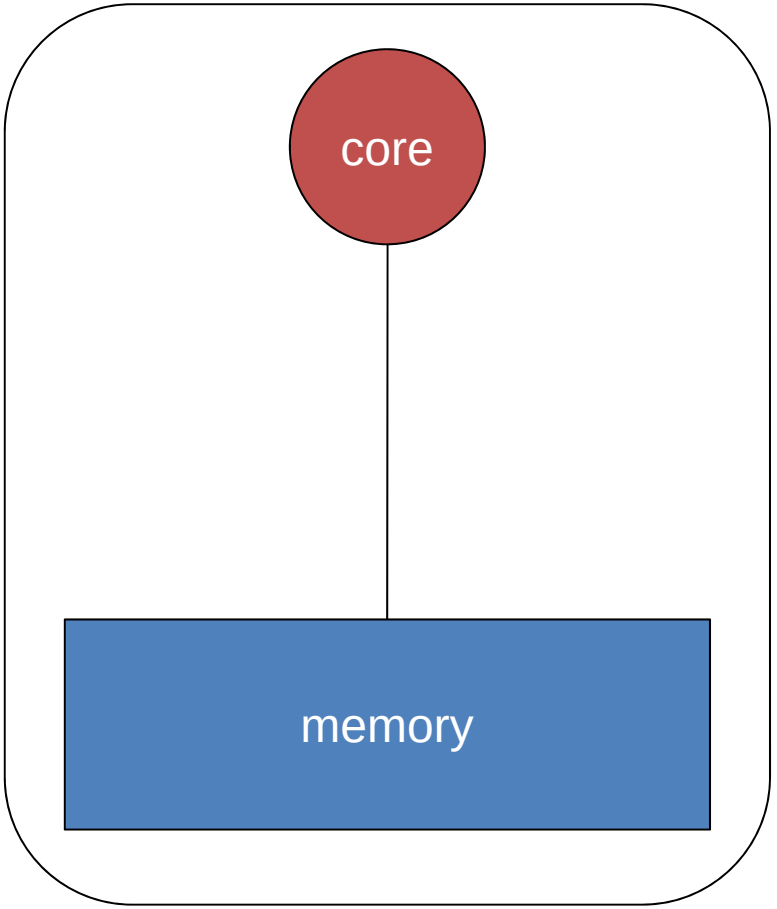
Computer Architectures, Parallelization at a Glance

Introduction - Contents

- **Computer Architectures**
  - Basic Computer Architectures
  - Shared-Memory Parallel Systems
  - Distributed-Memory Parallel Systems
- **Parallelization at a Glance**
  - Basic Concepts
  - Parallelization Strategies
  - Prominent Issues

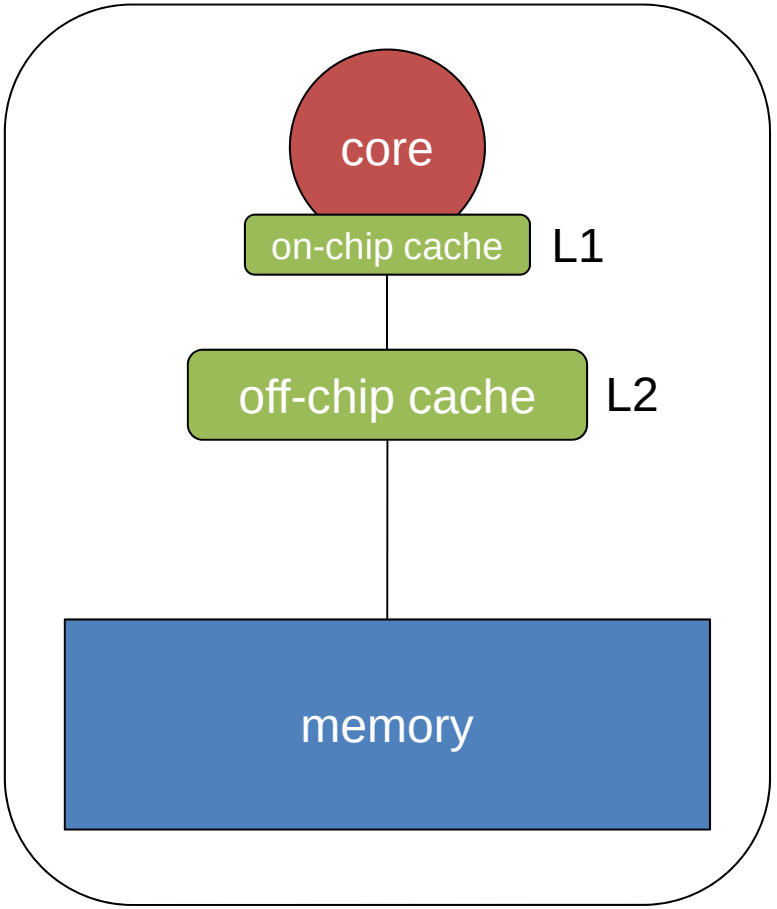
Single Processor Systems (1 / 2)

- **Processor**
  - Fetch program from memory
  - Execute program instructions
  - Load data from memory
  - Process data
  - Write results back to memory
- **Main Memory**
  - Store program
  - Store data
- **Input / Output is not covered here!**



Single Processor Systems (1 / 2)

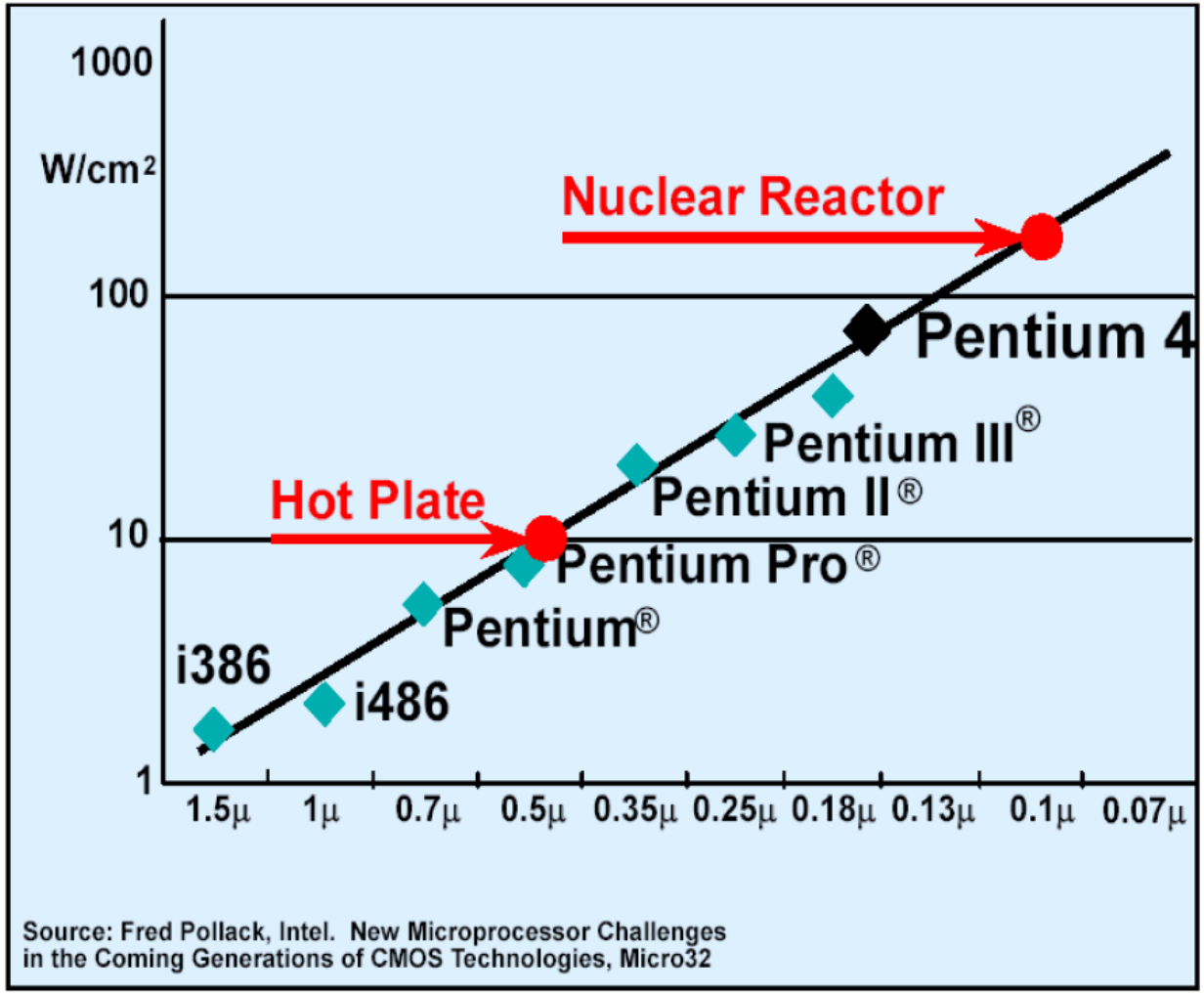
- **CPU**
  - Fast (order of **3.0 GHz**)
- **Main Memory**
  - Slow (order of **0.3 GHz**)
  - Large (order of **GB**)
- **Caches**
  - Fast, but expensive
  - Small (order of **MB**)



- **Usage of Cache is mandatory for good performance on parallel applications.**

Why aren't CPUs getting faster anymore?

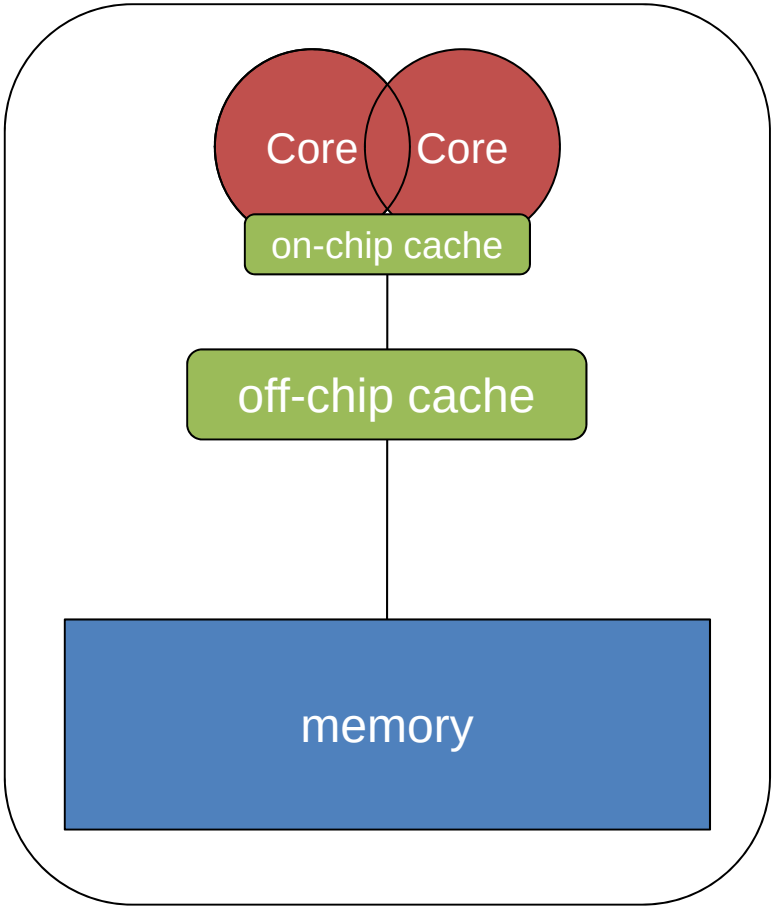
- The CPU would get too hot!



Fast clock cycles make processor chips more expensive, hotter and more power consuming.

Multi-Core Processor Systems

- **Since 2005/2006 dual-core processors are produced for the home user.**
- **Number of cores per chip increases since then**
  - Today: up to 8 cores per chip for a standard CPU
- **Any recently bought PC or Laptop is a multi-core system already.**



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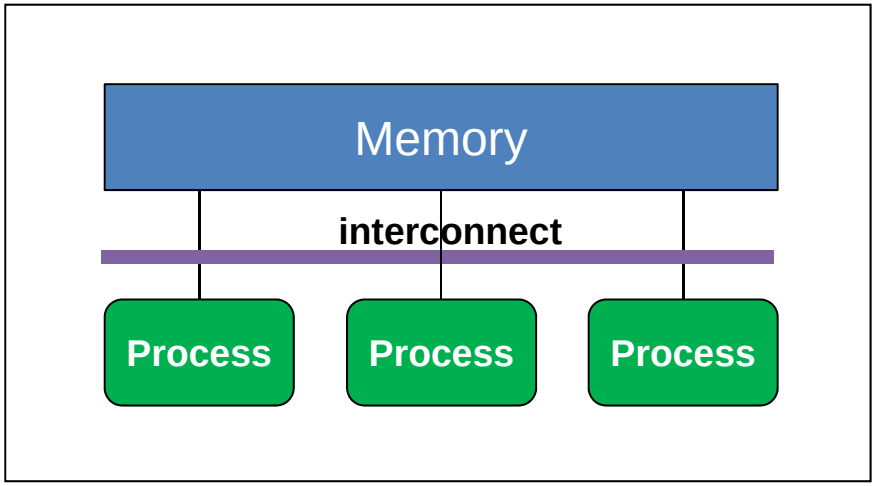
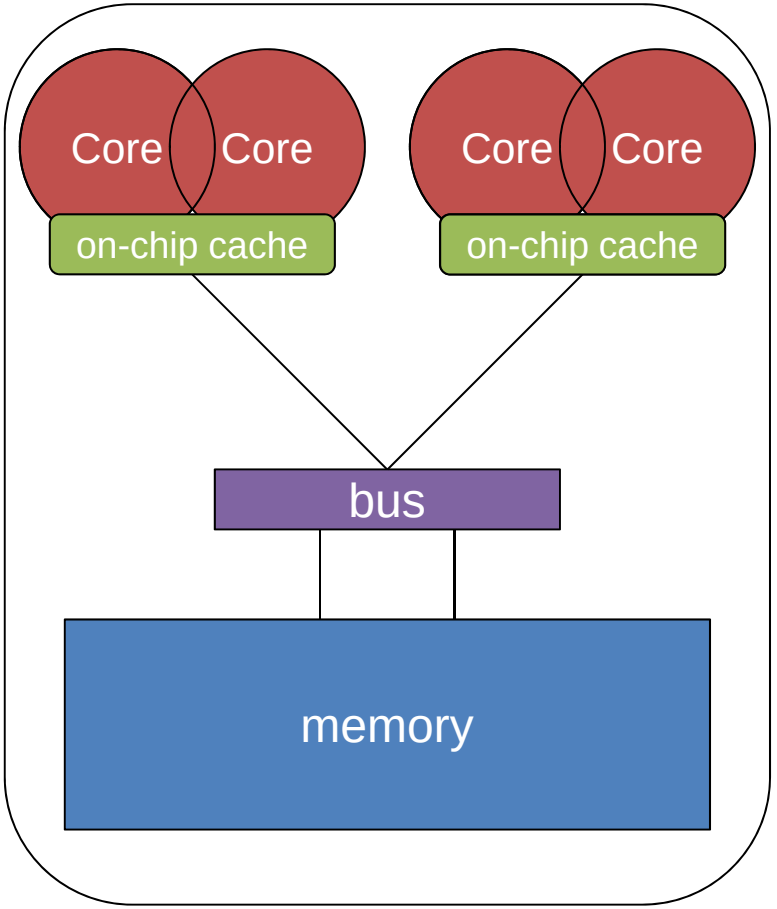
Shared-Memory Parallel Systems

- **Implicit data distribution**
- **Implicit communication**
- **Different types of shared-memory architectures**
- **Programming via …**
  - OpenMP
  - Java-Threads

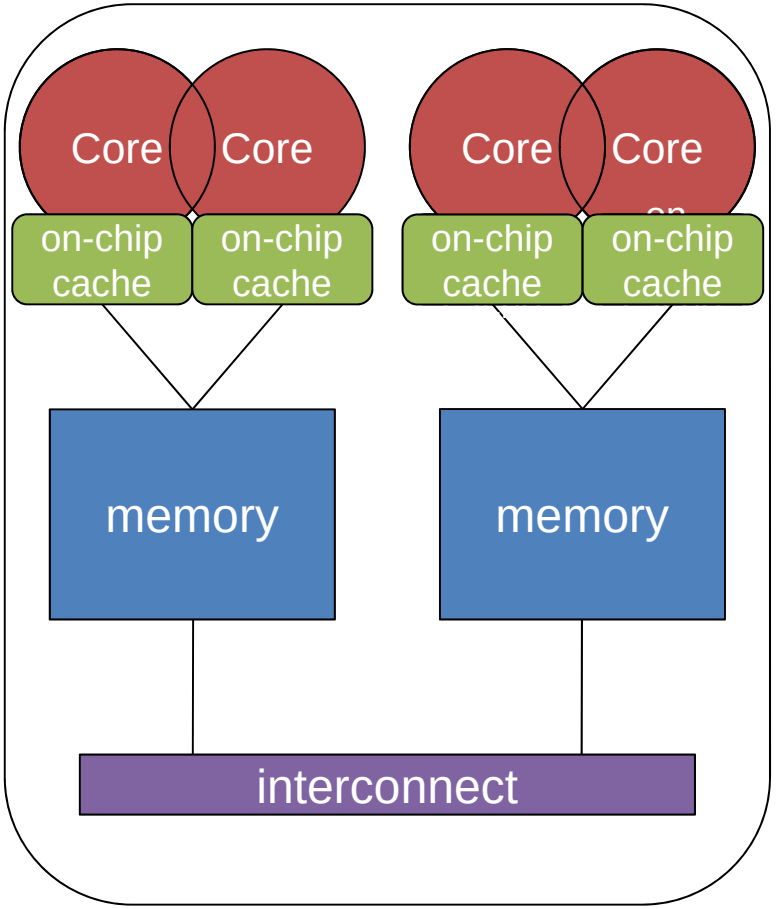


SMP

- **Abbr. for *Symmetric Multi Processing***
- **Memory access time is uniform on all cores**
- **Limited scalability**
- **Example: *Intel Woodcrest***
  - Two cores per chip, 3.0 GHz
  - Each chip has 4 MB of L2 cache on-chip, shared by both cores
  - No off-chip cache
  - Bus: Frontsidebus



- **Abbr. for *cache-coherent Non-Uniform Memory Architecture***
- **Memory access time is non-uniform**
- **Scalable**
- **Example: *AMD Opteron***
  - Two cores per chip, 2.4 GHz
  - Each core has separate 1 MB of L2-cache on-chip
  - No off-chip cache
  - Interconnect: Hypertransport



Cache Coherence (cc)

- **If there are multiple caches not shared by all cores in the system, the system takes care of the cache coherence.**

- **Example:**

```
int a[some_number]; //shared by all threads
thread 1: a[0] = 23;     thread 2: a[1] = 42;
--- thread + memory synchronization (barrier) ---
thread 1: x = a[1];      thread 2: y = a[0];
```

  - Both `a[0]` and `a[1]` are stored in caches of thread 1 and 2
  - Changes to data in the cache is at first only visible for the CPU that modified its cache
  - After synchronization point all threads need to have the same view of (shared) main memory

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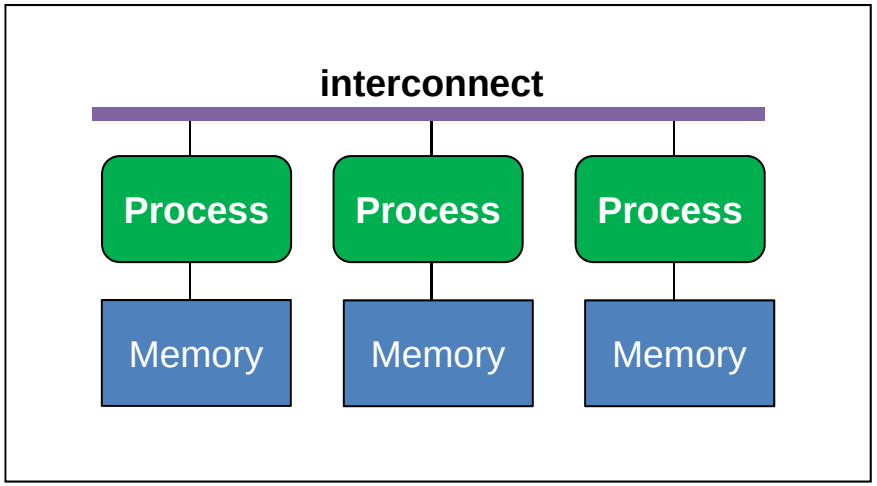
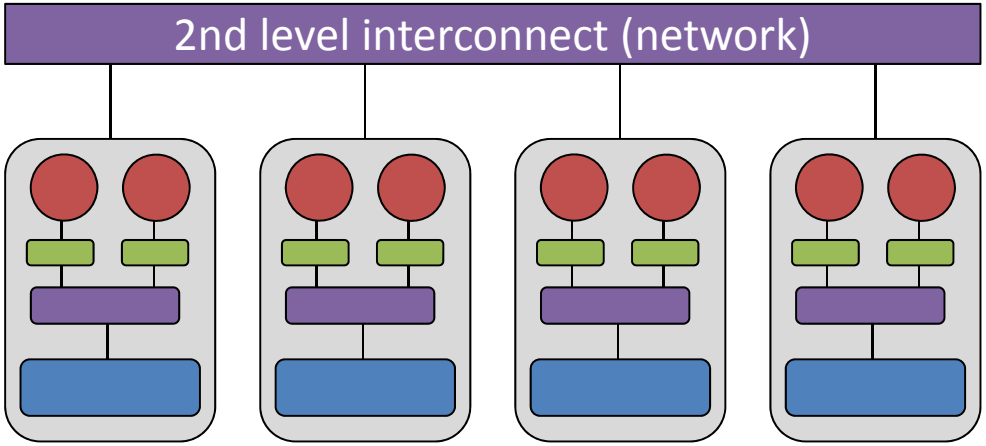
Distributed-memory Parallel Systems

- Explicit data distribution
- Explicit communication
- Scalable
- Programming via MPI



Clusters

- **Various independent computers are connected to each other over a non-cache-coherent *second level interconnect***
  - Infiniband
    - Latency: <= 5 µs
    - Bandwidth: >= 1200 MB/s
  - GigaBit Ethernet
    - Latency: <= 60 µs
    - Bandwidth: >= 100 MB/s



Latency:
Time required to send a message of size zero
(time to setup the communication)

Bandwidth:
Rate at which large messages (>= 2 MB) are transferred

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Processes

- **A process is the abstraction of a program in execution**
- **It can be in different states**
  - Running
  - Waiting
  - Ready
- **Each process has its own address-space**
  - → No common variables between processes

Threads

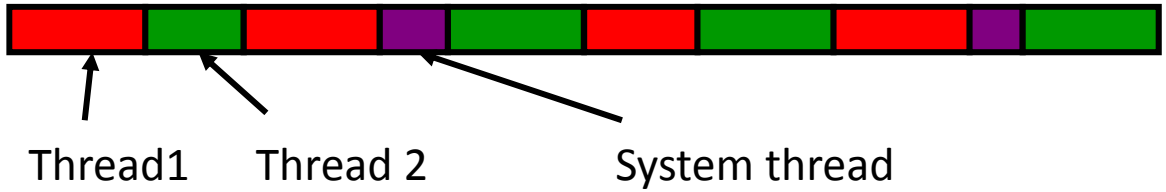
- **A thread is a *lightweight* process**

- **In difference to a process, a thread shares the address-space with all other threads of the process it belongs to, but has its own stack.**
  - ➝ Common variables between threads

Process and Thread Scheduling by the OS

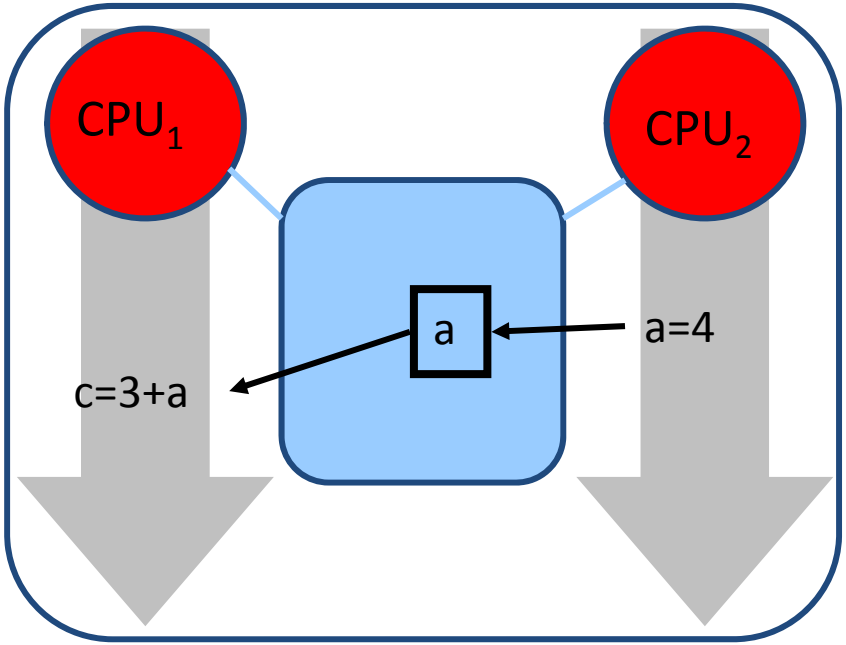
- **Even on a multi-socket / multi-core system you should not make any assumption which process / thread is executed when an where!**

- **Two threads on one core:**



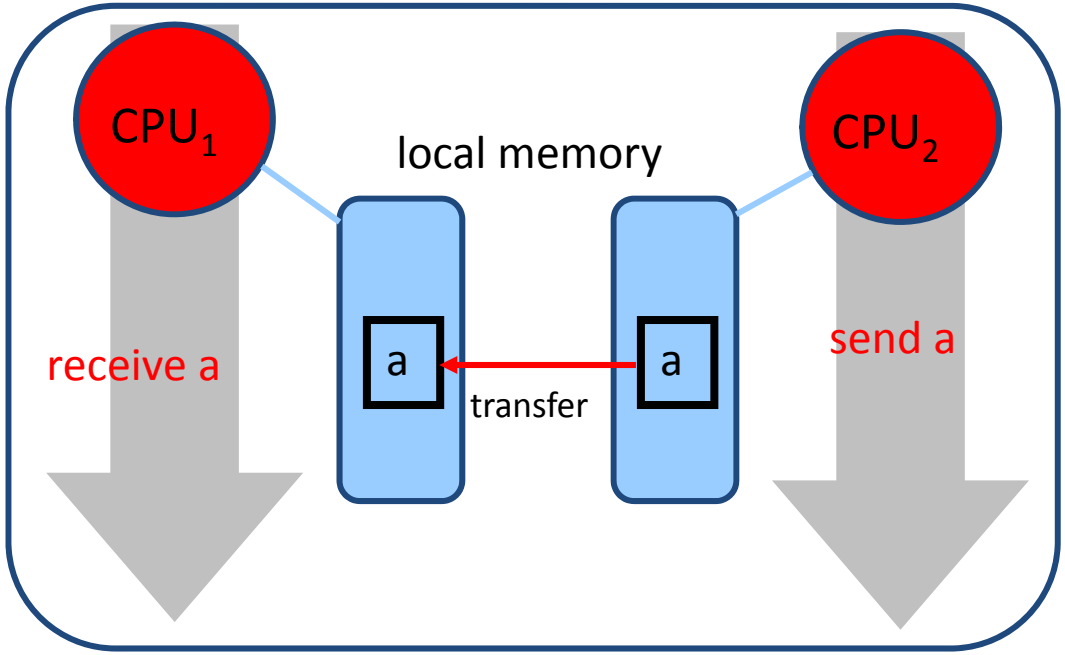
- **Two threads on two cores:**

- Memory can be accessed by several threads running on different cores in a multi-socket / multi-core system



Distributed-memory Parallelization

- Each process has its own distinct memory
- Communication via *Message Passing*



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Speedup and Efficiency (1 / 2)

- **Time using 1 CPU:** $\boldsymbol{T(1)}$
- **Time using p CPUs:** $\boldsymbol{T(p)}$
- **Speedup S:** $\boldsymbol{S(p) = \frac{T(1)}{T(p)}}$
  - Measures how much fast the parallel computation is
- **Efficiency E:** $\boldsymbol{E(p) = \frac{S(p)}{p}}$

Speedup and Efficiency (2 / 2)

- **Example:**
  - $T(1) = 6s,\ T(2) = 4s$
    - → $S(2) = \frac{6}{4} = \frac{3}{2} = 1.5$
    - → $E(2) = \frac{1.5}{2} = \frac{3}{4} = 0.75$
- **Ideal case: $T(p) = T(1)/p$**
  - $S(p) = p$
  - $E(p) = 1.0$

Amdahl's Law

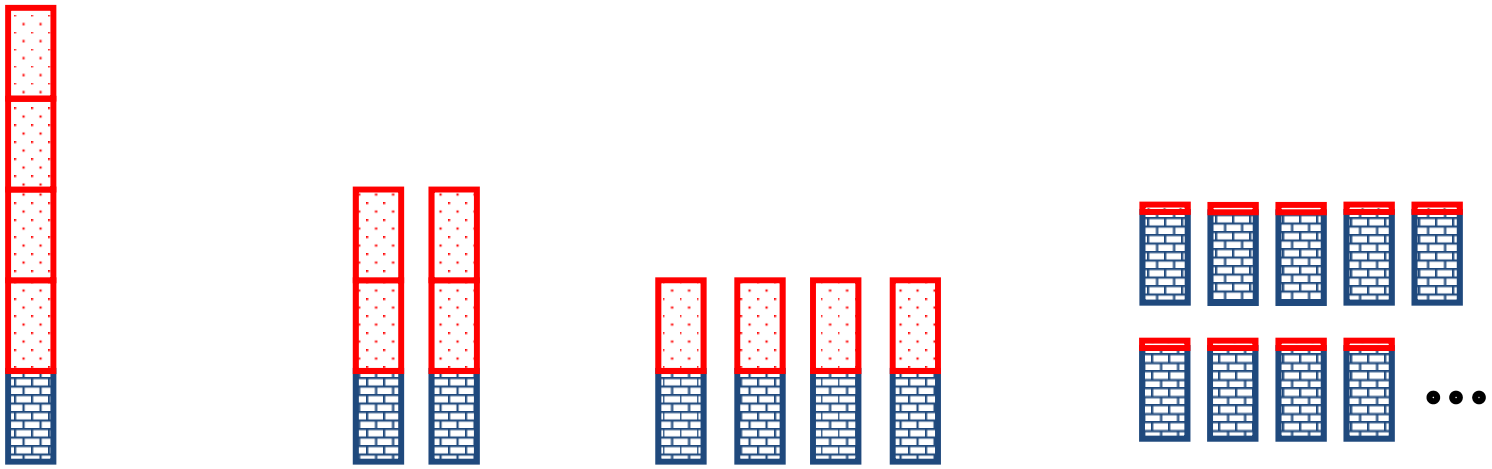
- **Describes the influence of the serial part onto scalability (without taking any overhead into account).**

- $S(p) = \frac{T(1)}{T(p)} = \frac{T(1)}{f * T(1) + (1-f) * \frac{T(1)}{p}} = \frac{1}{f + \frac{1-f}{p}}$
  - f: serial part ($0 \leq f \leq 1$)
  - $T(1)$: time using 1 CPU
  - $T(p)$: time using p CPUs
  - $S(p)$: speedup; $S(p) = \frac{T(1)}{T(p)}$
  - $E(p)$: efficiency; $E(p) = \frac{S(p)}{p}$

- **It is rather easy to scale to a small number of cores, but any parallelization is limited by the serial part of the program!**

Amdahl's Law illustrated

- **If 80% (measured in program runtime) of your work can be parallelized and "just" 20% are still running sequential, then your speedup will be:**



1 processor:
time: 100%
speedup: 1

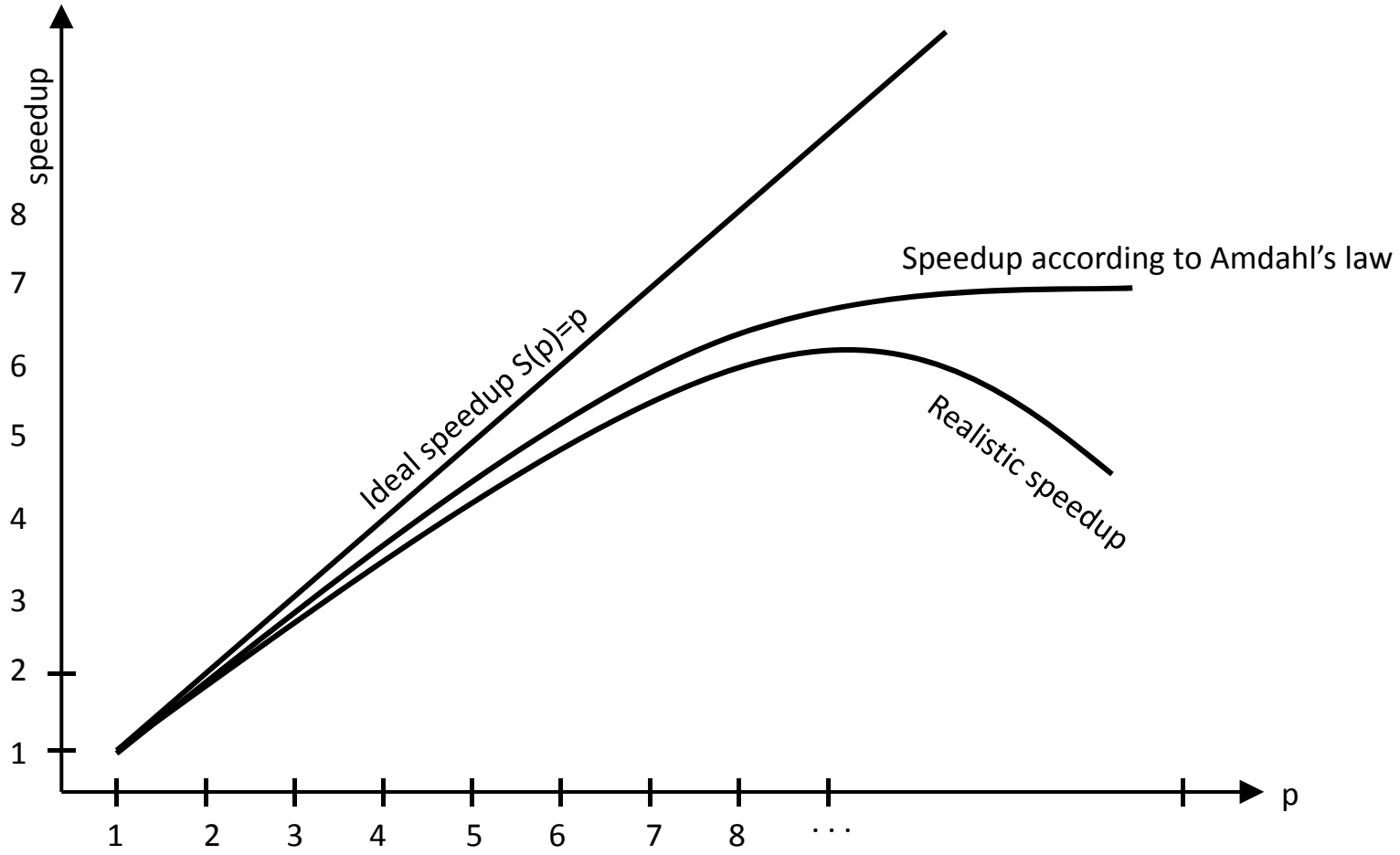
2 processors:
time: 60%
speedup: 1.7

4 processors:
time: 40%
speedup: 2.5

∞ processors:
time: 20%
speedup: 5

Speedup in Practice

- **After the initial parallelization of a program, you will typically see speedup curves like this:**



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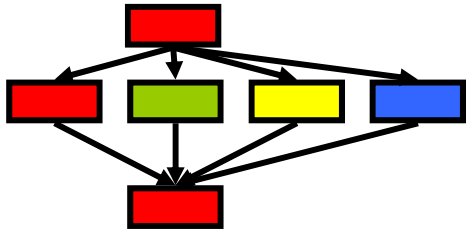
Chances for concurrent execution:

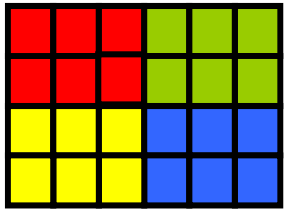
- Look for tasks that can be executed simultaneously

  (task decomposition)



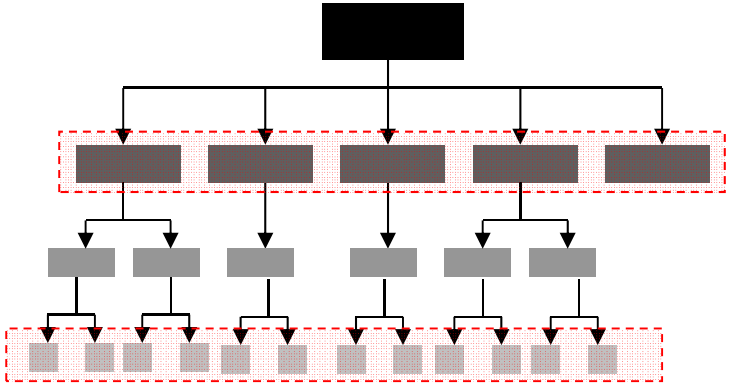
- Decompose data into distinct chunks to be processed independently

  (data decomposition)



Granularity

- **Parallelization on a High Level (low granularity)**
  - Chances of low synchronization / communication cost
  - Danger of load balancing issues
- **Parallelization on a Low Level (high granularity)**
  - Danger of high synchro-nization / communication cost
  - Chances of avoiding load balancing issues



- **Compute intensive programs may employ multiple levels of parallelization, maybe even with multiple parallelization paradigms (hybrid parallelization).**

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Issues in Parallel Programming: Overview

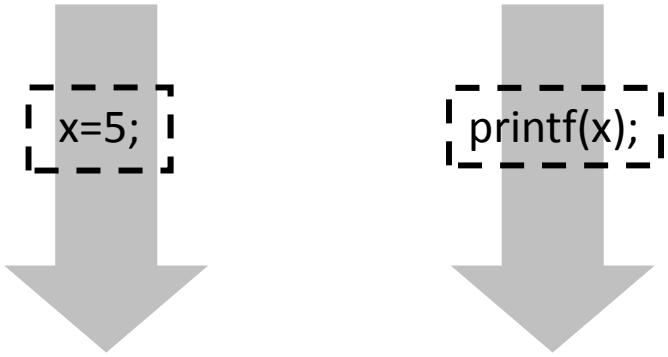
- **You can still run into all issues of Serial Programming ☹ !**
- **Additional issues:**
  - Is your parallelization correct?
  - It is harder to debug parallel code than serial code!
- **Specific issues of Parallel Programming:**
  - Introduction of overhead by parallelization
  - Data Races / Race Conditions
  - Deadlocks
  - Load Balancing
  - Serialization
  - Irreproducibility / Different numerical results

Parallelization Overhead

- **Overhead introduced by the parallelization:**
  - Time to start / end / manage threads
  - Time to send / exchange data
  - Time spent in synchronization of threads / processes
- **With parallelization:**
  - The total CPU time increases,
  - The Wall time decreases,
  - The System time stays the same.
- **Efficient parallelization is about minimizing the overhead introduced by the parallelization itself!**

Data Races / Race Conditions

- **Data Race: Concurrent access of the same memory location by multiple threads without proper synchronization**
  - Let x be initialized with 1



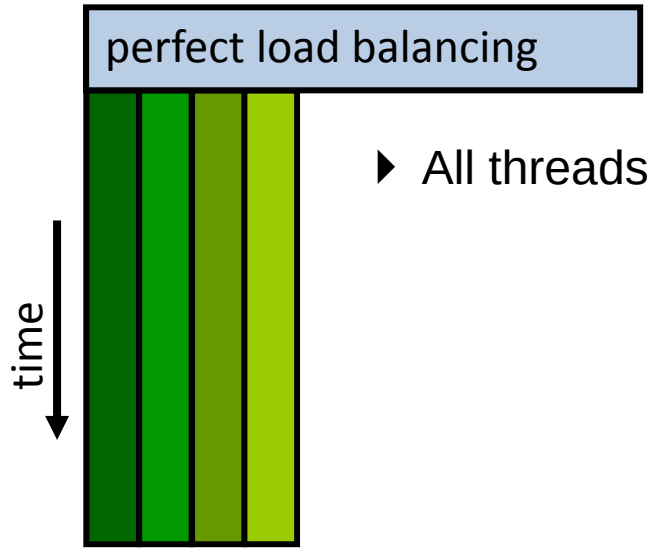
  - Depending on which thread is faster, you will see either 1 or 5
  - Result is nondeterministic (i.e. depends on OS scheduling)

- **Data Races (and how to detect and avoid them) will be covered in more detail later!**

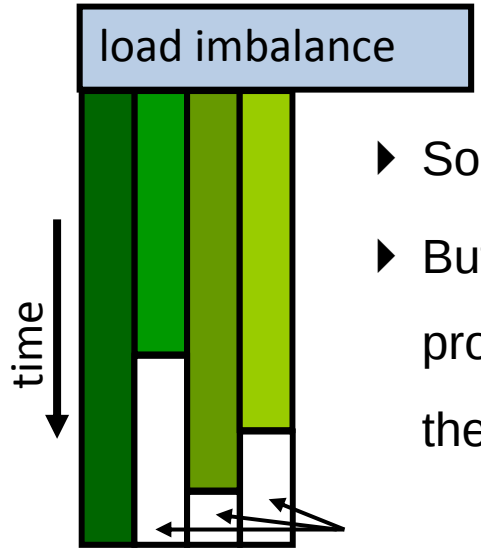
Deadlock

- When two or more threads / processes are waiting for another to release a resource in a circular chain, the program appears to „hang“:

Load Balancing



- All threads / processes finish at the same time



- Some threads / processes take longer than others
- But: All threads / processes have to wait for the slowest thread / process, which is thus limiting the scalability

- **Serialization: When threads / processes wait „too much“**
  - Limited scalability, if at all

- **Simple (and stupid) example:**