



Parallel Processing

WS 2017/18

Roland Wismüller
Universität Siegen
roland.wismueller@uni-siegen.de
Tel.: 0271/740-4050, Büro: H-B 8404

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1 Basics



Contents

- ➔ Motivation
- ➔ Parallelism
- ➔ Parallel computer architectures
- ➔ Parallel programming models
- ➔ Performance and scalability of parallel programs
- ➔ Strategies for parallelisation
- ➔ Organisation forms for parallel programs

Literature

- ➔ Ungerer
- ➔ Grama, Gupta, Karypis, Kumar

1.1 Motivation



What is parallelism?

- ➔ In general:
 - ➔ executing more than one action at a time
- ➔ Specifically with respect to execution of programs:
 - ➔ at some point in time
 - ➔ more than one statement is executed
 - and / or
 - ➔ more than one pair of operands is processed
- ➔ Goal: faster solution of the task to be processed
- ➔ Problems: subdivision of the task, coordination overhead



Why parallel processing?

- ➔ Applications with high computing demands, esp. simulations
 - ➔ climate, earthquakes, superconductivity, molecular design, ...
- ➔ Example: protein folding
 - ➔ 3D structure, function of proteins (Alzheimer, BSE, ...)
 - ➔ $1,5 \cdot 10^{11}$ floating point operations (Flop) / time step
 - ➔ time step: $5 \cdot 10^{-15} s$
 - ➔ to simulate: $10^{-3} s$
 - ➔ $3 \cdot 10^{22}$ Flop / simulation
 - ➔ \Rightarrow 1 year computation time on a PFlop/s computer!
- ➔ For comparison: world's currently fastest computer: Sunway TaihuLight (China), 93 PFlop/s (with 10.649.600 CPU cores!)

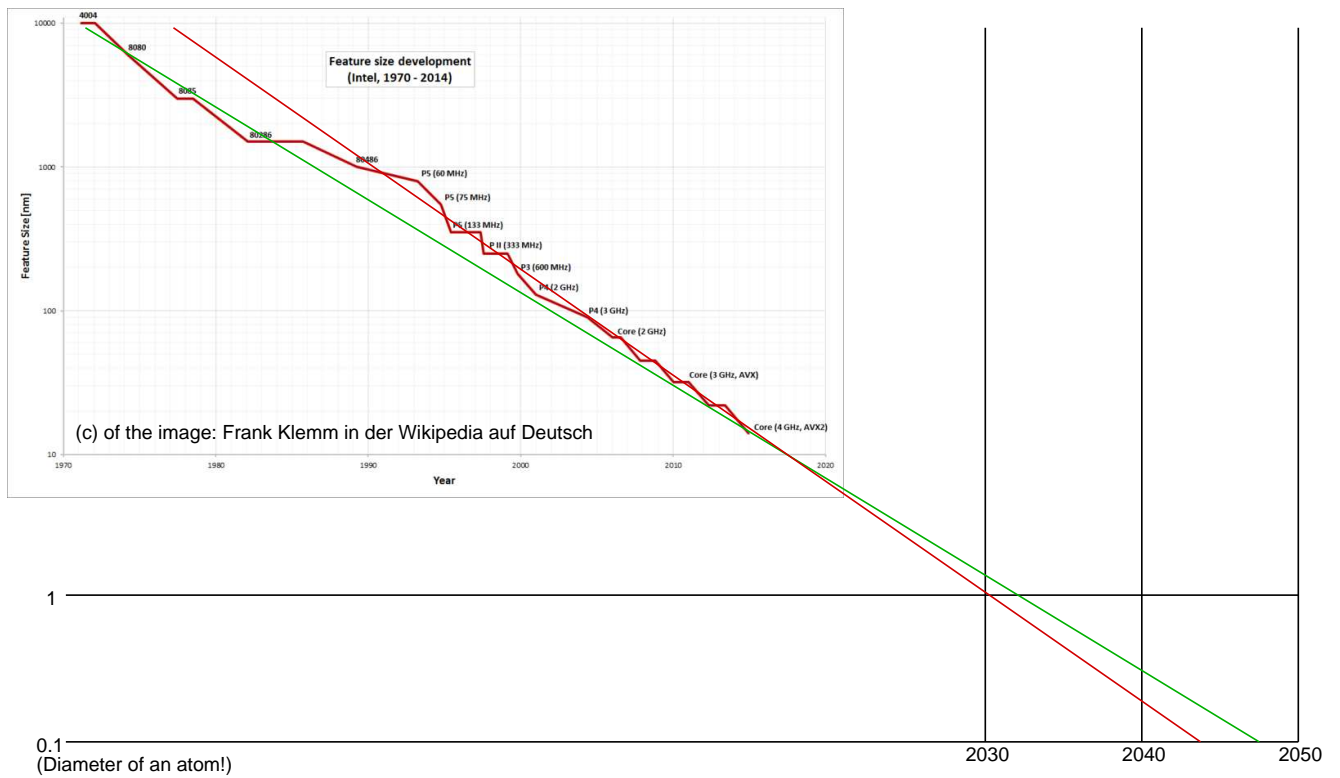


Why parallel processing? ...

- ➔ **Moore's Law:** the computing power of a processor doubles every 18 months
 - ➔ but: memory speed increases much slower
 - ➔ 2040 the latest: physical limit will be reached
- ➔ Thus:
 - ➔ high performance computers are based on parallel processing
 - ➔ even standard CPUs use parallel processing internally
 - ➔ super scalar processors, pipelining, multicore, ...
- ➔ Economic advantages of parallel computers
 - ➔ cheap standard CPUs instead of specifically developed ones

Notes for slide 24:

An estimation of the end of “Moore’s Law”:

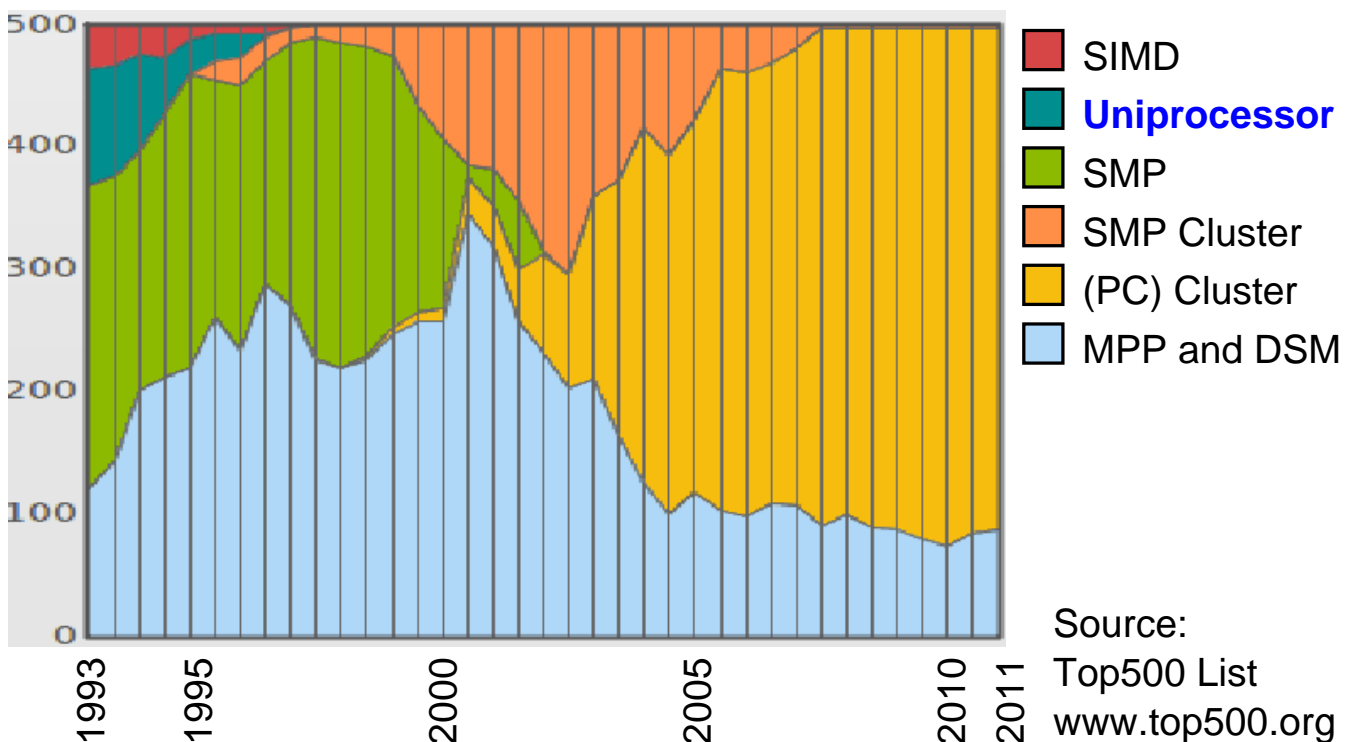


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1.1 Motivation ...



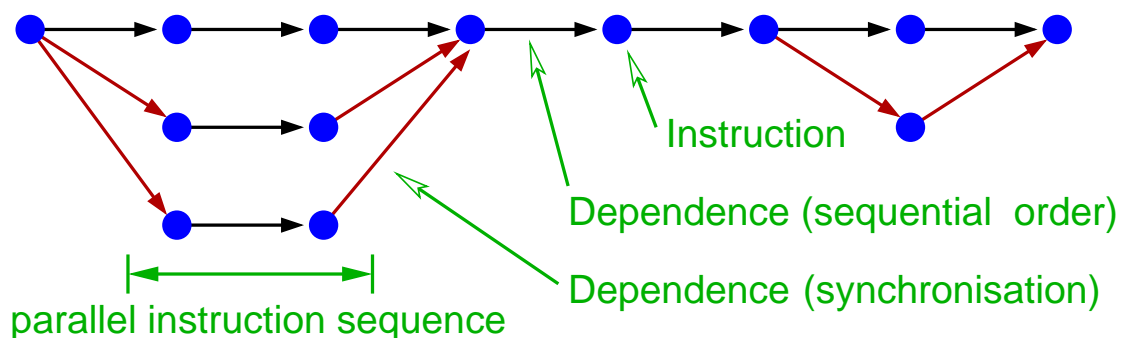
Architecture trend of high performance computers





What is a parallel programm?

- ➔ A parallel program can be viewed as a partially ordered set of instructions (activities)
 - ➔ the order is given by the dependences between the instructions
- ➔ Independent instructions can be executed in parallel



1.2 Parallelism ...

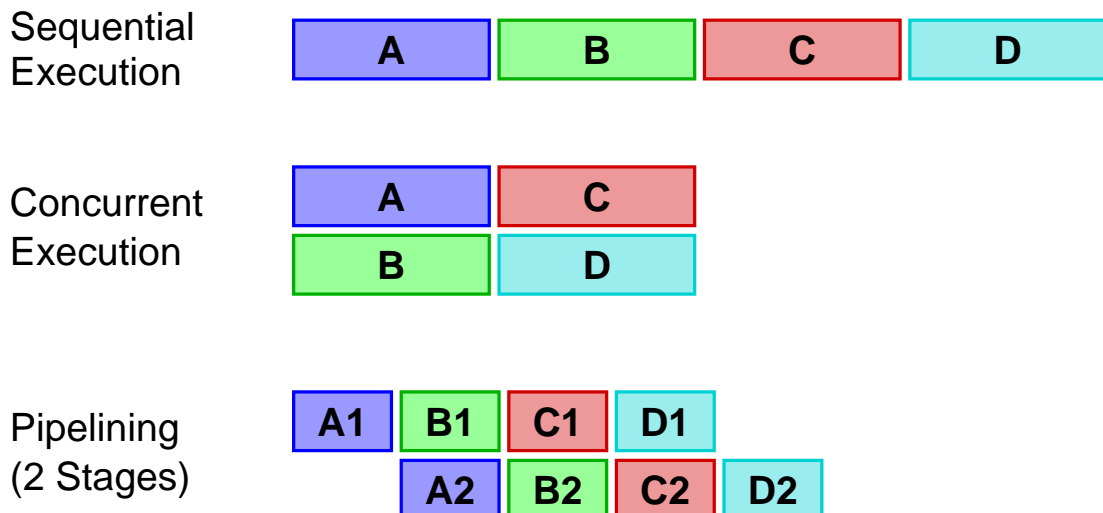


Concurrency vs. pipelining

- ➔ **Concurrency** (*Nebenläufigkeit*): instructions are executed simultaneously in different execution units
- ➔ **Pipelining**: execution of instructions is subdivided into sequential phases. Different phases of **different** instruction **instances** are executed simultaneously.
- ➔ Remark: here, the term “instruction” means a generic compute activity, depending on the layer of abstraction we are considering
 - ➔ e.g., machine instruction, execution of a sub-program



Concurrency vs. pipelining ...



At which layers of programming can we use parallelism?

- ➔ There is no consistent classification
- ➔ E.g., layers in the book from Waldschmidt, *Parallelrechner: Architekturen - Systeme - Werkzeuge*, Teubner, 1995:
 - ➔ application programs
 - ➔ cooperating processes
 - ➔ data structures
 - ➔ statements and loops
 - ➔ machine instruction

“They are heterogeneous, subdivided according to different characteristics, and partially overlap.”



View of the application developer (design phase):

- ➔ “Natural parallelism”
 - ➔ e.g., computing the foci for all stars of a galaxy
 - ➔ often too fine-grained
- ➔ **Data parallelism** (domain decomposition, *Gebietsaufteilung*)
 - ➔ e.g., sequential processing of all stars in a space region
- ➔ **Task parallelism**
 - ➔ e.g., pre-processing, computation, post-processing, visualisation



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Roland Wismüller
Universität Siegen
roland.wismueller@uni-siegen.de
Tel.: 0271/740-4050, Büro: H-B 8404

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View of the programmer:

➔ Explicit parallelism

- ➔ exchange of data (communication / synchronisation) must be explicitly programmed

➔ Implicit parallelism

- ➔ by the compiler
 - ➔ directive controlled or automatic
 - ➔ loop level / statement level
 - ➔ compiler generates code for communication
- ➔ within a CPU (that appears to be sequential from the outside)
 - ➔ super scalar processor, pipelining, ...



View of the system (computer / operating system):

➔ Program level (job level)

- ➔ independent programs

➔ Process level (task level)

- ➔ cooperating processes
- ➔ mostly with explicit exchange of messages

➔ Block level

- ➔ light weight processes (threads)
- ➔ communication via shared memory
- ➔ often created by the compiler
 - ➔ parallelisation of loops



View of the system (computer / operating system): ...

➔ Instruction level

- ➔ elementary instructions (operations that cannot be further subdivided in the programming language)
- ➔ scheduling is done automatically by the compiler and/or by the hardware at runtime
- ➔ e.g., in VLIW (EPIC) and super scalar processors

➔ Sub-operation level

- ➔ compiler or hardware subdivide elementary instructions into sub-operations that are executed in parallel
 - ➔ e.g., with vector or array operations



Granularity

- ➔ Defined by the ratio between computation and communication (including synchronisation)
 - ➔ intuitively, this corresponds to the length of the parallel instruction sequences in the partial order
 - ➔ determines the requirements for the parallel computer
 - ➔ especially its communication system
 - ➔ influences the achievable acceleration (*Speedup*)
- ➔ Coarse-grained: Program and Process level
- ➔ Mid-grained: block level
- ➔ Fine-grained: instruction level

1.3 Parallelisation and Data Dependences



(Animated slide)

- ➔ Important question: when can two instructions S_1 and S_2 be executed in parallel?
 - ➔ Answer: if there are no **dependences** between them
- ➔ Assumption: instruction S_1 can and should be executed **before** instruction S_2 according to the sequential code
 - ➔ e.g.: $S_1: x = b + 2 * a;$
 $y = a * (c - 5);$
 $S_2: z = \text{abs}(x - y);$
 - ➔ but also in different iterations of a loop

- ➔ **True / flow dependence** (*echte Abhängigkeit*) $S_1 \xrightarrow{\delta^t} S_2$

$S_1: a[1] = a[0] + b[1];$
 $S_2: a[2] = a[1] + b[2];$

S_1 ($i=1$) writes to $a[1]$, which is later read by S_2 ($i=2$)

1.3 Parallelisation and Data Dependences ...



(Animated slide)

- ➔ **Anti dependence** (*Antiabhängigkeit*) $S_1 \xrightarrow{\delta^a} S_2$

$S_1: a[1] = a[2];$
 $S_2: a[2] = a[3];$

S_1 ($i=1$) reads the value of $a[2]$, which is overwritten by S_2 ($i=2$)

- ➔ **Output dependence** (*Ausgabeabhängigkeit*) $S_1 \xrightarrow{\delta^o} S_2$

$S_1: s = a[1];$
 $S_2: s = a[2];$

S_1 ($i=1$) writes a value to s , which is overwritten by S_2 ($i=2$)

- ➔ **Anti** and **Output** dependences can always be removed by consistent renaming of variables

1.3 Parallelisation and Data Dependences ...



(Animated slide)

Data dependences and synchronisation

➔ Two instructions S_1 and S_2 with a data dependence $S_1 \rightarrow S_2$ can be distributed by different threads, **if** a correct synchronisation is performed

➔ S_2 must be executed **after** S_1

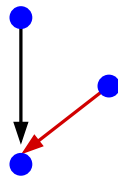
➔ e.g., by using `signal/wait` or a message

➔ in the previous example:

Thread 1

```
x = b + 2 * a;
```

```
wait(cond);  
z = abs(x-y);
```



Thread 2

```
y = a * (c-5);  
signal(cond);
```

1.4 Parallel Computer Architectures



Classification of computer architectures according to Flynn

➔ Criteria for differentiation:

➔ how many **instruction streams** does the computer process at a given point in time (single, multiple)?

➔ how many **data streams** does the computer process at a given point in time (single, multiple)?

➔ This leads to four possible classes:

➔ SISD: **S**ingle Instruction stream, **S**ingle **D**ata stream

➔ single processor (core) systems

➔ MIMD: **M**ultiple Instruction streams, **M**ultiple **D**ata streams

➔ all kinds of multiprocessor systems

➔ SIMD: vector computers, vector extensions, GPUs

➔ MISD: empty, not really sensible



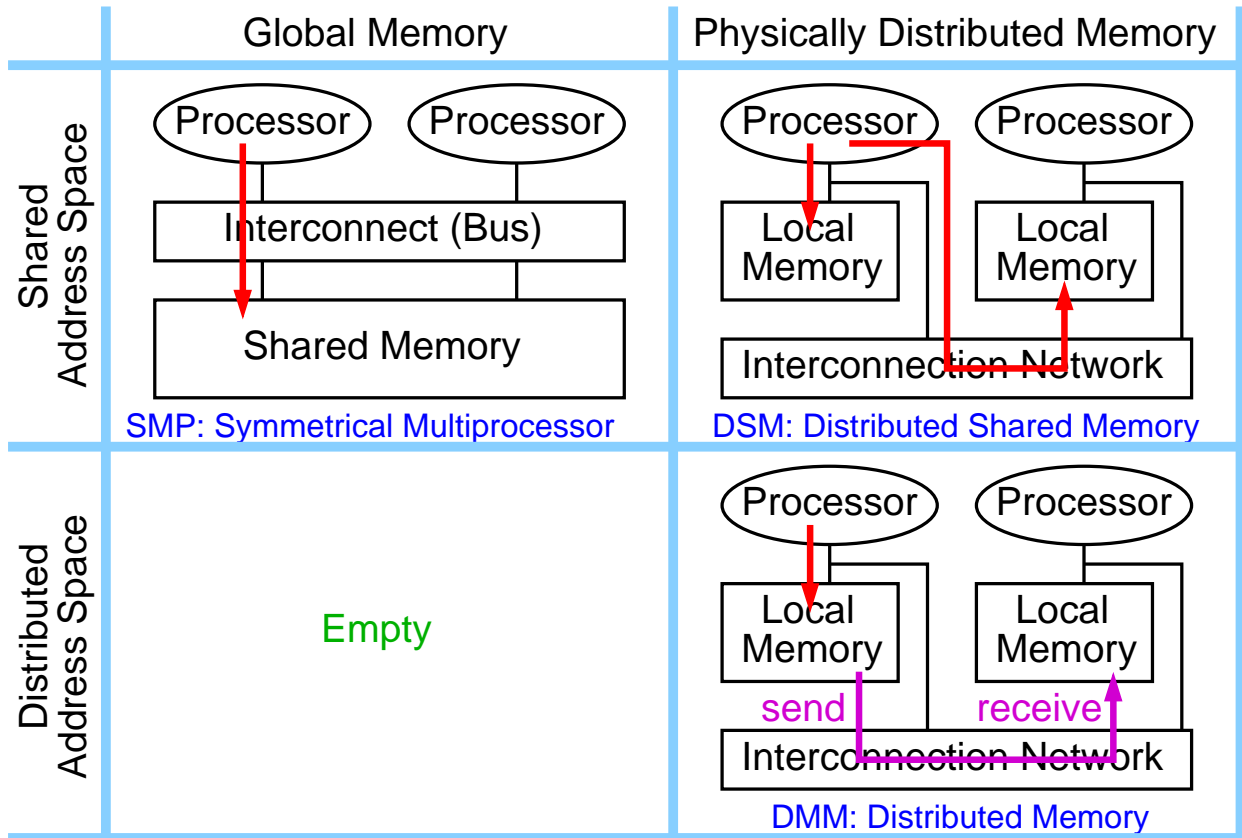
Classes of MIMD computers

- ➔ Considering two criteria:
 - ➔ physically global vs. distributed memory
 - ➔ shared vs. distributed address space
- ➔ **NORMA: No Remote Memory Access**
 - ➔ distributed memory, distributed address space
 - ➔ i.e., no access to memory modules of non-local nodes
 - ➔ communication is only possible via messages
 - ➔ typical representative of this class:
 - ➔ **distributed memory systems (DMM)**
 - ➔ also called MPP (massively parallel processor)
 - ➔ in principle also any computer networks (cluster, grid, cloud, ...)



Classes of MIMD computers ...

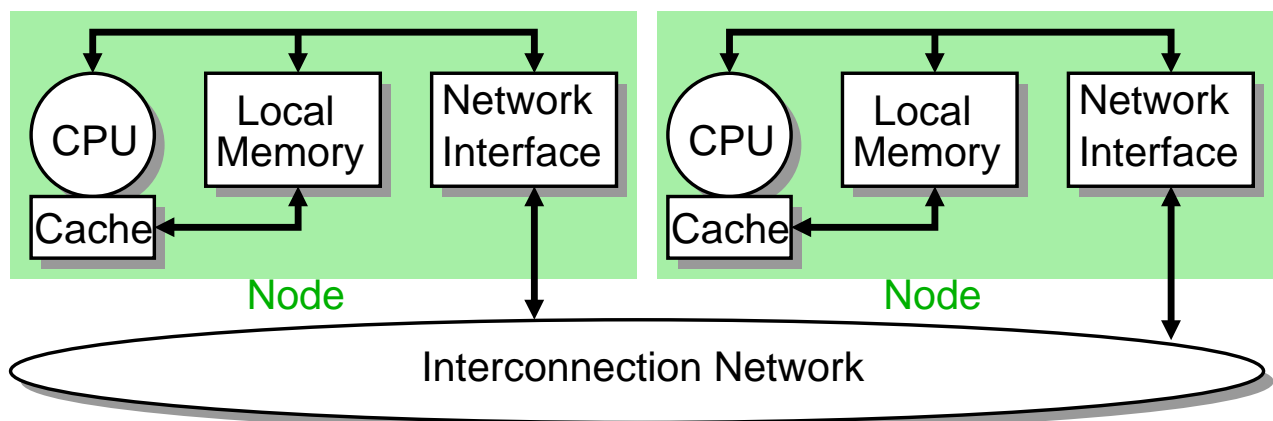
- ➔ **UMA: Uniform Memory Access**
 - ➔ global memory, shared address space
 - ➔ all processors access the memory in the same way
 - ➔ access time is equal for all processors
 - ➔ typical representative of this class:
symmetrical multiprocessor (SMP), multicore-CPU's
- ➔ **NUMA: Nonuniform Memory Access**
 - ➔ distributed memory, shared address space
 - ➔ access to local memory is faster than access to remote one
 - ➔ typical representative of this class:
distributed shared memory systems (DSM)



1.4.1 MIMD: Message Passing Systems



Multiprocessor systems with distributed memory



- ➔ **NORMA**: No Remote Memory Access
- ➔ Good scalability (up to several 100000 nodes)
- ➔ Communication and synchronisation via message passing



Historical evolution

- ➔ In former times: proprietary hardware for nodes and network
 - distinct node architecture (processor, network adapter, ...)
 - often static interconnection networks with *store and forward*
 - often distinct (mini) operating systems
- ➔ Today:
 - cluster with standard components (PC server)
 - often with high performance network (Infiniband, Myrinet, ...)
 - often with SMP and/or vector computers as nodes
 - for high performance computers
 - dynamic (switched) interconnection networks
 - standard operating systems (UNIX or Linux derivatives)



Properties

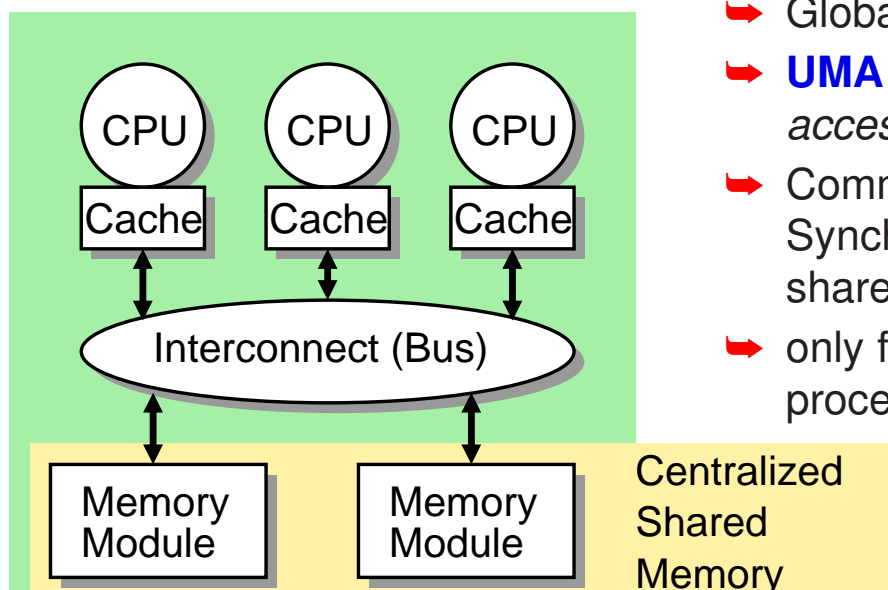
- ➔ No shared memory or address areas
- ➔ Communication via exchange of messages
 - application layer: libraries like e.g., MPI
 - system layer: proprietary protocols or TCP/IP
 - latency caused by software often much larger than hardware latency ($\sim 1 - 50\mu s$ vs. $\sim 20 - 100ns$)
- ➔ In principle unlimited scalability
 - z.B. BlueGene/Q (Sequoia): 98304 nodes, (1572864 cores)

Properties ...

- ➔ Independent operating system on each node
- ➔ Often with shared file system
 - e.g., parallel file system, connected to each node via a (distinct) interconnection network
 - or simply NFS (in small clusters)
- ➔ Usually no *single system image*
 - user/administrator “sees” several computers
- ➔ Often no direct, interactive access to all nodes
 - *batch queueing systems* assign nodes (only) on request to parallel programs
 - often exclusively: *space sharing*, partitioning
 - often small fixed partition for login and interactive use

1.4.2 MIMD: Shared Memory Systems

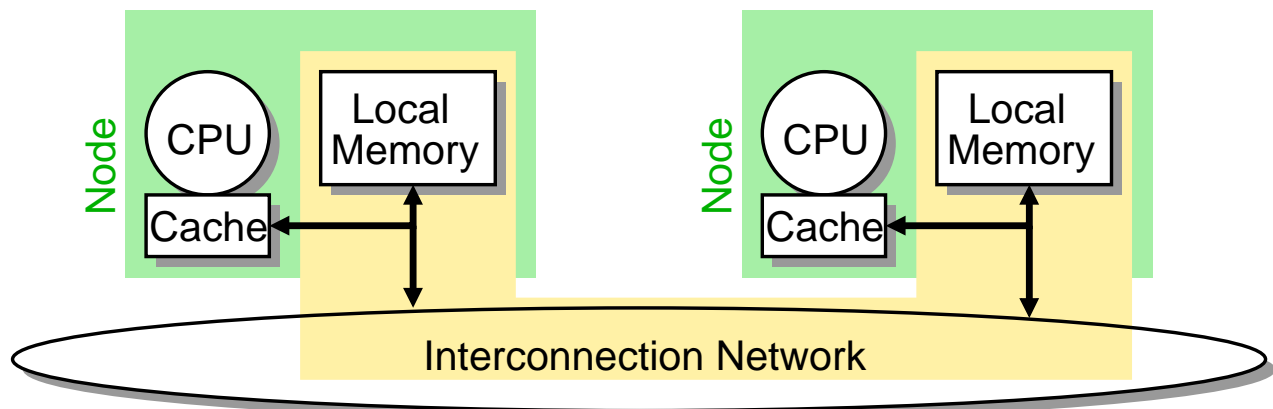
Symmetrical multiprocessors (SMP)



- ➔ Global address space
- ➔ **UMA**: *uniform memory access*
- ➔ Communication and Synchronisation via shared memory
- ➔ only feasible with few processors (ca. 2 - 32)



Multiprocessor systems with distributed shared memory (DSM)



- ➔ Distributed memory, accessible by all CPUs
- ➔ **NUMA**: *non uniform memory access*
- ➔ Combines shared memory and scalability



Properties

- ➔ All Processors can access all resources in the same way
 - but: different access times in NUMA architectures
 - distribute the data such that most accesses are local
- ➔ Only one instance of the operating systems for the whole computer
 - distributes processes/thread amongst the available processors
 - all processors can execute operating system services in an equal way
- ➔ *Single system image*
 - for user/administrator virtually no difference to a uniprocessor system
- ➔ Especially SMPs (UMA) only have limited scalability



Caches in shared memory systems

- ➔ **Cache**: fast intermediate storage, close to the CPU
 - ➔ stores copies of the most recently used data from main memory
 - ➔ when the data is in the cache: no access to main memory is necessary
 - ➔ access is 10-1000 times faster
- ➔ Cache are essential in multiprocessor systems
 - ➔ otherwise memory and interconnection network quickly become a bottleneck
 - ➔ exploiting the property of locality
 - ➔ each process mostly works on “its own” data
- ➔ But: the existence of multiple copies of data can lead to inconsistencies: **cache coherence problem** (👉 BS-1)



Enforcing cache coherency

- ➔ During a write access, all affected caches (= caches with copies) must be notified
 - ➔ caches invalidate or update the affected entry
- ➔ In UMA systems
 - ➔ Bus as interconnection network: every access to main memory is visible for everybody (broadcast)
 - ➔ Caches “listen in” on the bus (*bus snooping*)
 - ➔ (relatively) simple cache coherence protocols
 - ➔ e.g., MESI protocol
 - ➔ but: bad scalability, since the bus is a shared central resource



Enforcing cache coherency ...

- ➔ In NUMA systems (ccNUMA: *cache coherent NUMA*)
 - ➔ accesses to main memory normally are not visible to other processors
 - ➔ affected caches must be notified explicitly
 - ➔ requires a list of all affected caches (broadcasting to all processors is too expensive)
 - ➔ message transfer time leads to additional consistency problems
 - ➔ cache coherence protocols (*directory protocols*) become very complex
 - ➔ but: good scalability



Memory consistency (*Speicherkonsistenz*)

- ➔ Cache coherence only defines the behavior with respect to **one memory location** at a time
 - ➔ **which values** can a read operation return?
- ➔ Remaining question:
 - ➔ **when** does a processor see the value, which was written by another processor?
 - ➔ more exact: in **which order** does a processor see the write operations on **different** memory locations?



Memory consistency: a simple example

Thread T_1	Thread T_2
A = 0;	B = 0;
...	...
A = 1;	B = 1;
print B;	print A;

- ➔ Intuitive expectation: the output "0 0" can never occur
- ➔ But: with many SMPs/DSMs the output "0 0" is possible
 - (CPUs with dynamic instruction scheduling or write buffers)
- ➔ In spite of cache coherency: intuitively inconsistent view on the main memory:

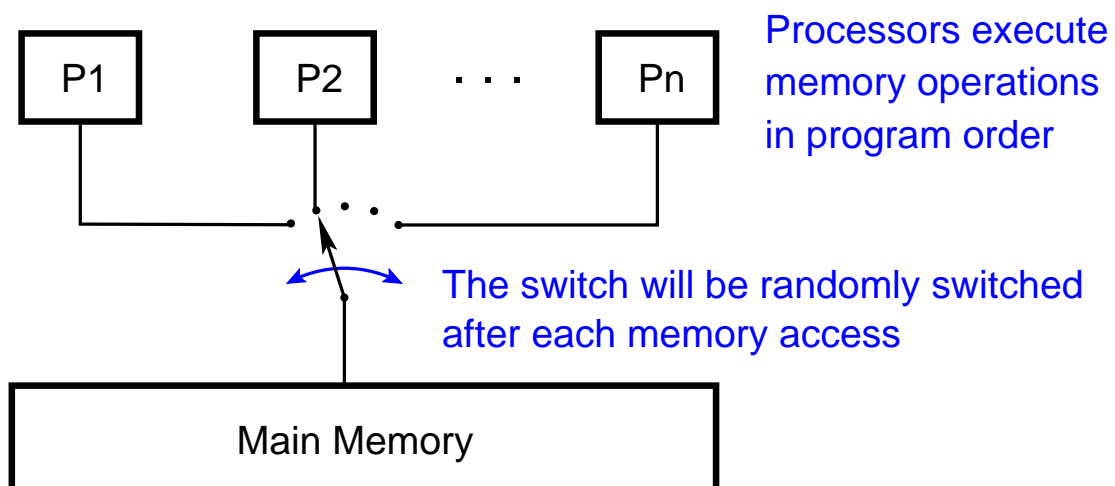
$$T_1: A=1, B=0 \quad T_2: A=0, B=1$$

1.4.2 MIMD: Shared Memory Systems ...



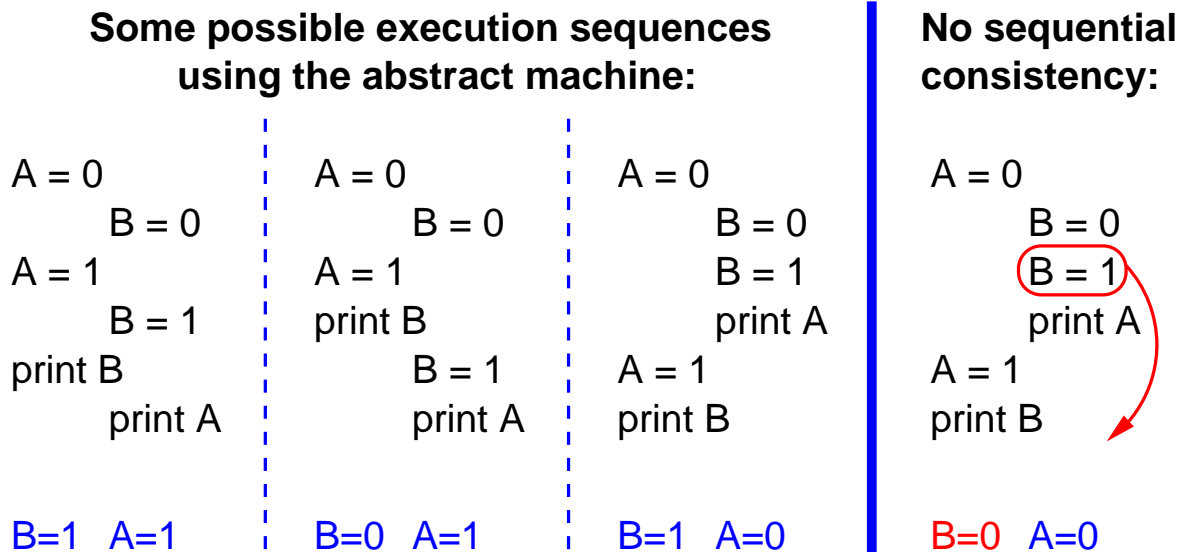
Definition: sequential consistency

Sequential consistency is given, when the result of each execution of a parallel program can also be produced by the following abstract machine:





Interleavings (*Verzahnungen*) in the example



Weak consistency models

- ➔ The requirement of sequential consistency leads to strong restrictions for the computer architecture
 - CPUs can not use instruction scheduling and write buffers
 - NUMA systems can not be realized efficiently
- ➔ Thus: parallel computers with shared memory (UMA and NUMA) use **weak consistency models!**
 - allows, e.g., swapping of write operations
 - however, each processor **always** sees **its own** write operations in program order
- ➔ Remark: also optimizing compilers can lead to weak consistency
 - swapping of instructions, register allocation, ...
 - declare the affected variables as `volatile!`



Consequences of weak consistency: examples

➔ all variables are initially 0

Possible results with sequential consistency ↴		"unexpected" behavior with weak consistency:	
<code>A=1;</code> <code>print B;</code>	<code>B=1;</code> <code>print A;</code>	0,1 1,0 1,1	due to swapping of the read and write accesses
<code>A=1;</code> <code>valid=1;</code>	<code>while (!valid);</code> <code>print A;</code>	1	due to swapping of the write accesses to A and valid



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Universität Siegen
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Weak consistency models ...

- ➔ Memory consistency can (and must!) be enforced as needed, using special instructions
 - ➔ *fence / memory barrier (Speicherbarriere)*
 - ➔ all previous memory operations are completed; subsequent memory operations are started only after the barrier
 - ➔ *acquire and release*
 - ➔ *acquire*: subsequent memory operations are started only after the *acquire* is finished
 - ➔ *release*: all previous memory operations are completed
 - ➔ pattern of use is equal to mutex locks

1.4.2 MIMD: Shared Memory Systems ...



Enforcing consistency in the examples

- ➔ Here shown with memory barriers:

<pre>A=1; fence; print B;</pre>	<pre>B=1; fence; print A;</pre>
---------------------------------	---------------------------------

Fence ensures that the write access is finished before reading

<pre>A=1; fence; valid=1;</pre>	<pre>while (!valid); fence; print A;</pre>
---------------------------------	--

Fence ensures that 'A' is valid before 'valid' is set and that A is read only after 'valid' has been set

1.4.3 SIMD



- ➔ Only a single instruction stream, however, the instructions have **vectors** as operands \Rightarrow data parallelism
- ➔ **Vector** = one-dimensional array of numbers
- ➔ Variants:
 - vector computers
 - pipelined arithmetic units (vector units) for the processing of vectors
 - SIMD extensions in processors (SSE)
 - Intel: 128 Bit registers with, e.g., four 32 Bit float values
 - graphics processors (GPUs)
 - multiple streaming multiprocessors
 - streaming multiprocessor contains several arithmetic units (*CUDA cores*), which all execute the same instruction

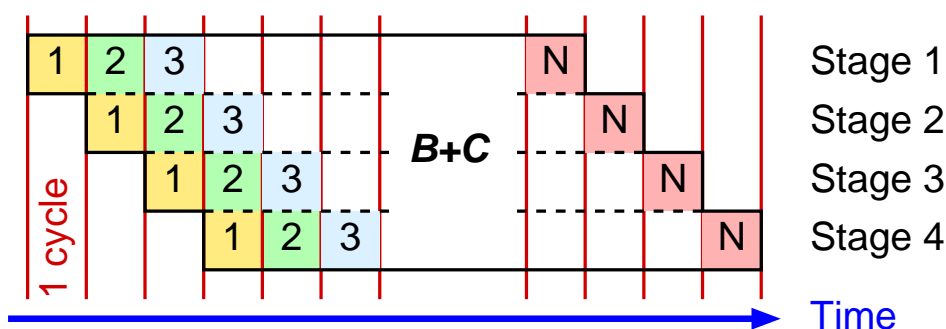
1.4.3 SIMD ...



(Animated slide)

Example: addition of two vectors

- ➔ $A(J) = B(J) + C(J)$, for all $J = 1, 2, \dots, N$
- ➔ Vector computer: the elements of the vectors are added in a pipeline: **sequentially**, but **overlapping**
 - if a scalar addition takes four clock cycles (i.e., 4 pipeline stages), the following sequence will result:



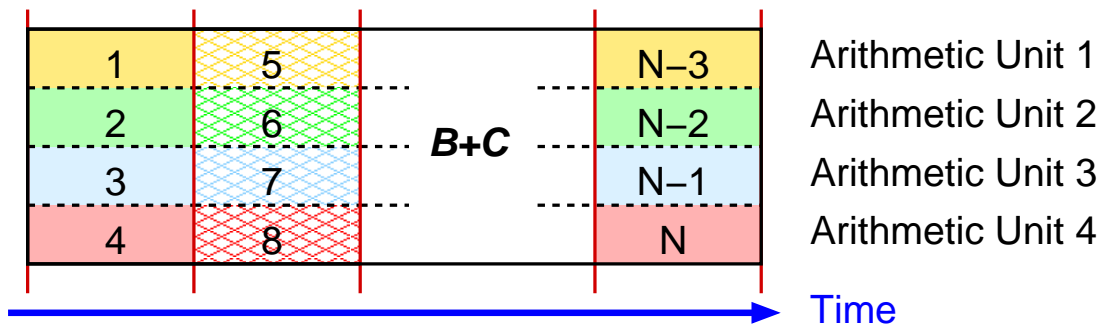
1.4.3 SIMD ...



(Animated slide)

Example: addition of two vectors

- ➔ $A(J) = B(J) + C(J)$, for all $J = 1, 2, \dots, N$
- ➔ SSE and GPU: several elements of the vectors are added **concurrently (in parallel)**
 - if, e.g., four additions can be done at the same time, the following sequence will result:

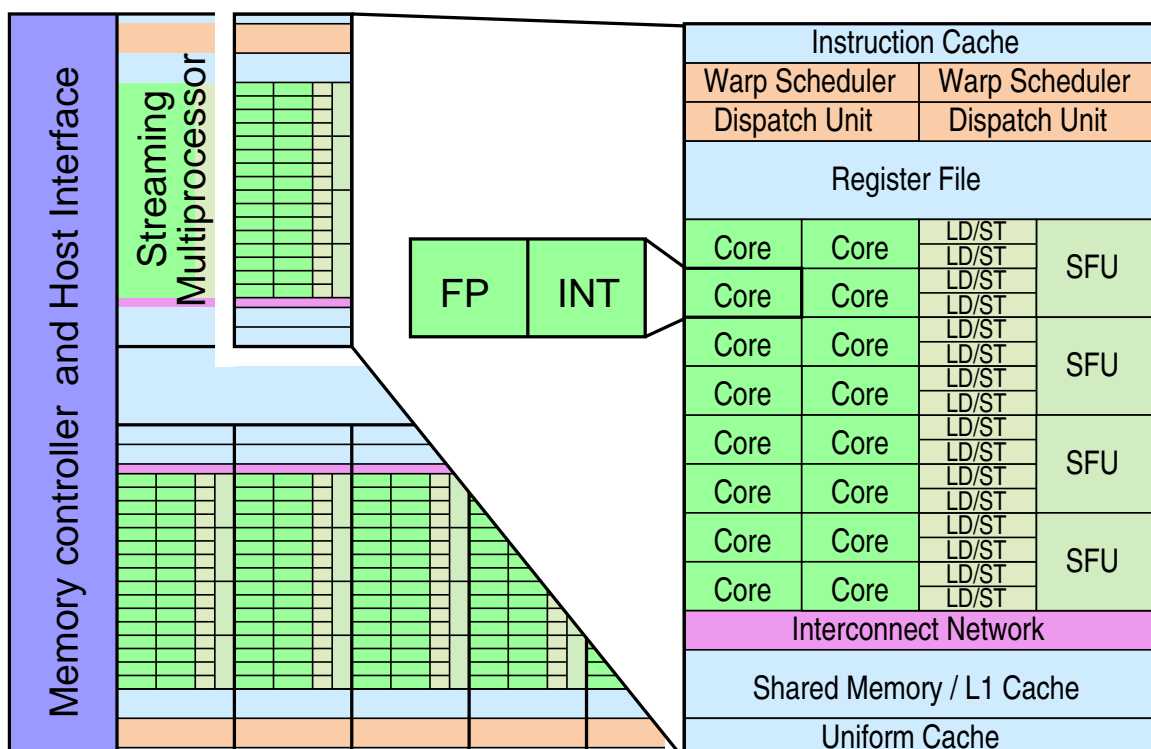


1.4.3 SIMD ...



(Animated slide)

Architecture of a GPU (NVIDIA Fermi)





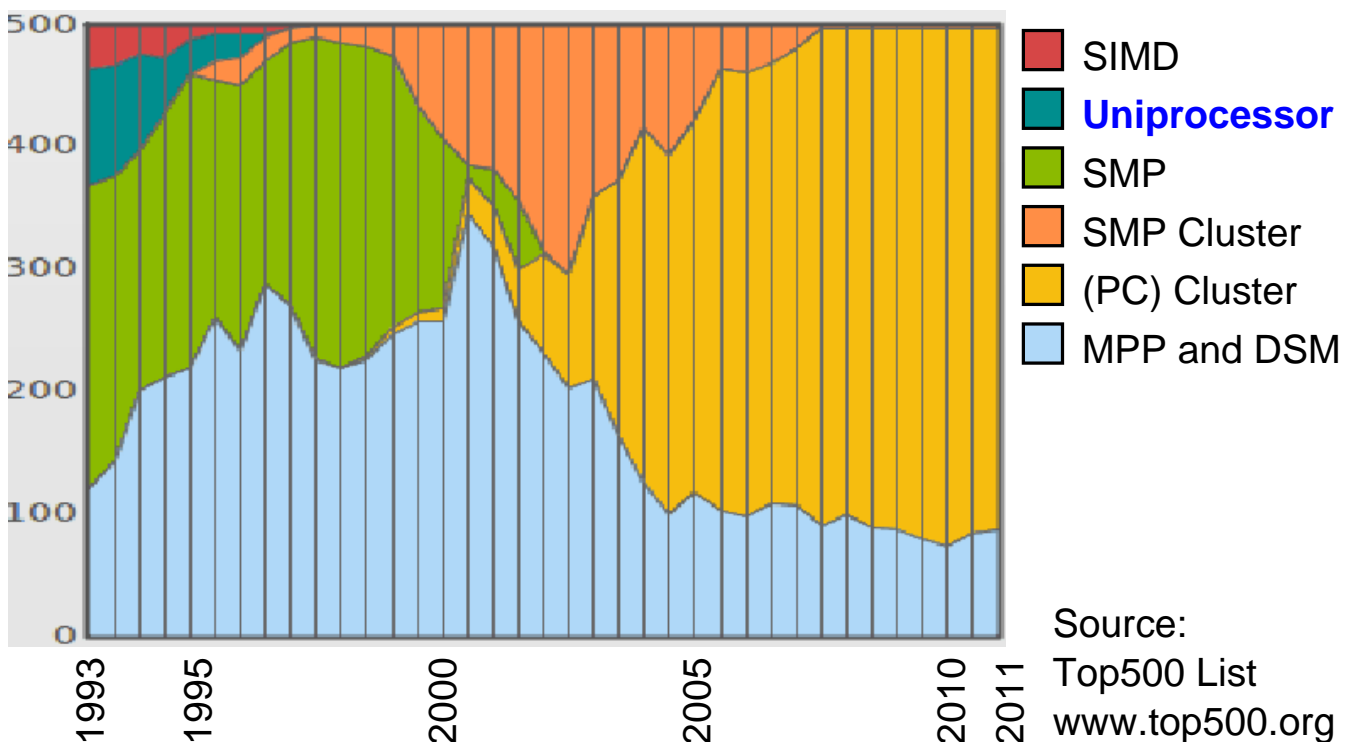
Programming of GPUs (NVIDIA Fermi)

- ➔ Partitioning of the code in groups (*warps*) of 32 threads
- ➔ *Warps* are distributed to the streaming multiprocessors (SEs)
- ➔ Each of the two *warp schedulers* of an SE executes one instruction with 16 threads per clock cycle
 - in a SIMD manner, i.e., the cores all execute the same instruction (on different data) or none at all
 - e.g., with `if-then-else`:
 - first some cores execute the `then` branch,
 - then the other cores execute the `else` branch
- ➔ Threads of one warp should address subsequent memory locations
 - only in this case, memory accesses can be merged

1.4.4 High Performance Supercomputers



Trends



1.4.4 High Performance Supercomputers ...



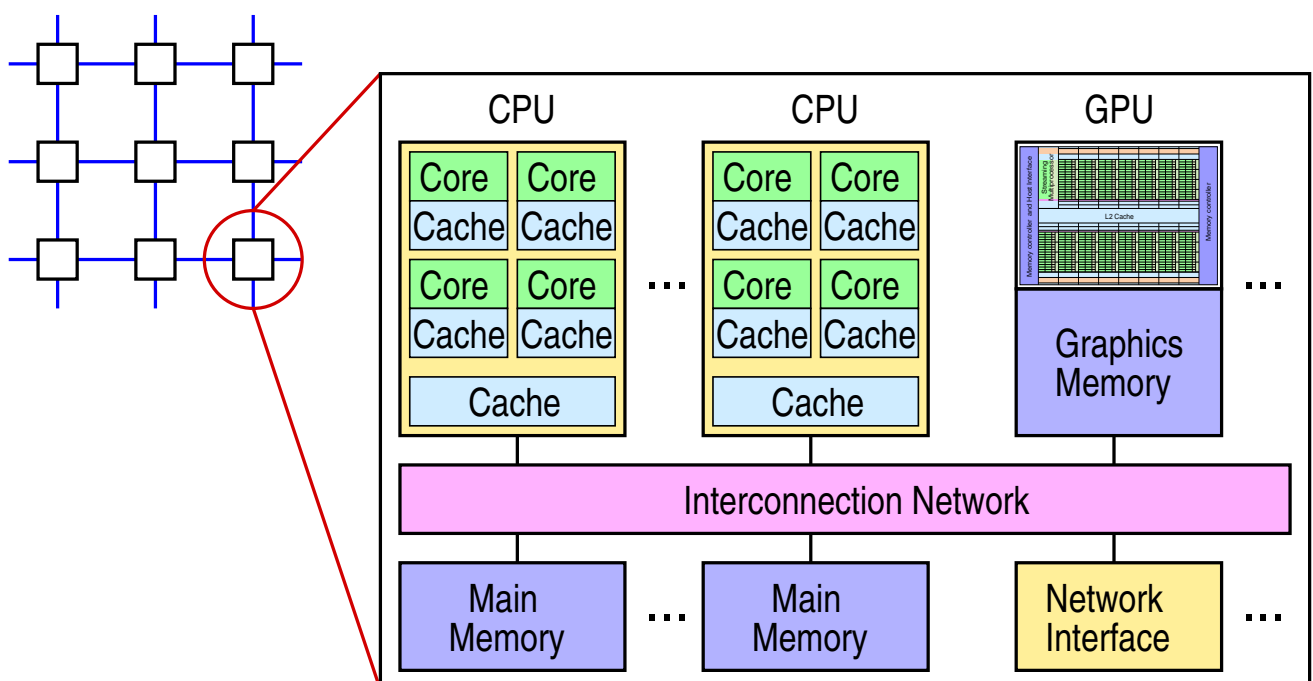
Typical architecture:

- ➔ Message passing computers with SMP nodes and accelerators (e.g. GPUs)
 - ➔ at the highest layer: systems with distributed memory
 - ➔ nodes: NUMA systems with partially shared cache hierarchy
 - ➔ in addition one or more accelerators per node
- ➔ Compromise between scalability, programmability and performance
- ➔ Programming with hybrid programming model
 - ➔ message passing between the nodes (manually, MPI)
 - ➔ shared memory on the nodes (compiler supported, e.g., OpenMP)
 - ➔ if need be, additional programming model for accelerators

1.4.4 High Performance Supercomputers ...



Typical architecture: ...



1.5 Parallel Programming Models



In the following, we discuss:

- ➔ Shared memory
 - ➔ Message passing
 - ➔ Distributed objects
 - ➔ Data parallel languages
- ➔ The list is not complete (e.g., data flow models, PGAS)

1.5.1 Shared Memory



- ➔ Light weight processes (threads) share a common virtual address space
- ➔ The “more simple” parallel programming model
 - ➔ all threads have access to all data
 - ➔ also good theoretical foundation (PRAM model)
- ➔ Mostly with shared memory computers
 - ➔ however also implementable on distributed memory computers (with large performance penalty)
 - ➔ *shared virtual memory* (SVM)
- ➔ Examples:
 - ➔ PThreads, Java Threads
 - ➔ Intel Threading Building Blocks (TBB)
 - ➔ OpenMP (👉 **2.3**)



Example for data exchange

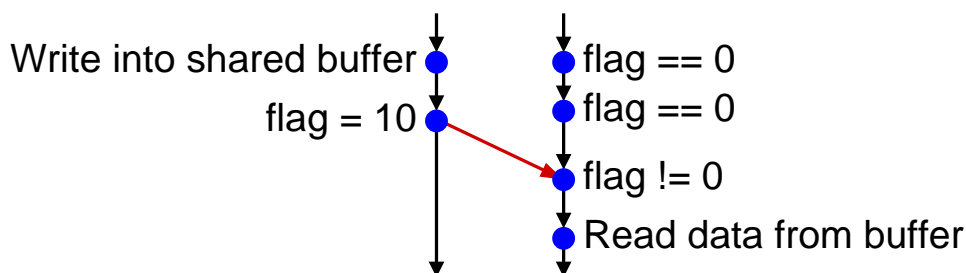
Producer Thread

```
for (i=0; i<size; i++)  
    buffer[i] = produce();  
flag = size;
```

Consumer Thread

```
while(flag==0);  
for (i=0; i<flag; i++)  
    consume(buffer[i]);
```

Execution Sequence:



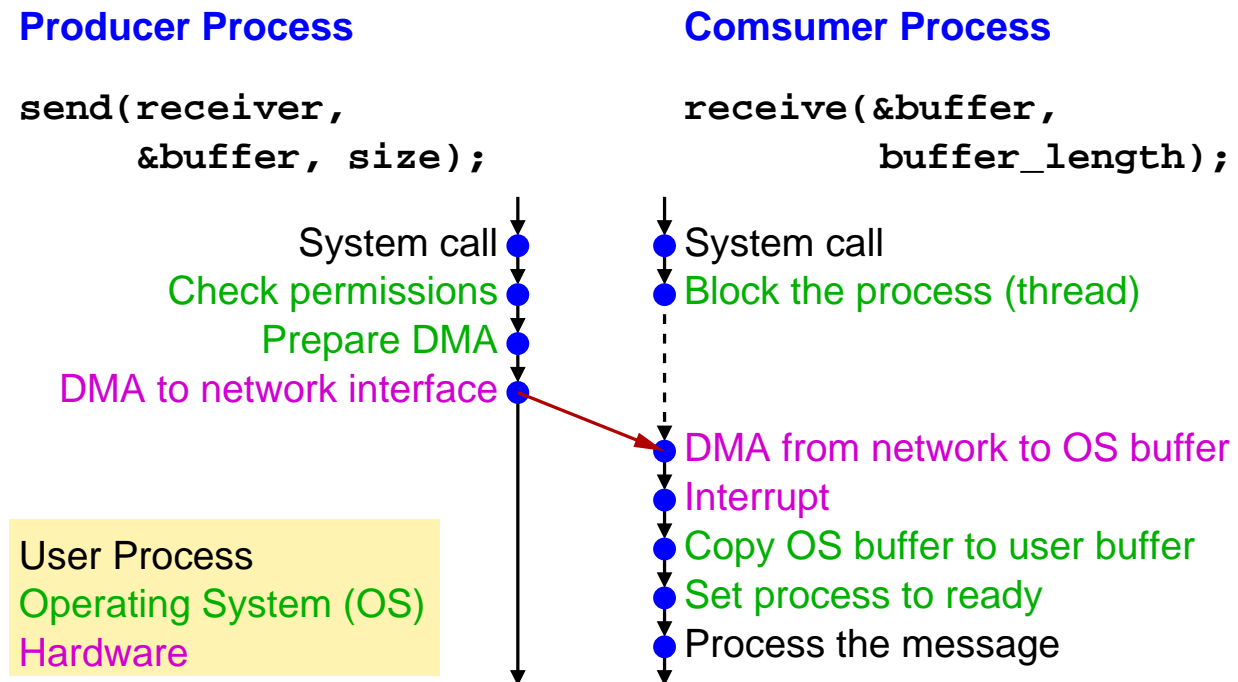
1.5.2 Message Passing



- ➔ Processes with separate address spaces
- ➔ Library routines for sending and receiving messages
 - ➔ (informal) standard for parallel programming:
MPI (*Message Passing Interface*, ↗ **3.2**)
- ➔ Mostly with distributed memory computers
 - ➔ but also well usable with shared memory computers
- ➔ The “more complicated” parallel programming model
 - ➔ explicit data distribution / explicit data transfer
 - ➔ typically no compiler and/or language support
 - ➔ parallelisation is done completely manually



Example for data exchange



1.5.3 Distributed Objects



- ➔ Basis: (purely) object oriented programming
 - ➔ access to data **only** via method calls
- ➔ Then: objects can be distributed to different address spaces (computers)
 - ➔ at object creation: additional specification of a node
 - ➔ object reference then also identifies this node
 - ➔ method calls via RPC mechanism
 - ➔ e.g., *Remote Method Invocation* (RMI) in Java
 - ➔ more about this: lecture "Verteilte Systeme"
- ➔ Distributed objects alone do not yet enable parallel processing
 - ➔ additional concepts / extensions are necessary
 - ➔ e.g., threads, asynchronous RPC, futures

Notes for slide 73:

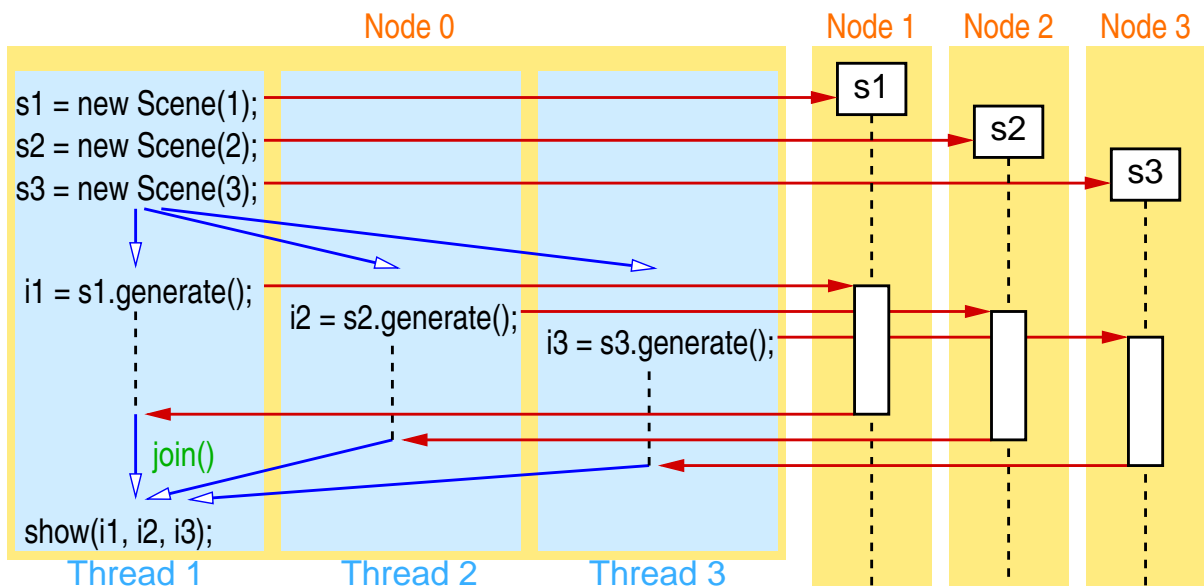
Example

- ➔ Class Scene as description of a scene
 - ➔ constructor Scene(int param)
 - ➔ method Image generate() computes the image
- ➔ Computation of three images with different parameters (sequentially):

```
Scene s1 = new Scene(1);  
Scene s2 = new Scene(2);  
Scene s3 = new Scene(3);  
Image i1 = s1.generate();  
Image i2 = s2.generate();  
Image i3 = s3.generate();  
show(i1, i2, i3);
```

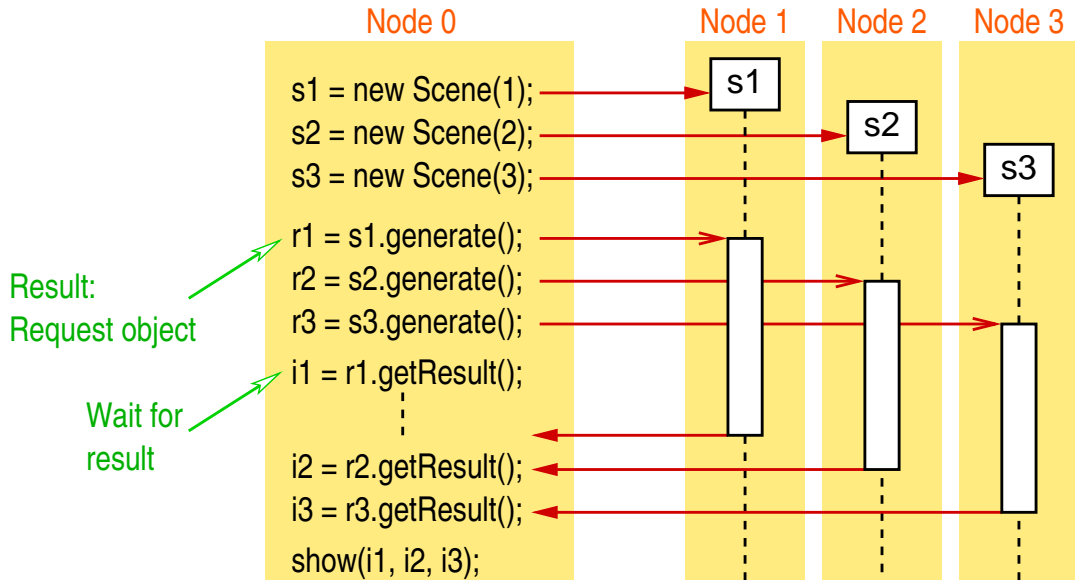
73-1

Parallel computing with threads



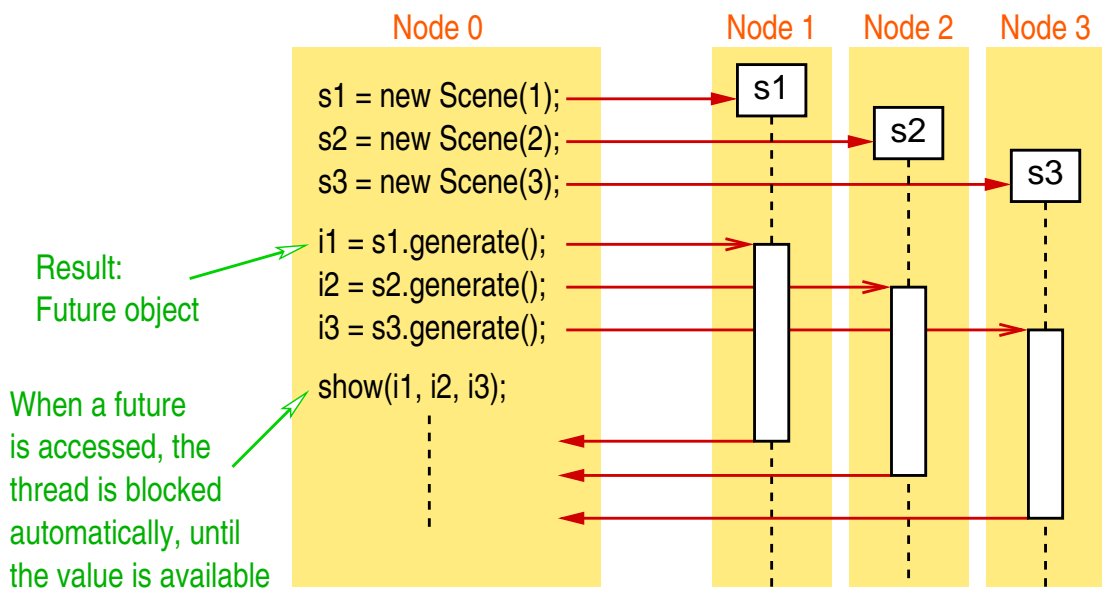
73-2

Parallel computing with asynchronous RPC



73-3

Parallel computing with futures



73-4

1.5.4 Data Parallel Languages



- ➔ Goal: support for data parallelism
- ➔ Sequential code is amended with compiler directives
 - Specification, how to distribute data structures (typically arrays) to processors
- ➔ Compiler automatically generates code for synchronisation or communication, respectively
 - operations are executed on the processor that “possesses” the result variable (*owner computes* rule)
- ➔ Example: HPF (*High Performance Fortran*)
- ➔ Despite easy programming not really successful
 - only suited for a limited class of applications
 - good performance requires a lot of manual optimization

1.5.4 Data Parallel Languages ...

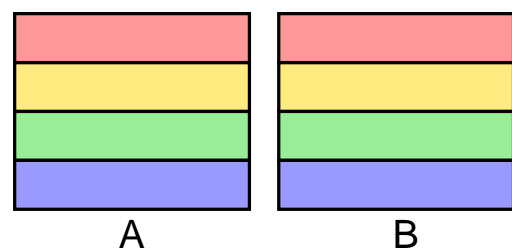


(Animated slide)

Example for HPF

```
REAL A(N,N), B(N,N)
!HPF$ DISTRIBUTE A(BLOCK,*)
!HPF$ ALIGN B(:, :) WITH A(:, :)
DO I = 1, N
  DO J = 1, N
    A(I,J) = A(I,J) + B(J,I)
  END DO
END DO
```

Distribution with 4 processors:



- ➔ Processor 0 executes computations for $I = 1 .. N/4$
- ➔ Problem in this example: a lot of communication is required
 - B should be distributed in a different way

1.6 Focus of this Lecture



- ➔ Explicit parallelism
- ➔ Process and block level
- ➔ Coarse and mid grained parallelism

- ➔ MIMD computers (with SIMD extensions)

- ➔ Programming models:
 - ➔ shared memory
 - ➔ message passing

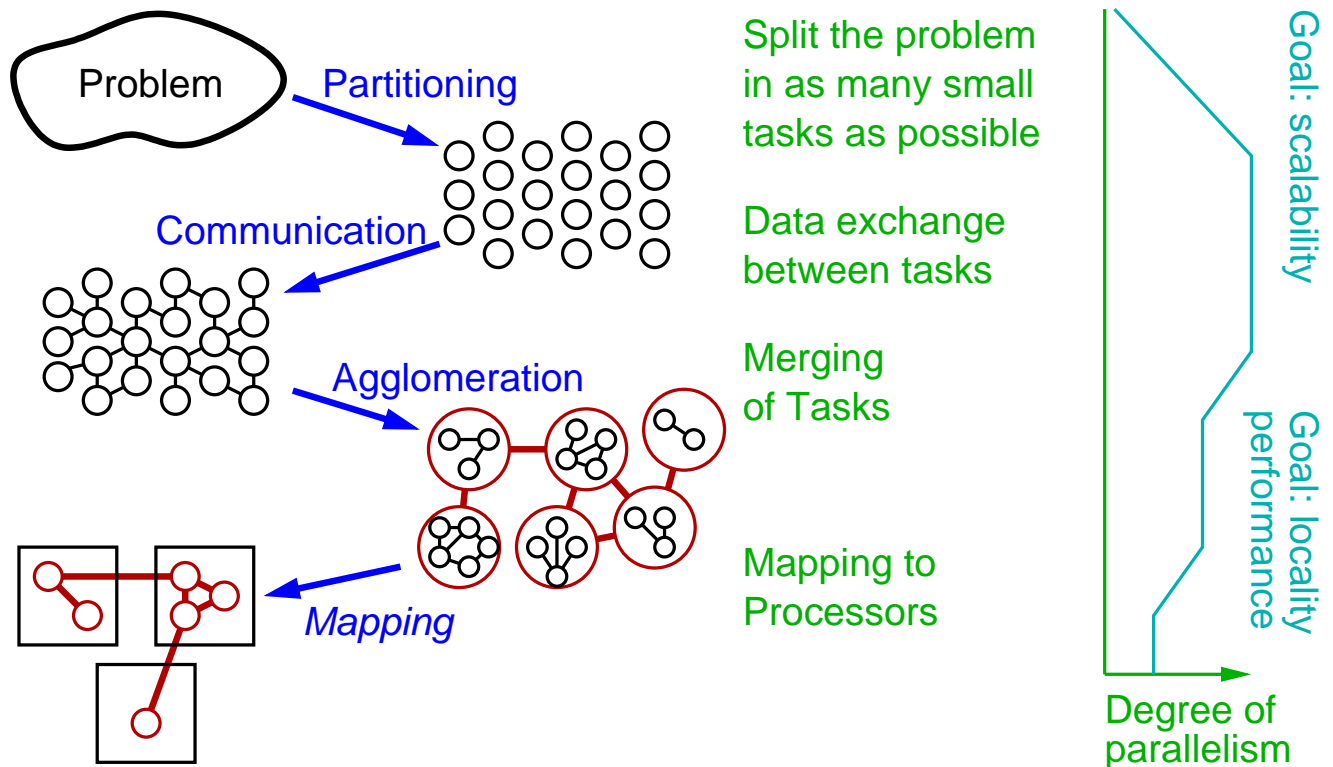
1.7 A Design Process for Parallel Programs



Four design steps:

1. Partitioning
 - ➔ split the problem into many tasks
2. Communication
 - ➔ specify the information flow between the tasks
 - ➔ determine the communication structure
3. Agglomeration
 - ➔ evaluate the performance (tasks, communication structure)
 - ➔ if need be, aggregate tasks into larger tasks
4. Mapping
 - ➔ map the tasks to processors

(See Foster: *Designing and Building Parallel Programs*, Ch. 2)



1.7.1 Partitioning



- ➔ Goal: split the problem into as many small tasks as possible

Data partitioning (data parallelism)

- ➔ Tasks specify **identical computations** for a **part** of the data
- ➔ In general, high degree of parallelism is possible
- ➔ We can distribute:
 - ➔ input data
 - ➔ output data
 - ➔ intermediate data
- ➔ In some cases: recursive distribution (*divide and conquer*)
- ➔ Special case: distribution of search space in search problems

1.7.1 Partitioning ...



Example: matrix multiplication

➔ Product $C = A \cdot B$ of two square matrices

$$\rightarrow c_{ij} = \sum_{k=1}^n a_{ik} \cdot b_{kj}, \text{ for all } i, j = 1 \dots n$$

➔ This formula also holds when square sub-matrices A_{ik}, B_{kj}, C_{ij} are considered instead of single scalar elements

➔ block matrix algorithms:

$$\begin{array}{|c|c|} \hline A_{1,1} & A_{1,2} \\ \hline A_{2,1} & A_{2,2} \\ \hline \end{array} \cdot \begin{array}{|c|c|} \hline B_{1,1} & B_{1,2} \\ \hline B_{2,1} & B_{2,2} \\ \hline \end{array} = \begin{array}{|c|c|} \hline C_{1,1} & C_{1,2} \\ \hline C_{2,1} & C_{2,2} \\ \hline \end{array} \quad \begin{array}{l} C_{1,1} = A_{1,1} \cdot B_{1,1} \\ \quad + A_{1,2} \cdot B_{2,1} \end{array}$$

1.7.1 Partitioning ...



Example: matrix multiplication ...

➔ Distribution of output data: each task computes a sub-matrix of C

➔ E.g., distribution of C into four sub-matrices

$$\begin{pmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{pmatrix} \cdot \begin{pmatrix} B_{1,1} & B_{1,2} \\ B_{2,1} & B_{2,2} \end{pmatrix} \rightarrow \begin{pmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{pmatrix}$$

➔ Results in four independent tasks:

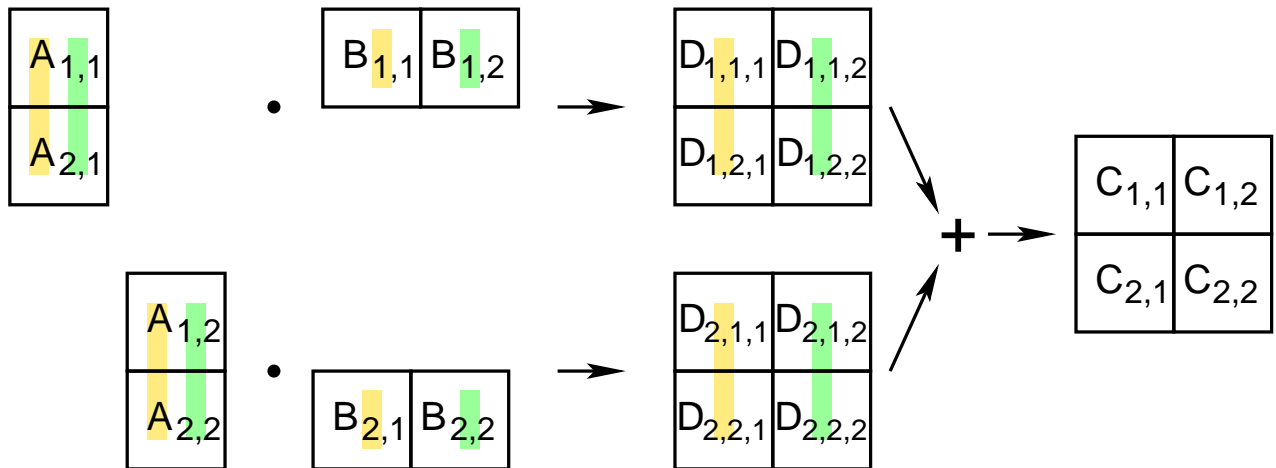
1. $C_{1,1} = A_{1,1} \cdot B_{1,1} + A_{1,2} \cdot B_{2,1}$
2. $C_{1,2} = A_{1,1} \cdot B_{1,2} + A_{1,2} \cdot B_{2,2}$
3. $C_{2,1} = A_{2,1} \cdot B_{1,1} + A_{2,2} \cdot B_{2,1}$
4. $C_{2,2} = A_{2,1} \cdot B_{1,2} + A_{2,2} \cdot B_{2,2}$

1.7.1 Partitioning ...



Example: matrix multiplication $A \cdot B \rightarrow C$

- ➔ Distribution of intermediate data (higher degree of parallelism)
- here: 8 multiplications of sub-matrices

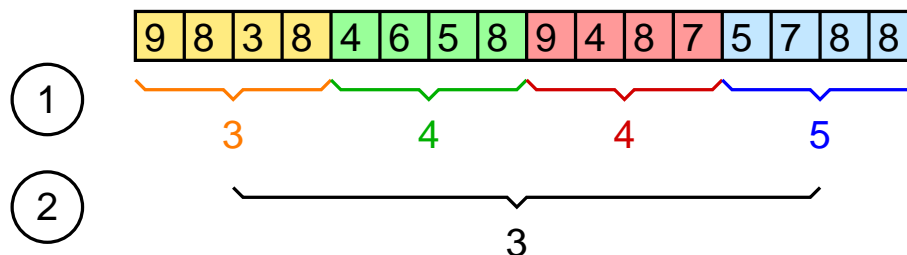


1.7.1 Partitioning ...



Example: minimum of an array

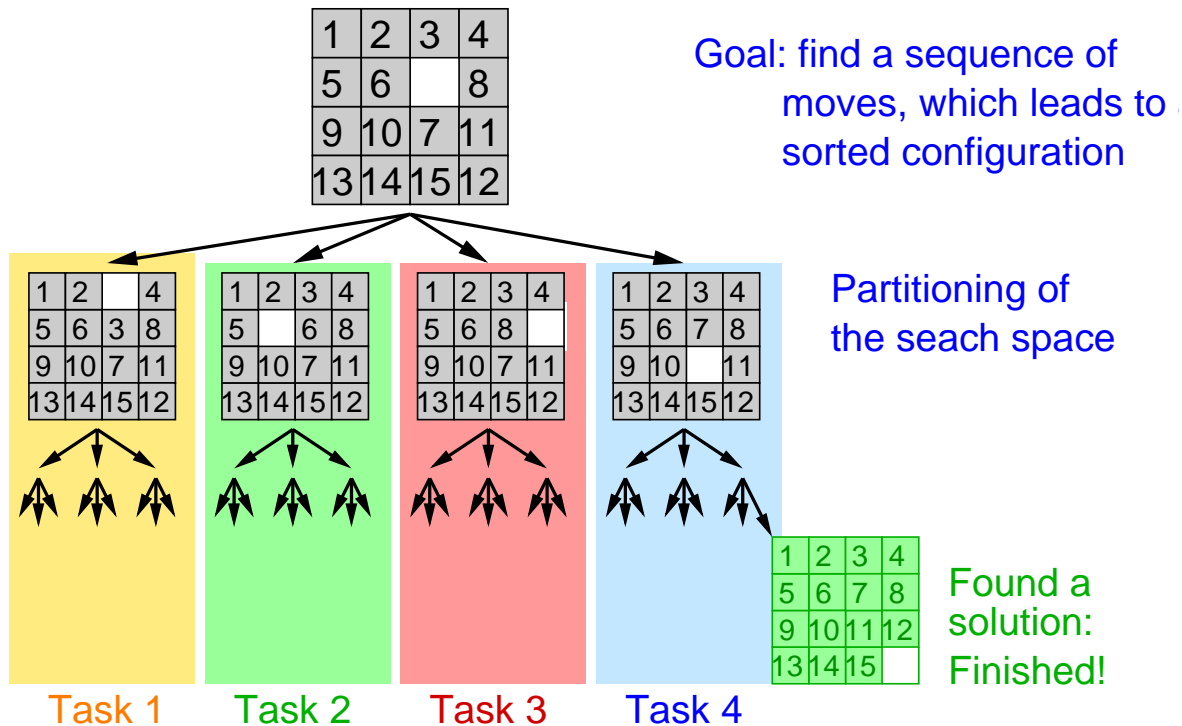
- ➔ Distribution of input data
- each threads computes its local minimum
- afterwards: computation of the global minimum



1.7.1 Partitioning ...



Example: sliding puzzle (partitioning of search space)

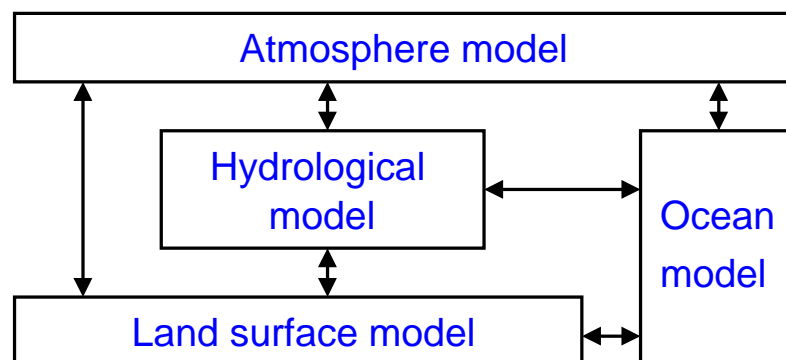


1.7.1 Partitioning ...



Task partitioning (task parallelism)

- ➔ Tasks are **different** sub-problems (execution steps) of a problem
- ➔ E.g., climate model



- ➔ Tasks can work concurrently or in a pipeline
- ➔ max. gain: number of sub-problems (typically small)
- ➔ often in addition to data partitioning



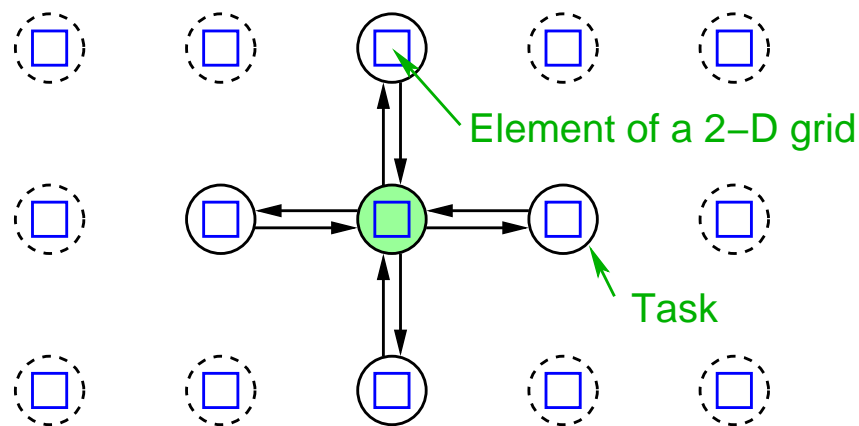
- ➔ Two step approach
 - definition of the communication structure
 - who must exchange data with whom?
 - sometimes complex, when using data partitioning
 - often simple, when using task partitioning
 - definition of the messages to be sent
 - which data must be exchanged when?
 - taking data dependences into account



Different communication patterns:

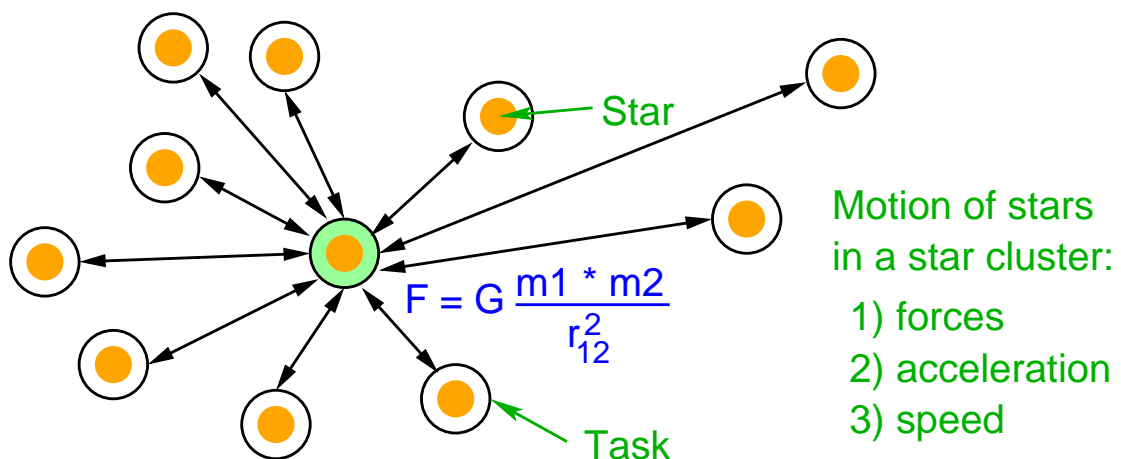
- ➔ Local vs. global communication
 - lokal: task communicates only with a small set of other tasks (its “neighbors”)
 - global: task communicates with many/all other tasks
- ➔ Structured vs. unstructured communication
 - structured: regular structure, e.g., grid, tree
- ➔ Static vs. dynamic communication
 - dynamic: communication structure is changing during run-time, depending on computed data
- ➔ Synchronous vs. asynchronous communication
 - asynchronous: the task owning the data does not know, when other tasks need to access it

Example for local communication: stencil algorithms



- ➔ Here: 5-point stencil (also others are possible)
- ➔ Examples: Jacobi or Gauss-Seidel methods, filters for image processing, ...

Example for global communication: N-body problem



- ➔ The effective force on a star in a star cluster depends on the masses and locations of all other stars
 - possible approximation: restriction to relatively close stars
 - will, however, result in dynamic communication

Parallel Processing

WS 2017/18

19.10.2017

Roland Wismüller
 Universität Siegen
 roland.wismueller@uni-siegen.de
 Tel.: 0271/740-4050, Büro: H-B 8404

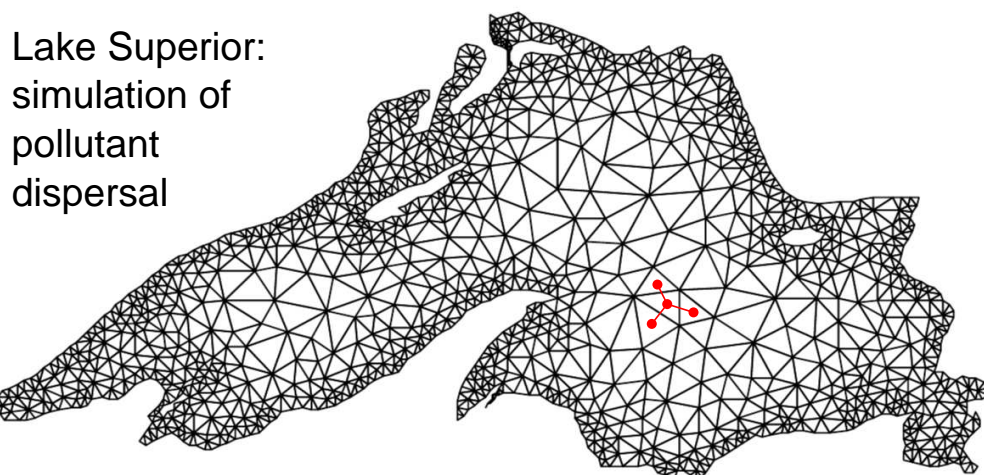
Stand: October 23, 2017

1.7.2 Communication ...



Example for structured / unstructured communication

- ➔ Structured: stencil algorithms
- ➔ Unstructured: “unstructured grids”



- ➔ grid points are defined at different density
- ➔ edges: neighborhood relation (communication)

1.7.3 Agglomeration



- ➔ So far: abstract parallel algorithms
- ➔ Now: concrete formulation for real computers
 - limited number of processors
 - costs for communication, process creation, process switching, ...
- ➔ Goals:
 - reducing the communication costs
 - aggregation of tasks
 - replication of data and/or computation
 - retaining the flexibility
 - sufficiently fine-grained parallelism for mapping phase

1.7.4 Mapping

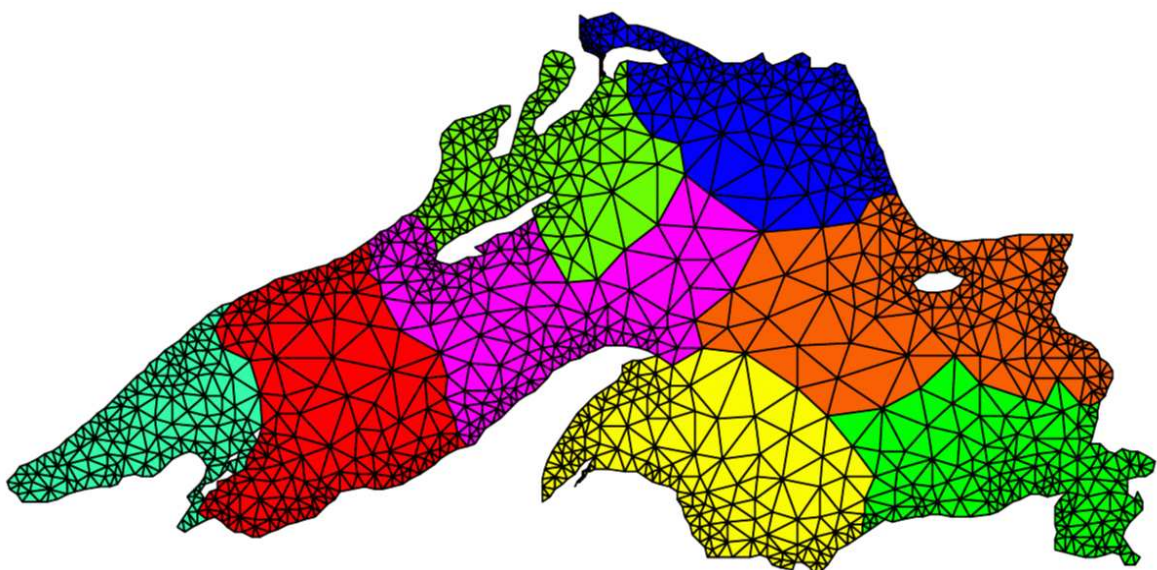


- ➔ Task: assignment of tasks to available processors
- ➔ Goal: minimizing the execution time
- ➔ Two (conflicting) strategies:
 - map concurrently executable tasks to different processors
 - high degree of parallelism
 - map communicating tasks to the same processor
 - higher locality (less communication)
- ➔ Constraint: load balancing
 - (roughly) the same computing effort for each processor
- ➔ The mapping problem is NP complete

Variants of mapping techniques

- ➔ Static mapping
 - fixed assignment of tasks to processors when program is started
 - for algorithms on arrays or Cartesian grids:
 - often manually, e.g., block wise or cyclic distribution
 - for unstructured grids:
 - graph partitioning algorithms, e.g., greedy, recursive coordinate bisection, recursive spectral bisection, ...
- ➔ Dynamic mapping (dynamic load balancing)
 - assignment of tasks to processors at runtime
 - variants:
 - tasks stay on their processor until their execution ends
 - task migration is possible during runtime

Example: static mapping with unstructured grid



- ➔ (Roughly) the same number of grid points per processor
- ➔ Short boundaries: small amount of communication

1.8 Organisation Forms for Parallel Programs



- ➔ Models / patterns for parallel programs

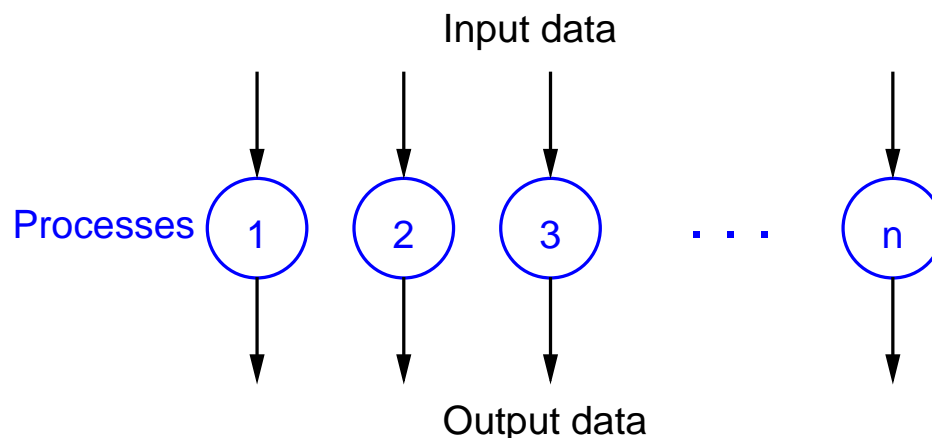
1.8.1 Embarrassingly Parallel

- ➔ The task to be solved can be divided into a set of **completely independent** sub-tasks
- ➔ All sub-tasks can be solved in parallel
- ➔ No data exchange (communication) is necessary between the parallel threads / processes
- ➔ Ideal situation!
 - when using n processors, the task will (usually) be solved n times faster
 - (for reflection: why only usually?)

1.8.1 Embarrassingly Parallel ...



Illustration





Examples for embarrassingly parallel problems

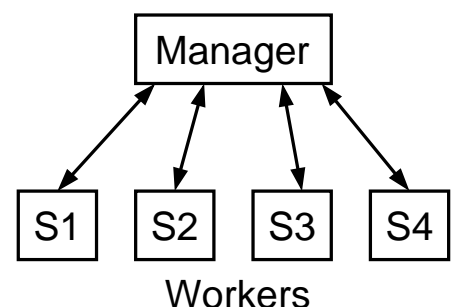
- ➔ Computation of animations
 - animated cartoons, zoom into the Mandelbrot Set, ...
 - each image (frame) can be computed independently
- ➔ Parameter studies
 - multiple / many simulations with different input parameters
 - e.g., weather forecast with provision for measurement errors, computational fluid dynamics for optimizing an airfoil, ...

1.8 Organisation Forms for Parallel Programs ...



1.8.2 Manager/Worker Model (Master/Slave Model)

- ➔ A manager process creates tasks and assigns them to worker processes
 - several managers are possible, too
 - a hierarchy is possible, too: a worker can itself be the manager of own workers

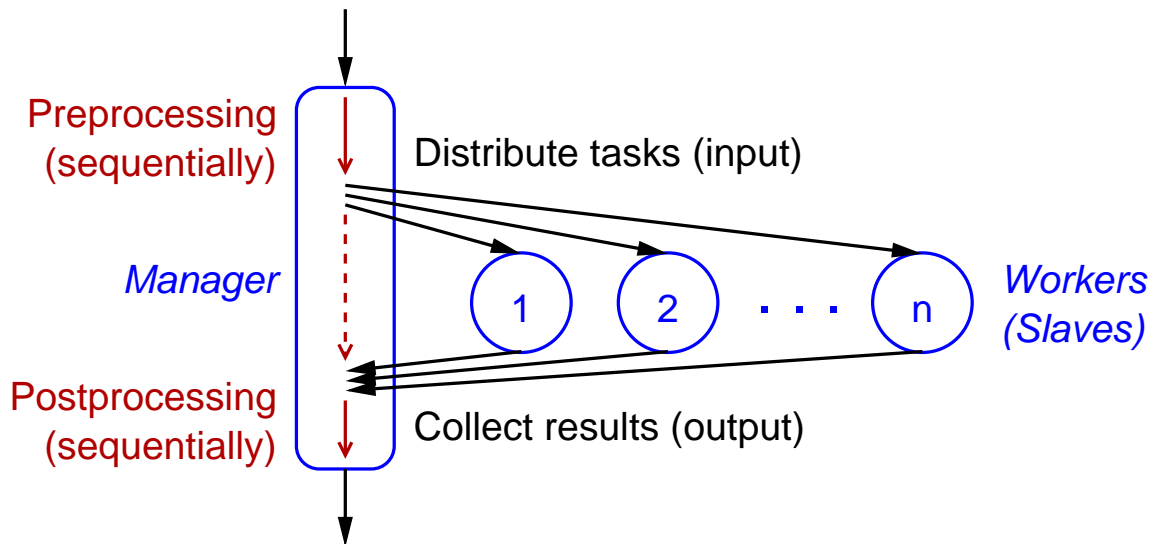


- ➔ The manager (or sometimes also the workers) can create additional tasks, while the workers are working
- ➔ The manager can become a bottleneck
- ➔ The manager should be able to receive the results asynchronously (non blocking)



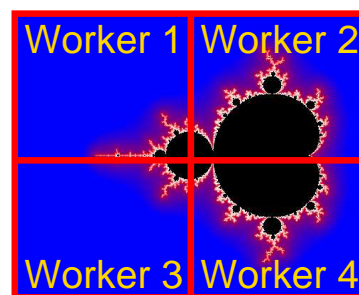
Typical application

- ➔ Often only a part of a task can be parallelised in an optimal way
- ➔ In the easiest case, the following flow will result:

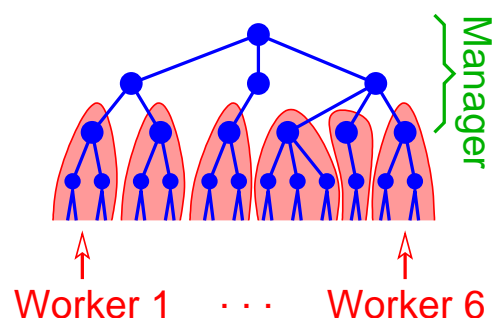


Examples

- ➔ Image creation and processing
 - ➔ manager partitions the image into areas; each area is processed by one worker



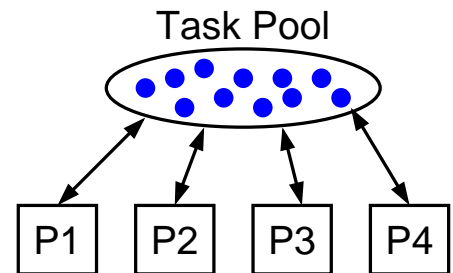
- ➔ Tree search
 - ➔ manager traverses the tree up to a predefined depth; the workers process the sub-trees





1.8.3 Work Pool Model (Task Pool Model)

- ➔ Tasks are explicitly specified using a data structure
- ➔ Centralized or distributed pool (list) of tasks
 - threads (or processes) fetch tasks from the pool
 - usually much more tasks than processes
 - good load balancing is possible
 - accesses must be synchronised
- ➔ Threads can put new tasks into the pool, if need be
 - e.g., with divide-and-conquer



1.8.4 Divide and Conquer

- ➔ **Recursive** partitioning of the task into independent sub-tasks
- ➔ Dynamic creation of sub-tasks
 - by all threads (or processes, respectively)
- ➔ Problem: limiting the number of threads
 - execute sub-tasks in parallel only if they have a minimum size
 - maintain a task pool, which is executed by a fixed number of threads

1.8.4 Divide and Conquer ...



(Animated slide)

Example: parallel quicksort

$Qsort(A_1 .. n)$

If $n = 1$: done.

Else:

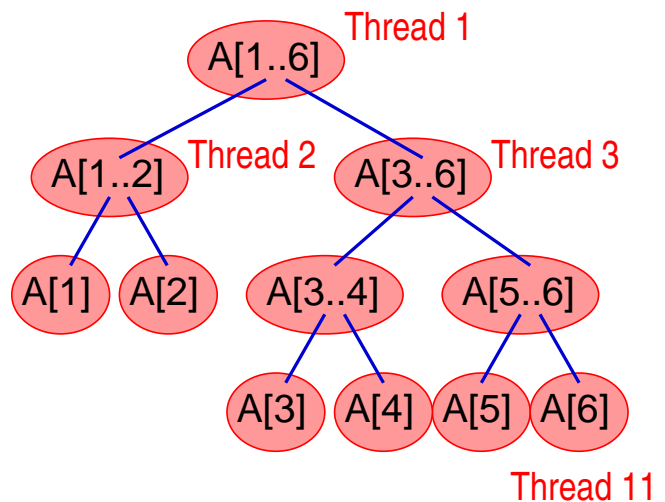
Determine the *pivot* S .

Reorder A such that

$A_i \leq S$ for $i \in [1, k[$ and
 $A_i \geq S$ for $i \in [k, n]$.

Execute $Qsort(A_1 .. k-1)$
and $Qsort(A_k .. n)$
in parallel.

Example:



1.8.4 Divide and Conquer ...



(Animated slide)

Example: parallel quicksort

$Qsort(A_1 .. n)$

If $n = 1$: done.

Else:

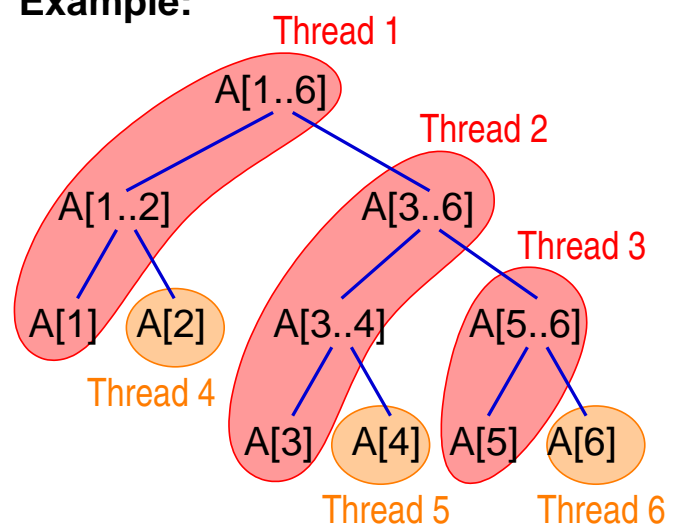
Determine the *pivot* S .

Reorder A such that

$A_i \leq S$ for $i \in [1, k[$ and
 $A_i \geq S$ for $i \in [k, n]$.

Execute $Qsort(A_1 .. k-1)$
and $Qsort(A_k .. n)$
in parallel.

Example:



* Assumption: thread executes first call itself
and creates new thread for the second one

1.8.4 Divide and Conquer ...



(Animated slide)

Example: parallel quicksort

Qsort($A_1 .. n$)

If $n = 1$: done.

Else:

Determine the *pivot* S .

Reorder A such that

$A_i \leq S$ for $i \in [1, k[$ and

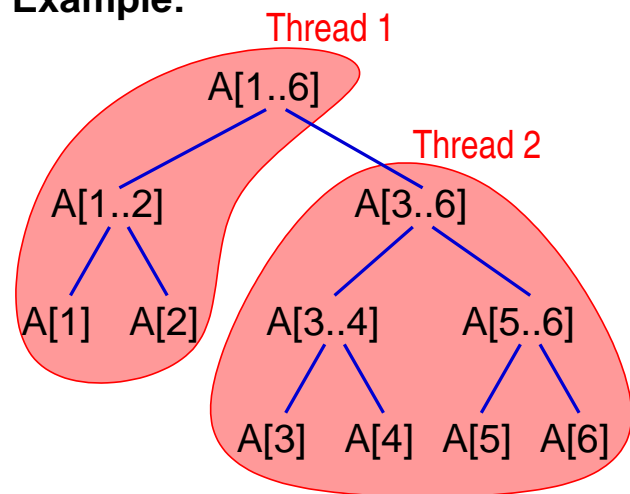
$A_i \geq S$ for $i \in [k, n]$.

Execute Qsort($A_1 .. k-1$)

and Qsort($A_k .. n$)

in parallel.

Example:



* Additional Assumption: new thread is created only if array length > 2

1.8 Organisation Forms for Parallel Programs ...

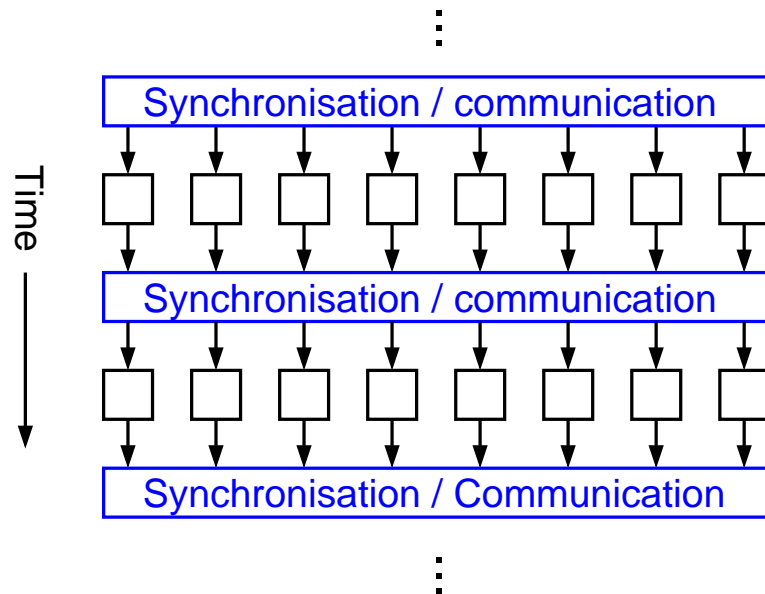


1.8.5 Data parallel Model: SPMD

- ➔ Fixed, constant number of processes (or threads, respectively)
- ➔ One-to-one correspondence between tasks and processes
- ➔ All processes execute the same program code
 - however: conditional statements are possible ...
- ➔ For program parts which cannot be parallelised:
 - replicated execution in each process
 - execution in only one process; the other ones wait
- ➔ Usually loosely synchronous execution:
 - alternating phases with independent computations and communication / synchronisation



Typical sequence

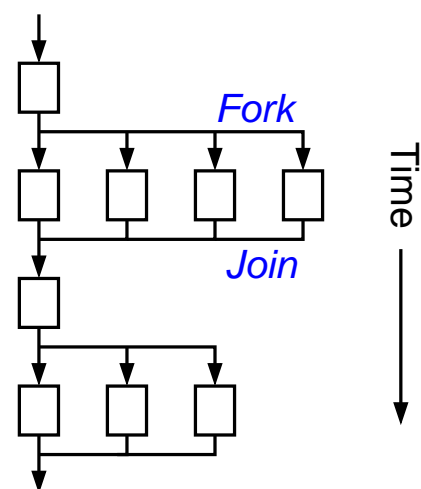


1.8 Organisation Forms for Parallel Programs ...



1.8.6 Fork/Join Model

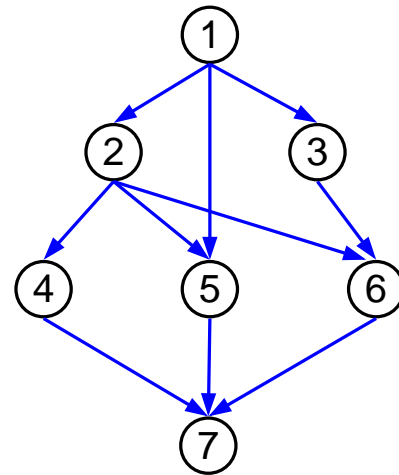
- ➔ Program consists of sequential and parallel phases
- ➔ Thread (or processes, resp.) for parallel phases are created at run-time (*fork*)
 - ➔ one for each task
- ➔ At the end of each parallel phase: synchronisation and termination of the threads (*join*)





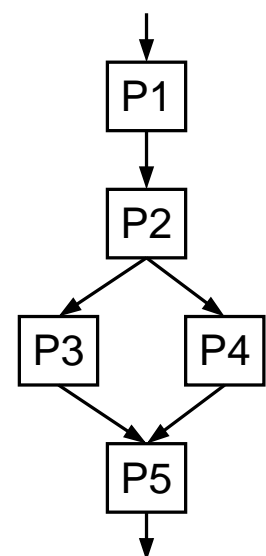
1.8.7 Task-Graph Model

- ➔ Tasks and their dependences (data flow) are represented as a graph
- ➔ An edge in the graph denotes a data flow
 - e.g., task 1 produces data, task 2 starts execution, when this data is entirely available
- ➔ Assignment of tasks to processors usually in such a way, that the necessary amount of communication is as small as possible
 - e.g., tasks 1, 5, and 7 in one process



1.8.8 Pipeline Model

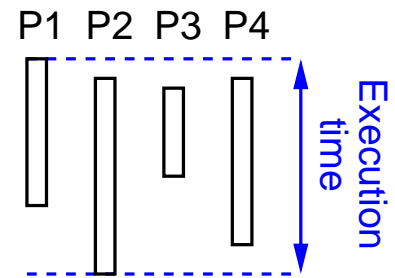
- ➔ A *stream* of data elements is directed through a sequence of processes
- ➔ The execution of a task starts as soon as a data element arrives
- ➔ Pipeline needs not necessarily be linear
 - general (acyclic) graphs are possible, as with the task-graph model
- ➔ Producer/consumer synchronisation between the processes



1.9 Performance Considerations



- ➔ Which performance gain results from the parallelisation?
- ➔ Possible performance metrics:
 - ➔ execution time, throughput, memory requirements, processor utilisation, development cost, maintenance cost, ...
- ➔ In the following, we consider execution time
 - ➔ **execution time** of a parallel program: time between the start of the program and the end of the computation on the last processor



1.9.1 Performance Metrics



Speedup (*Beschleunigung*)

- ➔ Reduction of execution time due to parallel execution
- ➔ **Absolute speedup**

$$S(p) = \frac{T_s}{T(p)}$$

- ➔ T_s = execution time of the sequential program (or the best sequential algorithm, respectively)
- ➔ $T(p)$ = execution time of the parallel program (algorithm) with p processors

Speedup (*Beschleunigung*) ...

➔ **Relative speedup** (for “sugarcoated” results ...)

$$S(p) = \frac{T(1)}{T(p)}$$

➔ $T(1)$ = execution time of the parallel program (algorithm) with one processor

➔ Optimum: $S(p) = p$

➔ Often: with **fixed** problem size, $S(p)$ declines again, when p increases

➔ more communication, less computing work per processor

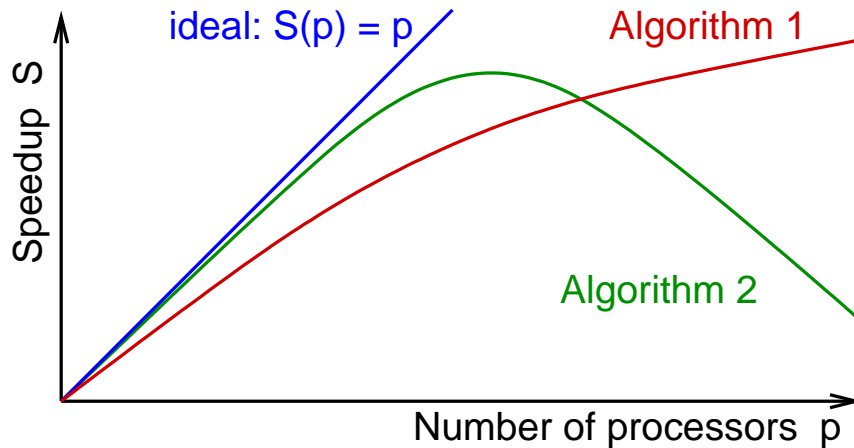
Notes for slide 113:

Sometimes, the relative speedup is computed with respect to the parallel execution on a small number of processors. This is necessary, when the problem cannot be solved sequentially, e.g., due to time or memory constraints.



Speedup (*Beschleunigung*) ...

➔ Typical trends:



➔ Statements like “speedup of 7.5 with 8 processors” can not be extrapolated to a larger number of processors

1.9.1 Performance Metrics ...



Superlinear speedup

➔ Sometimes we observe $S(p) > p$, although this should actually be impossible

➔ Causes:

➔ implicit change in the algorithm

➔ e.g., with parallel tree search: several paths in the search tree are traversed simultaneously

➔ limited breadth-first search instead of depth-first search

➔ cache effects

➔ with p processors, the amount of cache is p times higher than that with one processor

➔ thus, we also have higher cache hit rates

Amdahl's Law

- ➔ Defines an upper limit for the achievable speedup
- ➔ Basis: usually, not all parts of a program can be parallelized
 - due to the programming effort
 - due to data dependences
- ➔ Let a be the **portion of time** of these program parts in the **sequential** version of the program. Then:

$$S(p) = \frac{T_s}{T(p)} \leq \frac{1}{a + (1 - a)/p} \leq \frac{1}{a}$$

- ➔ With a 10% sequential portion, this leads to $S(p) \leq 10$

Notes for slide 116:

If a portion a of the sequential execution time is not parallelizable, then the parallel execution time in the best case is

$$T(p) = a \cdot T_s + (1 - a) \cdot \frac{T_s}{p}$$

Thus

$$S(p) = \frac{T_s}{T(p)} \leq \frac{T_s}{a \cdot T_s + (1 - a) \cdot \frac{T_s}{p}} = \frac{1}{a + (1 - a)/p}$$



Efficiency

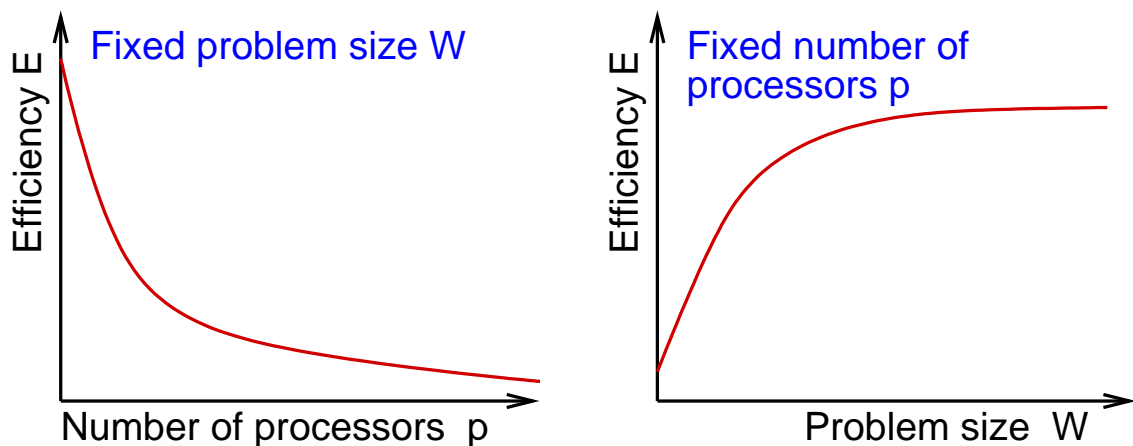
$$E(p) = \frac{S(p)}{p}$$

- ➔ Metrics for the utilisation of a parallel computer
- ➔ $E(p) \leq 1$, the optimum would be $E(p) = 1$



Scalability

- ➔ Typical observations:



- ➔ Reason: with increasing p : less work per processor, but the same amount of (or even more) communication

Scalability ...

- ➔ How must the problem size W increase with increasing number of processors p , such that the efficiency stays the same?
- ➔ Answer is given by the **isoefficiency function**
- ➔ Parallel execution time

$$T(p) = \frac{W + T_o(W, p)}{p}$$

- ➔ $T_o(W, p)$ = overhead of parallel execution
- ➔ T and W are measured as the number of elementary operations

➔ Thus:

$$W = \frac{E}{1 - E} \cdot T_o(W, p)$$

Notes for slide 119:

With

$$T(p) = \frac{W + T_o(W, p)}{p}$$

we get

$$S = \frac{W}{T(p)} = \frac{W \cdot p}{W + T_o(W, p)}$$

and

$$E = \frac{S}{p} = \frac{W}{W + T_o(W, p)} = \frac{1}{1 + T_o(W, p)/W}$$

Thus:

$$\frac{T_o(W, p)}{W} = \frac{1 - E}{E}$$

and

$$W = \frac{E}{1 - E} \cdot T_o(W, p)$$



Scalability ...

- ➔ Isoefficiency function $I(p)$
 - solution of the equation $W = K \cdot T_o(W, p)$ w.r.t. W
 - $K = \text{constant}$, depending on the required efficiency
- ➔ Good scalability: $I(p) = \mathcal{O}(p)$ or $I(p) = \mathcal{O}(p \log p)$
- ➔ Bad scalability: $I(p) = \mathcal{O}(p^k)$
- ➔ Computation of $T_o(W, p)$ by analysing the parallel algorithm
 - how much time is needed for communication / synchronisation and potentially additional computations?
 - more details and examples in chapter 1.9.5

1.9.2 Reasons for Performance Loss



- ➔ **Access losses** due to data exchange between tasks
 - e.g., message passing, remote memory access
- ➔ **Conflict losses** due to shared use of resources by multiple tasks
 - e.g., conflicts when accessing the network, mutual exclusion when accessing data
- ➔ **Utilisation losses** due to insufficient degree of parallelism
 - e.g., waiting for data, load imbalance
- ➔ **Breaking losses** when computations should end
 - e.g., with search problems: all other processes must be notified that a solution has been found



- ➔ **Complexity losses** due to additional work necessary for the parallel execution
 - ➔ e.g., partitioning of unstructured grids
- ➔ **Dumping losses** due to computations, which are executed redundantly but not used later on
 - ➔ e.g., lapsed search in branch-and-bound algorithms
- ➔ **Algorithmic losses** due to modifications of the algorithms during the parallelisation
 - ➔ e.g., worse convergence of an iterative method



Parallel Processing

WS 2017/18

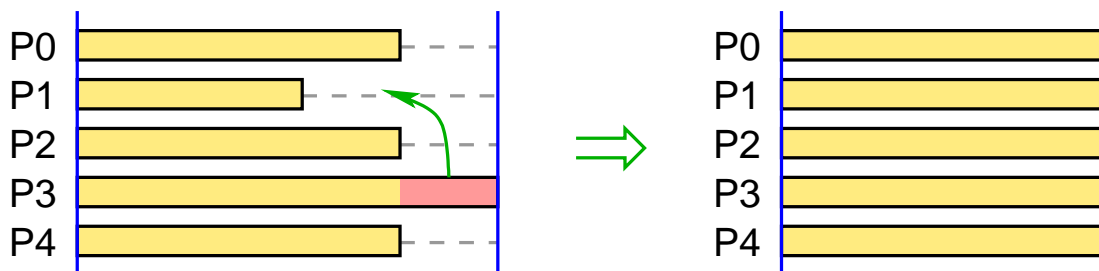
23.10.2017

Roland Wismüller
Universität Siegen
roland.wismueller@uni-siegen.de
Tel.: 0271/740-4050, Büro: H-B 8404

Stand: October 23, 2017

Introduction

- ➔ For optimal performance: processors should compute equally long between to (global) synchronisations
- synchronisation: includes messages and program start / end



- ➔ Load in this context: execution time between two synchronisations
- other load metrics are possible, e.g., communication load
- ➔ Load balancing is one of the goals of the mapping phase

1.9.3 Load Balancing ...

Reasons for load imbalance

- ➔ Unequal computational load of the tasks
 - e.g., atmospheric model: areas over land / water
- ➔ Heterogeneous execution platform
 - e.g., processors with different speed
- ➔ Computational load of the tasks changes dynamically
 - e.g., in atmospheric model, depending on the simulated time of day (solar radiation)
- ➔ Background load on the processors
 - e.g., in a PC cluster

static

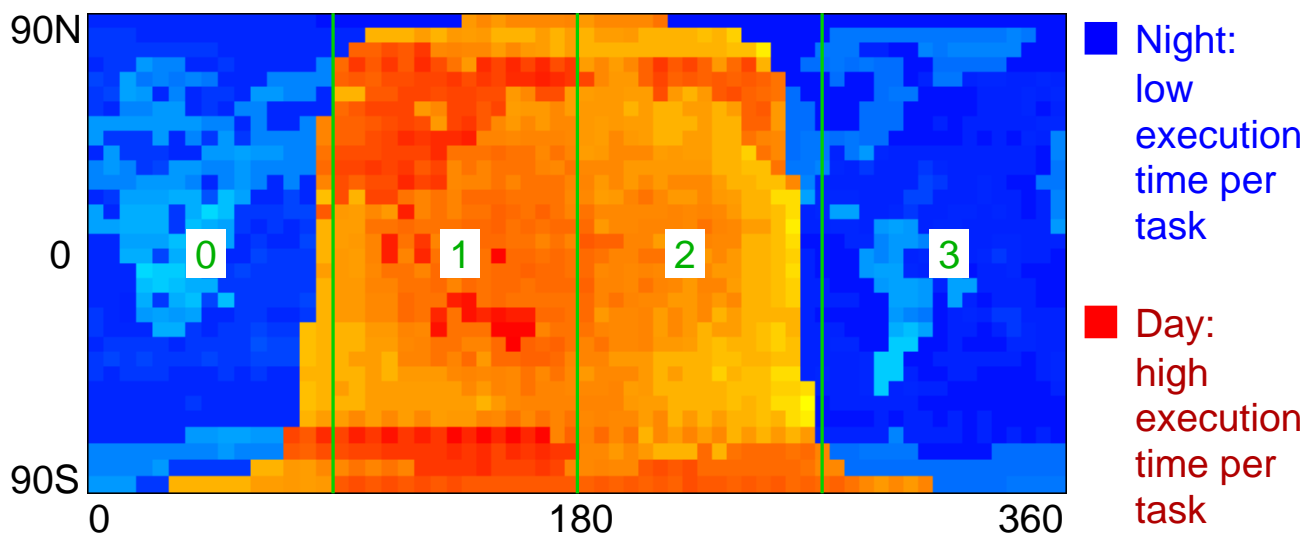
dynamic

1.9.3 Load Balancing ...



(Animated slide)

Example: atmospheric model



➔ Continents: static load imbalance

➔ Border between day and night: dynamic load imbalance

1.9.3 Load Balancing ...



Static load balancing

➔ Goal: distribute the tasks to the processors at / before program start, such that the computational load of the processors is equal

➔ Two fundamentally different approaches:

➤ take into account the tasks' different computational load when mapping them to processors

➤ extension of graph partitioning algorithms

➤ requires a good estimation of a task's load

➤ no solution, when load changes dynamically

➤ fine grained cyclic or random mapping

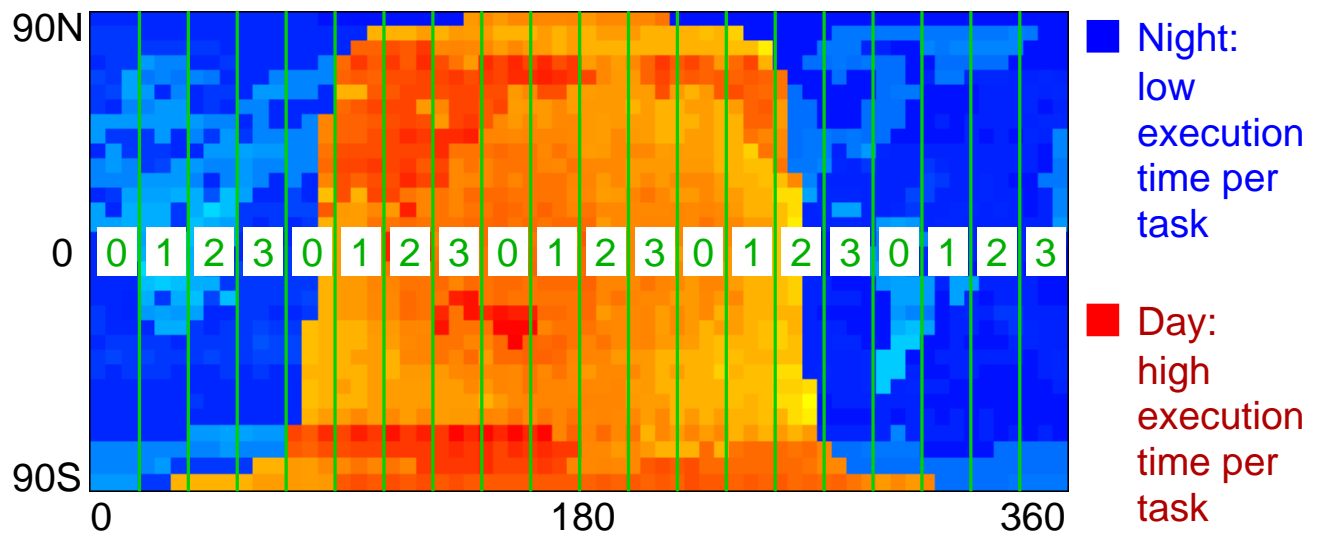
➤ results (most likely) in a good load balancing, even when the load changes dynamically

➤ price: usually higher communication cost

1.9.3 Load Balancing ...



Example: atmospheric model, cyclic mapping



➔ Each processor has tasks with high and low computational load

1.9.3 Load Balancing ...



Dynamic load balancing

- ➔ Independent (often dyn. created) tasks (e.g., search problem)
 - goal: processors do not idle, i.e., always have a task to process
 - even at the end of the program, i.e., all processes finish at the same time
 - tasks are dynamically **allocated** to processors and stay there until their processing is finished
 - optimal: allocate task with highest processing time first
- ➔ Communicating tasks (SPMD, e.g., stencil algorithm)
 - goal: equal computing time between synchronisations
 - if necessary, tasks are **migrated** between processors during their execution



How to determine performance metrics

- ➔ Analytical model of the algorithm
 - ➔ approach: determine computation and communication time
 - ➔ $T(p) = t_{comp} + t_{comm}$
 - ➔ computation/communication ratio t_{comp}/t_{comm} allows a rough estimation of performance
 - ➔ requires a computation model (model of the computer hardware)
- ➔ Measurement with the real programm
 - ➔ explicit timing measurement in the code
 - ➔ performance analysis tools

1.9.5 Analytical Performance Modelling

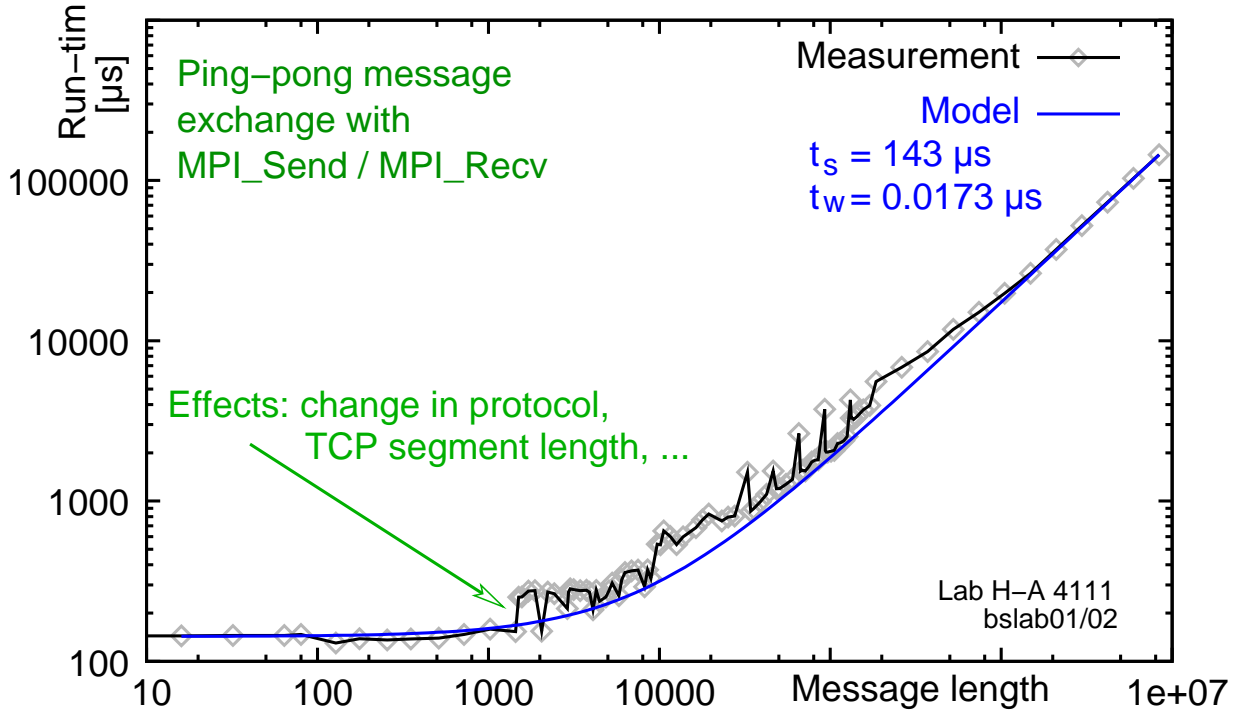


Models for communication time

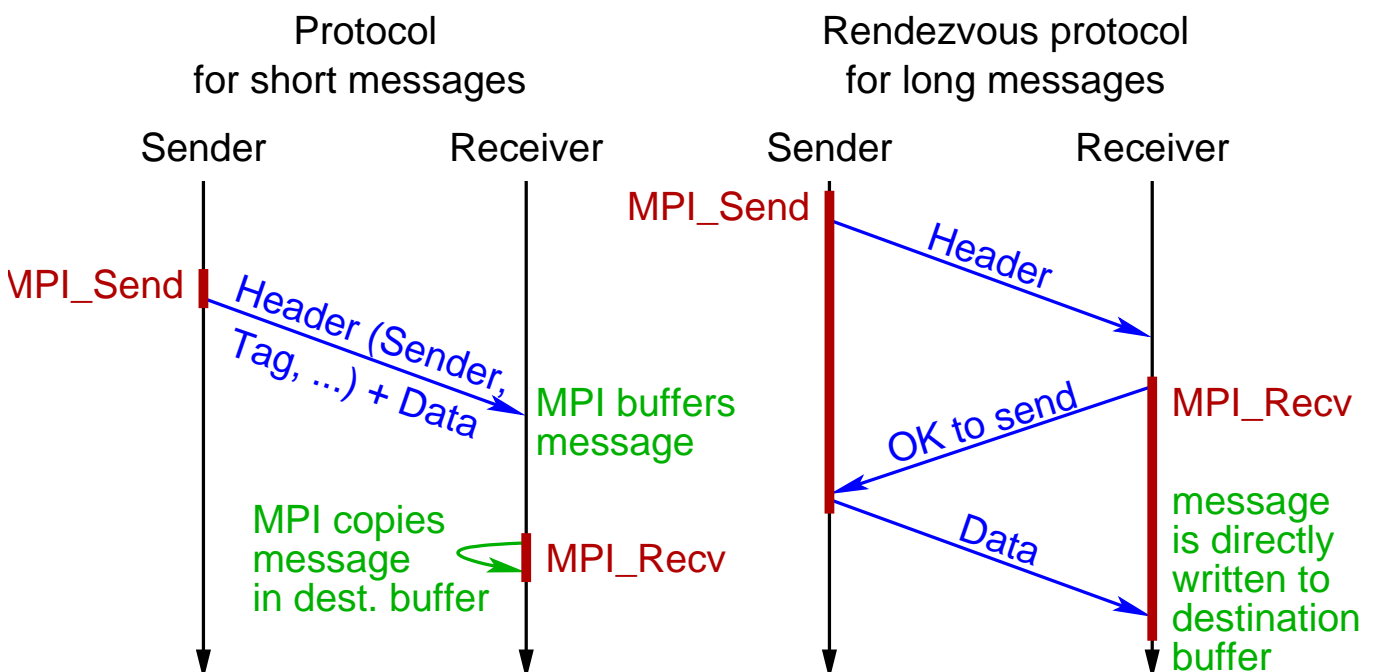
- ➔ E.g., for MPI (following Rauber: “*Parallele und verteilte Programmierung*”)
 - ➔ point-to-point send: $t(m) = t_s + t_w \cdot m$
 - ➔ broadcast: $t(p, m) = \tau \cdot \log p + t_w \cdot m \cdot \log p$
- ➔ Parameters (t_s, t_w, τ) are obtained via **micro benchmarks**
 - ➔ selectively measure a single aspect of the system
 - ➔ also allow the deduction of implementation characteristics
 - ➔ fitting, e.g., using the least square method
 - ➔ e.g., for point-to-point send:
 - PC cluster H-A 4111: $t_s = 71.5 \mu s, t_w = 8,6 ns$
 - SMP cluster (remote): $t_s = 25.6 \mu s, t_w = 8,5 ns$
 - SMP cluster (local): $t_s = 0,35 \mu s, t_w = 0,5 ns$



Example: results of the micro benchmark SKaMPI



Communication protocols in MPI





Example: matrix multiplication

- ➔ Product $C = A \cdot B$ of two square matrices
- ➔ Assumption: A, B, C are distributed blockwise on p processors
 - processor P_{ij} has A_{ij} and B_{ij} and computes C_{ij}
- ➔ P_{ij} needs A_{ik} and B_{kj} for $k = 1 \dots \sqrt{p}$
- ➔ Approach:
 - all-to-all broadcast of the A blocks in each row of processors
 - all-to-all broadcast of the B blocks in each column of processors

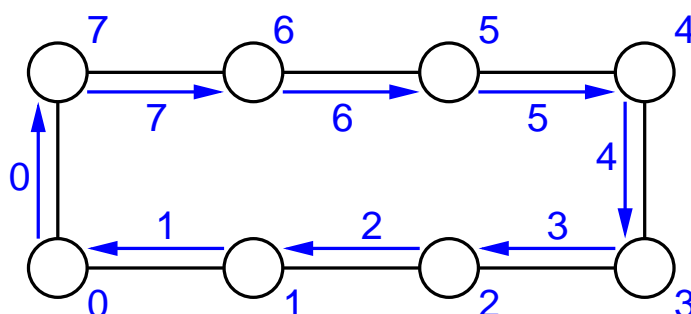
➔ computation of $C_{ij} = \sum_{k=1}^{\sqrt{p}} A_{ik} \cdot B_{kj}$



(Animated slide)

All-to-all broadcast

- ➔ Required time depends on selected communication structure
- ➔ This structure may depend on the network structure of the parallel computer
 - who can directly communicate with whom?
- ➔ Example: ring topology



$p-1$ steps:
send "newest"
data element to
successor in ring

- ➔ Cost: $t_s(p - 1) + t_w m(p - 1)$ (m : data length)

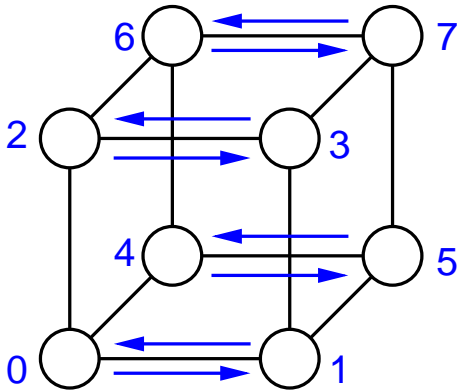
1.9.5 Analytical Performance Modelling ...



(Animated slide)

All-to-all broadcast ...

- ➔ Example: communication along a hyper cube
- ➔ requires only $\log p$ steps with p processors



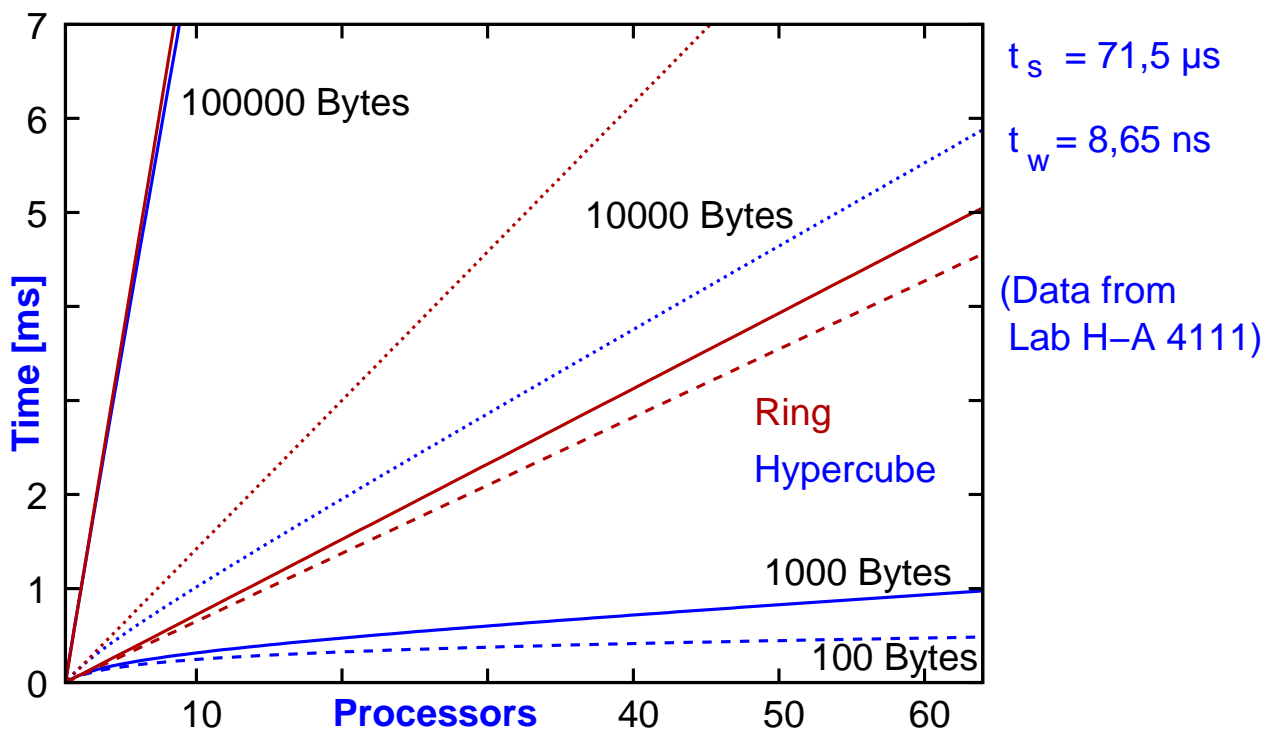
1. Pairwise exchange in x direction
2. Pairwise exchange in y direction
3. Pairwise exchange in z direction

➔ Cost:
$$\sum_{i=1}^{\log p} (t_s + 2^{i-1} t_w m) = t_s \log p + t_w m (p - 1)$$

1.9.5 Analytical Performance Modelling ...



All-to-all broadcast ...



Complete analysis of matrix multiplication

- ➔ Two all-to-all broadcast steps between \sqrt{p} processors
 - ➔ each step concurrently in \sqrt{p} rows / columns
- ➔ Communication time: $2(t_s \log(\sqrt{p}) + t_w(n^2/p)(\sqrt{p} - 1))$
- ➔ \sqrt{p} multiplications of $(n/\sqrt{p}) \times (n/\sqrt{p})$ sub-matrices
- ➔ Computation time: $t_c \sqrt{p} \cdot (n/\sqrt{p})^3 = t_c n^3 / p$
- ➔ Parallel run-time: $T(p) \approx t_c n^3 / p + t_s \log p + 2t_w(n^2 / \sqrt{p})$
- ➔ Sequential run-time: $T_s = t_c n^3$

Notes for slide 137:

When we compare the result for $T(p)$ with the formula $T(p) = \frac{W + T_o(W, p)}{p}$ from slide 119, we get:

$$T_o(n, p) = p \cdot (t_s \log p + 2t_w(n^2 / \sqrt{p}))$$

(We use the problem size n instead of the work W here).

Now, to get the isoefficiency function of our matrix multiplication, we must solve the equation $n = K \cdot T_o(n, p)$ w.r.t. n . We can do this in approximation by neglect the term $t_s \log p$. Then we get:

$$n = K \cdot p \cdot (2t_w(n^2 / \sqrt{p})) = 2 \cdot K \cdot t_w \cdot n^2 \cdot p^{\frac{3}{2}}$$

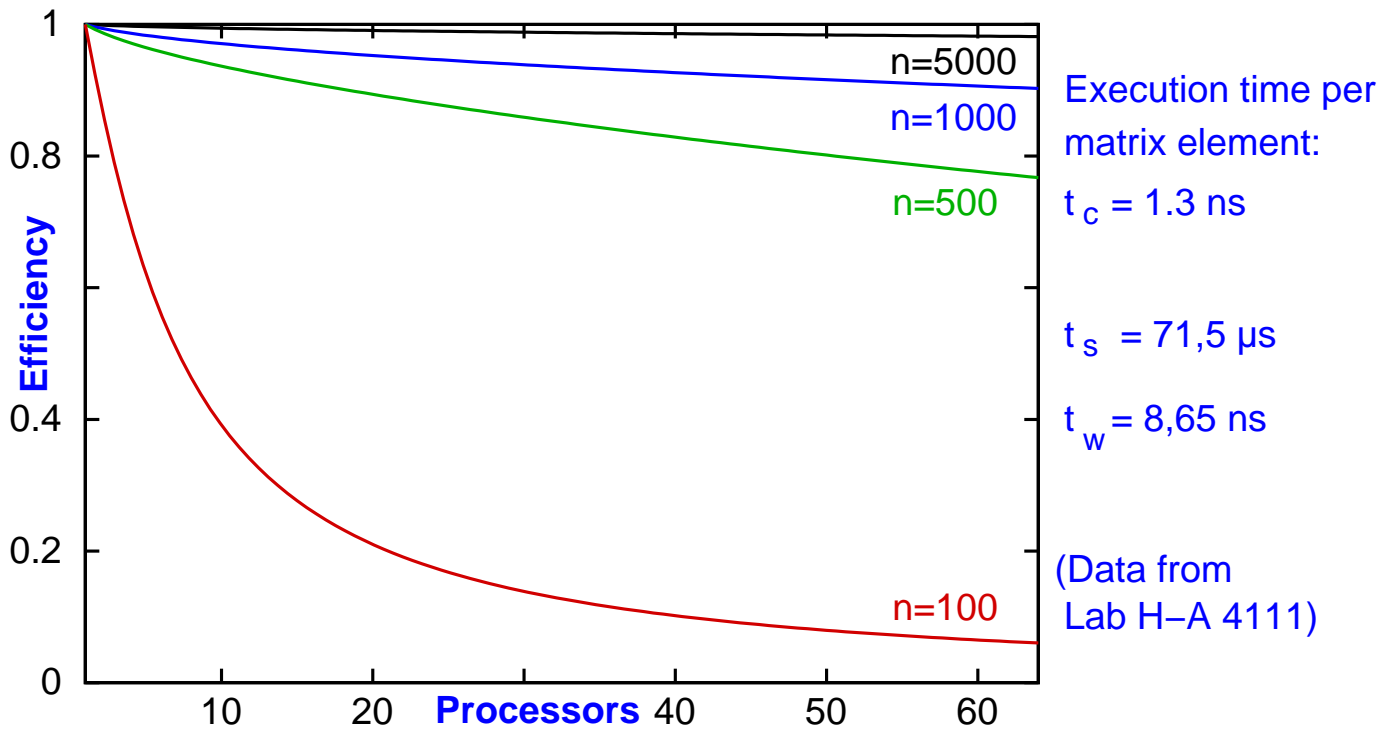
Or (by dividing both sizes by n and reordering):

$$n = \frac{1}{2 \cdot K \cdot t_w} \cdot p^{\frac{2}{3}}$$

That is $n(p) = \mathcal{O}(p^{\frac{2}{3}})$, which implies $n(p) = \mathcal{O}(p)$. Thus, matrix multiplication offers (very) good scalability.



Efficiency of matrix multiplication



1.9.6 Performance Analysis Tools



- ➔ Goal: performance debugging, i.e., finding and eliminating performance bottlenecks
- ➔ Method: measurement of different quantities (metrics), if applicable separated according to:
 - ➔ execution unit (compute node, process, thread)
 - ➔ source code position (procedure, source code line)
 - ➔ time
- ➔ Tools are very different in their details
 - ➔ method of measurement, required preparation steps, processing of information, ...
- ➔ Some tools are also usable to visualise the program execution



Metrics for performance analysis

- ➔ CPU time (assessment of computing effort)
- ➔ Wall clock time (includes times where thread is blocked)
- ➔ Communication time and volume
- ➔ Metrics of the operating system:
 - page faults, process switches, system calls, signals
- ➔ Hardware metrics (only with hardware support in the CPU):
 - CPU cycles, floating point operations, memory accesses
 - cache misses, cache invalidations, ...



Sampling (sample based performance analysis)

- ➔ Program is interrupted periodically
- ➔ Current value of the program counter is read (and maybe also the call stack)
- ➔ The full measurement value is assigned to this place in the program, e.g., when measuring CPU time:
 - periodic interruption every $10ms$ CPU time
 - `CPU_time[current_PC_value] += 10ms`
- ➔ Mapping to source code level is done offline
- ➔ Result: measurement value for each function / source line



Profiling and tracing (event based performance analysis)

- ➔ Requires an **instrumentation** of the programs, e.g., insertion of measurement code at interesting places
 - often at the beginning and end of library routines, e.g., MPI_Recv, MPI_Barrier, ...
- ➔ Tools usually do the instrumentation automatically
 - typically, the program must be re-compiled or re-linked
- ➔ Analysis of the results is done during the measurement (profiling) or after the program execution (tracing)
- ➔ Result:
 - measurement value for each measured function (profiling, tracing)
 - development of the measurement value over time (tracing)



Example: measurement of cache misses

- ➔ Basis: hardware counter for cache misses in the processor
- ➔ Sampling based:
 - when a certain counter value (e.g., 419) is reached, an interrupt is triggered
 - `cache_misses[current_PC_value] += 419`
- ➔ Event based:
 - insertion of code for reading the counters:

```
old_cm = read_hw_counter(25);
for (j=0; j<1000; j++)
    d += a[i][j];
cache_misses += read_hw_counter(25)-old_cm;
```

Pros and cons of the methods

- ➔ Sampling
 - ➔ low and predictable overhead; reference to source code
 - ➔ limited precision; no resolution in time
- ➔ Tracing
 - ➔ acquisition of all relevant data with high resolution in time
 - ➔ relatively high overhead; large volumes of data
- ➔ Profiling
 - ➔ reduced volume of data, but less flexible