PARALLEL PROGRAMMING

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CONTENT

- Introduction
- Parallel program design
- Patterns for parallel programming
  - A: Algorithm structure
  - B: Supporting structures

INTRODUCTION

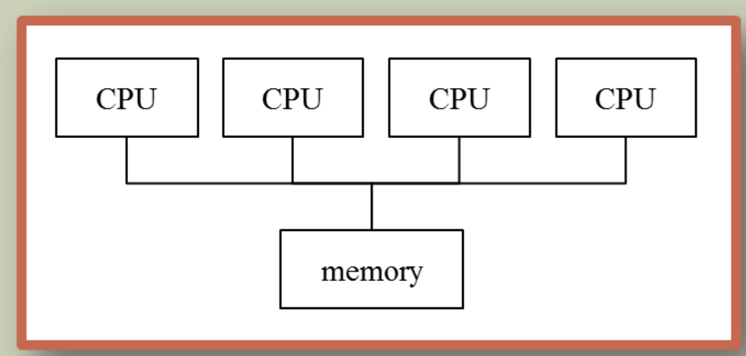
Context around parallel programming

PARALLEL PROGRAMMING MODELS

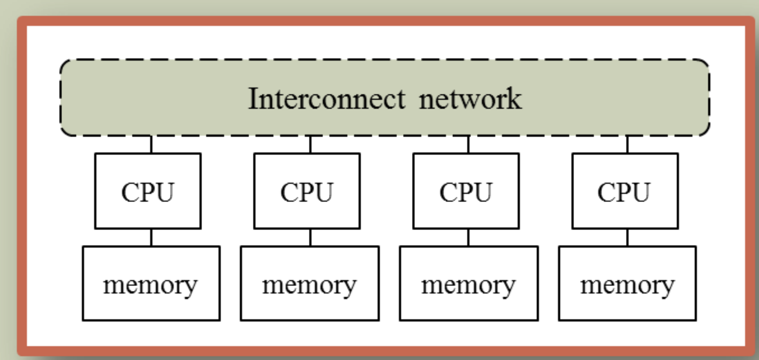
- Many different models reflecting the various different parallel hardware architectures
- 2 or rather 3 most common models:
  - Shared memory
  - Distributed memory
  - Hybrid models (combining shared and distributed memory)

PARALLEL PROGRAMMING MODELS

Shared memory



Distributed memory



PROGRAMMING CHALLENGES

Shared memory

- Synchronize memory access
- Locking vs. potential race conditions

Distributed memory

- Communication bandwidth and resulting latency
- Manage message passing
- Synchronous vs. asynchronous communication

PARALLEL PROGRAMMING STANDARDS

- 2 common standards as examples for the 2 parallel programming models:
  - *Open Multi-Processing* (OpenMP)
  - *Message passing interface* (MPI)

OpenMP

- Collection of libraries and compiler directives for parallel programming on shared memory computers

- Programmers have to explicitly designate blocks that are to run in parallel by adding directives like:

```
#pragma omp parallel
```

- OpenMP then creates a number of threads executing the designated code block

MPI

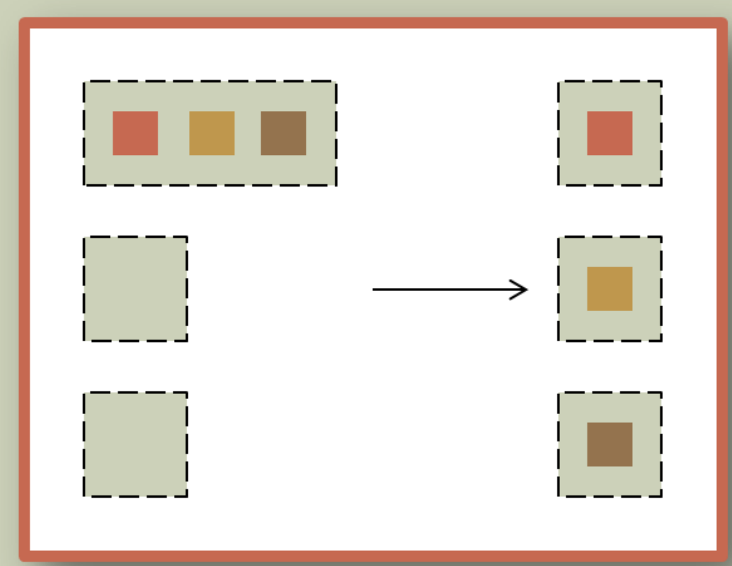
- Library with routines to manage message passing for programming on distributed memory computers

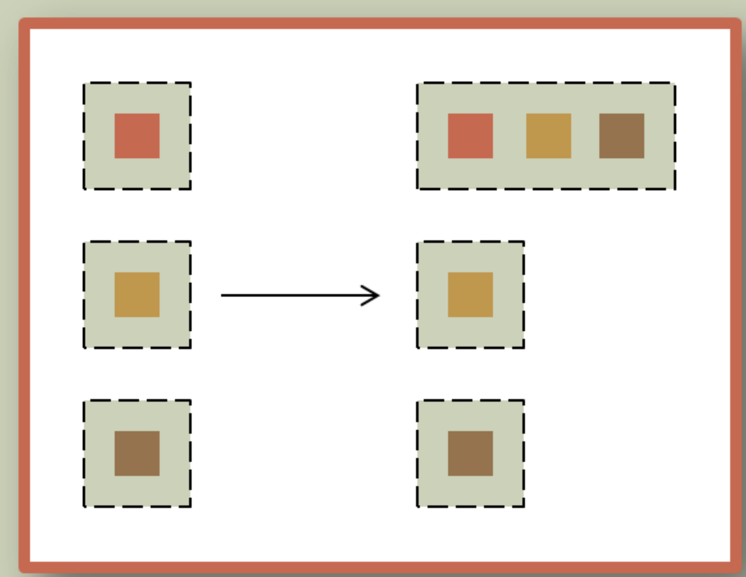
- Messages are sent from one process to another
- Routines for synchronization, broadcasts, blocking and non blocking communication

MPI EXAMPLE

MPI.Scatter

MPI.Gather





PARALLEL PROGRAM DESIGN

General strategies for finding concurrency

FINDING CONCURRENCY

- General approach: Analyze a problem to identify exploitable concurrency
- Main concept is *decomposition*: Divide a computation into smaller parts all or some of which can run concurrently

SOME TERMINOLOGY

- *Tasks*: Programmer-defined units into which the main computation is decomposed
- *Unit of execution (UE)*: Generalization of processes and threads

TASK DECOMPOSITION

- Decompose a problem into tasks that can run concurrently
- Few large tasks vs. many small tasks
- Minimize dependencies among tasks

GROUP TASKS

- Group tasks to simplify managing their dependencies
- Tasks within a group run at the same time
- Based on decomposition: Group tasks that belong to the same high-level operations
- Based on constraints: Group tasks with the same constraints

ORDER TASKS

- Order task groups to satisfy constraints among them

- Order must be:
  - Restrictive enough to satisfy constraints
  - Not too restrictive to improve flexibility and hence efficiency
- Identify dependencies – e.g.:
  - Group A requires data from group B
- Important: Also identify the independent groups
- Identify potential dead locks

DATA DECOMPOSITION

- Decompose a problem‘s data into units that can be operated on relatively independent

- Look at problem‘s central data structures
- Decomposition already implied by **or** basis for task decomposition
- Again: Few large chunks vs. many small chunks
  - Improve flexibility: Configurable granularity

DATA SHARING

- Share decomposed data among tasks

- Identify task-local and shared data
- Classify shared data: read/write or read only?
- Identify potential race conditions
- Note: Sometimes data sharing implies communication

PATTERNS FOR PARALLEL PROGRAMMING

Typical parallel program structures

A: ALGORITHM STRUCTURE

- How can the identified concurrency be used to build a program?
- 3 examples for typical parallel algorithm structures:
  - Organize by tasks: *Divide & conquer*
  - Organize by data decomposition: *Geometric/domain decomposition*
  - Organize by data flow: *Pipeline*

DIVIDE & CONQUER

- Principle: Split a problem recursively into smaller solvable sub problems and merge their results
- Potential concurrency: Sub problems can be solved simultaneously

DIVIDE & CONQUER

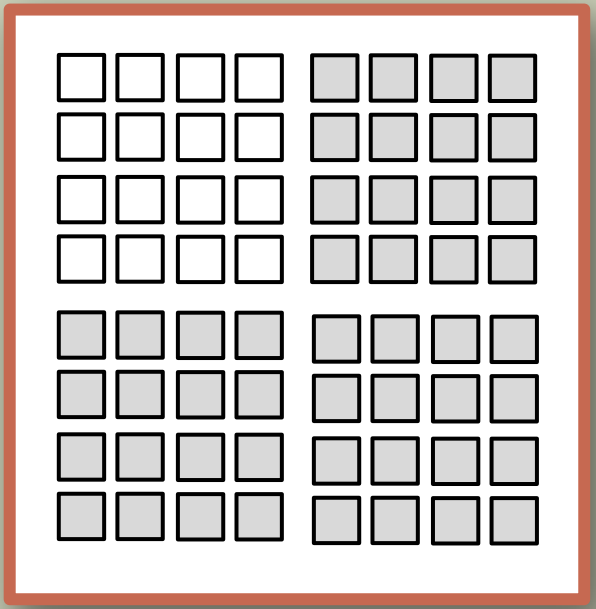
- Precondition: Sub problems can be solved independently
- Efficiency constraint: Split and merge should be trivial compared to sub problems
- Challenge: Standard base case can lead to too many too small tasks
  - End recursion earlier?

GEOMETRIC/DOMAIN DECOMPOSITION

- Principle: Organize an algorithm around a linear data structure that was decomposed into concurrently updatable chunks
- Potential concurrency: Chunks can be updated simultaneously

GEOMETRIC/DOMAIN DECOMPOSITION

- Example: Simple blur filter where every pixel is set to the average value of its surrounding pixels
  - Image can be split into squares
  - Each square is updated by a task
  - To update square border information from other squares is required

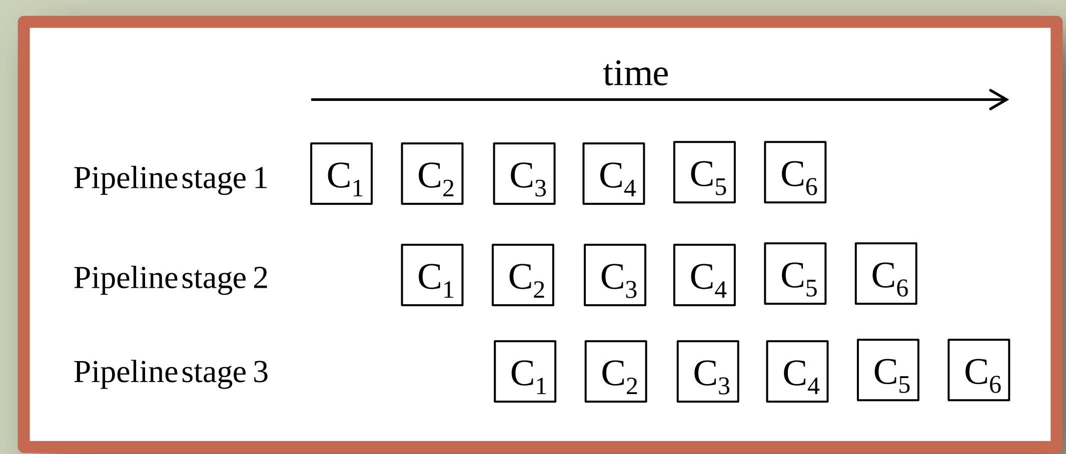


GEOMETRIC/DOMAIN DECOMPOSITION

- Again: Granularity of decomposition?
- Choose square/cubic chunks to minimize surface and thus nonlocal data
- Replicating nonlocal data can reduce communication → "ghost boundaries"
- Optimization: Overlap update and exchange of nonlocal data
- Number of tasks > number of UEs for better load balance

PIPELINE

- Principle based on analogy *assembly line*: Data flowing through a set of stages
- Potential concurrency: Operations can be performed simultaneously on different data items



PIPELINE

- Example: Instruction pipeline in CPUs
  - Fetch (instruction)
  - Decode
  - Execute
  - ...

PIPELINE

- Precondition: Dependencies among tasks allow an appropriate ordering
- Efficiency constraint: Number of stages << number of processed items
- Pipeline can also be nonlinear

B: SUPPORTING STRUCTURES

- Intermediate stage between problem oriented algorithm structure patterns and their realization in a programming environment
- Structures that "support" the realization of parallel algorithms
- 4 examples:
  - Single program, multiple data (SPMD)
  - Task farming/Master & Worker
  - Fork & Join
  - Shared data

SINGLE PROGRAM, MULTIPLE DATA

- Principle: The same code runs on every UE processing different data
- Most common technique to write parallel programs!

SINGLE PROGRAM, MULTIPLE DATA

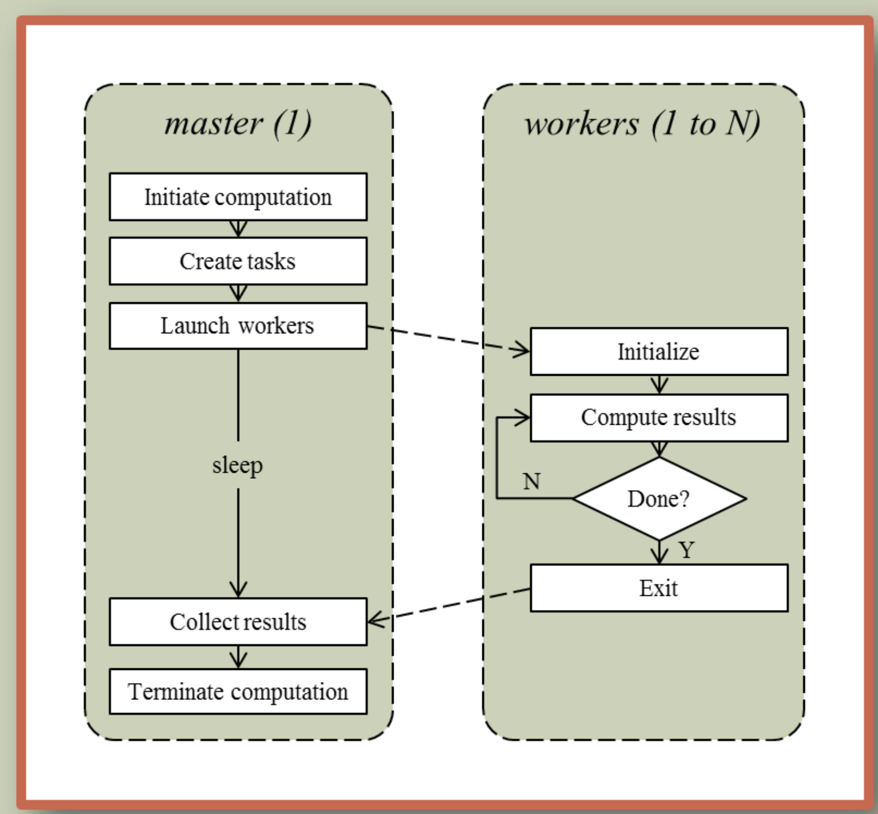
- Program stages:
  1. Initialize and obtain unique ID for each UE
  2. Run the same program on every UE: Differences in the instructions are driven by the ID
  3. Distribute data by decomposing or sharing/copying global data

- Risk: Complex branching and data decomposition can make the code awful to understand and maintain

TASK FARMING/MASTER & WORKER

- Principle: A master task (“farmer”) dispatches tasks to many worker UEs and collects (“farms”) the results

TASK FARMING/MASTER & WORKER



TASK FARMING/MASTER & WORKER

- Precondition: Tasks are relatively independent
- Master:
  - Initiates computation
  - Creates a bag of tasks and stores them e.g. in a shared queue
  - Launches the worker tasks and waits
  - Collects the results and shuts down the computation
- Workers:
  - While the bag of tasks is not empty pop a task and solve it
- Flexible through indirect scheduling
- Optimization: Master can become a worker too

FORK & JOIN

- Principle: Tasks create ("fork") and terminate ("join") other tasks dynamically
- Example: An algorithm designed after the *Divide & Conquer* pattern

FORK & JOIN

- Mapping the tasks to UEs can be done directly or indirectly

- *Direct*: Each subtask is mapped to a new UE
  - Disadvantage: UE creation and destruction is expensive
  - Standard programming model in OpenMP
- *Indirect*: Subtasks are stored inside a shared queue and handled by a static number of UEs

- Concept behind OpenMP

SHARED DATA

- Problem: Manage access to shared data
- Principle: Define an access protocol that assures that the results of a computation are correct for any ordering of the operations on the data

SHARED DATA

- Model shared data as a(n) (abstract) data type with a fixed set of operations
- Operations can be seen as transactions (→ *ACID properties*)
- Start with a simple solution and improve performance step-by-step:
  - Only one operation can be executed at any point in time
  - Improve performance by separating operations into noninterfering sets
  - Separate operations in read and write operations
  - Many different lock strategies…

QUESTIONS?

REFERENCES

- T. Mattson, B. Sanders and B. Massingill. *Patterns for parallel programming*. Addison-Wesley, 2004.
- A. Grama, A. Gupta, G. Karypis and V. Kumar. *Introduction to parallel computing*. Addison Wesley, 2nd Edition, 2003.
- P. S. Pacheco. *An introduction to parallel programming*. Morgan Kaufmann, 2011.

- Images from Mattson et al. 2004