Requirements for Parallel Programs

- Real problem(observation, experiments) ⇒ Parallel algorithm(descriptive pseudo code) ⇒ Parallel computer program (programming language code).
- To devise an efficient parallel program we have to identify:
  - concurrency,
  - scalability,
  - locality, and
  - modularity.

Concurrency

- Ability of performing calculation at the same time
  - independent calculation
  - accessible data in the time of calculation
- Sum of integers 1-10 (instead of 10 steps we use 4 steps)
  1. a=1+2, b=3+4, c=5+6, d=7+8, e=9+10
  2. a=a+b, b=c+d, e,
  3. a=a+b
  4. a=a+e
- Can not start step 3 before step 2 is finished..
- But the price is: a need for more adders able to compute concurrently and more memory locations.

Scalability

- Resilience to increasing processor counts.
- Ability to execute a parallel program with a similar efficiency on different number of processors.
- Usually, efficiency decreases with the increased number of processors.
- Program able to use only a fixed number of processors is a bad parallel program.
- Scalability enables portability for protecting software investments.

Locality

- A possibility of a program for exploiting accesses to local memory (same-node).
- Local accesses are less expensive (faster) than accesses to remote memory (different-node). i.e.: read and write are less costly than send and receive.
- The ratio remote/local cost can vary from 10:1 to 1000:1 or greater, depending on the relative performance of the local computer, the network, and the mechanisms used to move data to and from the network.
- Efficiency of a parallel algorithm depends on the ratio of the number of remote to local access.

Modularity

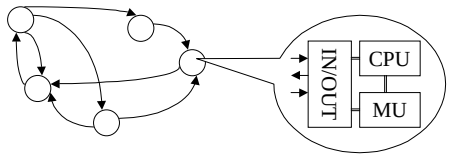
- In modular program design its components are developed separately, as independent modules.
- These modules can be combined or reuse to obtain a new complete program.
- Interactions between modules should be restricted to well-defined interfaces.
- A module implementation can be changed without modifying other program modules.
- The properties of a program can be determined from the specifications of program modules and the main program code.
- Modular design reduces program complexity and facilitates code reuse.

Amdhal's Law

- Let a program Pr be composed of sequential part Sq (e.g.: reading data from disk), and a parallel part Pp that can be ideally parallelized: Pr = Sq + Pp.
- On a single processor Sq takes 10% of the total CPU time, Pp can be implemented in 90% of the total execution time TPr.
- What is the maximal speedup that can be reached with an arbitrary large number of processors?
  S = T1/Tp = (TSq+TPp) / (TSq + (TPp/p)] =
  = 1 + (TPp/TSq) = 1 + (0.9/0.1) = 10
- The parallel program has to be probably redesigned !

Parallel Programming Model

- Parallel programs can be represented by a set of tasks and channels, and modelled by a directed graph, where vertices represent tasks and edges represent channels.
- A task incorporates sequential program and in/out ports connected to channels.



Task Actions

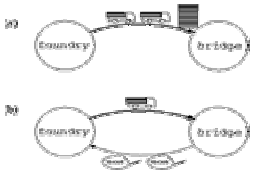
- Read or write from/to local memory,
- Send or receive messages to/from other tasks,
- Create new tasks,
- Terminate task execution,
- Create new channels,
- Change connectivity.

Task Mapping

- If one task requires data from another task, in order to proceed, we talk about **data dependency**.
- If these two tasks are mapped on different computers, send/receive communication is needed, else only read/write to local memory is used.
- Tasks can be mapped on physical processors with no effect on the program semantic. For example, single task or multiple tasks can be mapped on a single processor.
- But after mapping, all processors should be loaded equally because the slowest processor dictates the execution time of the parallel program.

Illustration-Bridge Construction

- Case (a)-two tasks: foundry (girders production) and bridge (bridge construction) and a single channel: trucks transporting girders (overflowing?)

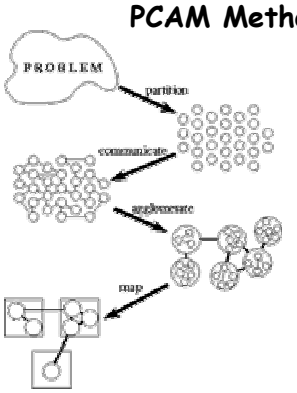


- Case (b): one additional channel for requesting girders and for finishing the job when the bridge is complete.

Methodology for Designing Parallel Algorithms

- Composed of four stages:
  - **P**artitioning
  - **C**ommunication
  - **A**gglomeration
  - **M**apping
- Acronym PCAM
- First two stages are focused on concurrency and scalability
- Third and fourth stages search for locality and other performance-related issues.

PCAM Methodology



1. Start with problem specification,
2. Develop a partition,
3. Determine communi-cation requirements,
4. Agglomerate tasks, and finally
5. Map tasks to processors.

Partitioning

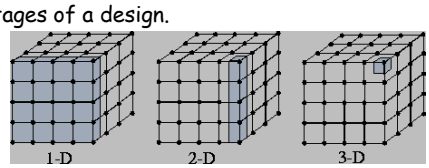
- Partitioning - opportunities for parallel execution.
- Defining a large number of small tasks able to being executed in parallel: fine-grained decomposition.
- Domain decomposition - data first then computation
- Functional decomposition - computation first then data.
- In later design stages the original partition is revisited and
- agglomerate tasks to increase their size, or granularity.

Domain decomposition

- In the domain decomposition approach to problem partitioning, we seek first to decompose the data associated with a problem.
- If possible, we divide these data into small pieces of approximately equal size.
- Next, we partition the computation that is to be performed, typically by associating each operation with the data on which it operates.
- This partitioning yields a number of tasks, each comprising some data and a set of operations on that data. An operation may require data from several tasks.
- In this case, communication is required to move data between tasks.

Domain decomposition (exm.)

- Example of a domain decompositions for a problem involving a three-dimensional grid. One-, two-, and three-dimensional decompositions are possible; in each case, data associated with a single task are shaded.
- A three-dimensional decomposition offers the greatest flexibility and should be used in the early stages of a design.

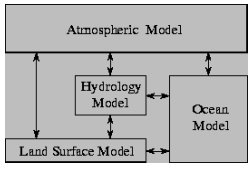


Functional decomposition

- Functional decomposition represents a complementary way of thinking about problems. The initial focus is on the computation that is to be performed rather than on the data manipulated by the computation.
- If we are successful in dividing this computation into disjoint tasks, we proceed to examine the data requirements of these tasks.
- These data requirements may be disjoint, in which case the partition is complete. Alternatively, they may overlap significantly, in which case considerable communication will be required to avoid replication of data.
- This is often a sign that a domain decomposition approach should be considered instead.

Functional decomposition (exm.)

- Functional decomposition in a computer model of climate. Each model component can be thought of as a separate task, to be parallelized by domain decomposition.
- Arrows represent exchanges of data between components during computation: the atmosphere model generates wind velocity data that are used by the ocean model, the ocean model generates sea surface temperature data that are used by the atmosphere model, and so on.



Communication

- The tasks generated by a partition are intended to execute concurrently but cannot, in general, execute independently.
- The computation to be performed in one task will typically require data associated with another task.
- Data must then be transferred between tasks so as to allow computation to proceed.
- This information flow is specified in the communication phase of a design.

Communication (cont.)

- First, we define a channel structure that links, either directly or indirectly, tasks that require data (consumers) with tasks that possess those data (producers).
- Second, we specify the messages that are to be sent and received on these channels.
- In domain decomposition problems, communication requirements can be difficult to determine.
- In contrast, communication requirements in parallel algorithms obtained by functional decomposition are often straightforward: they correspond to the data flow between tasks.

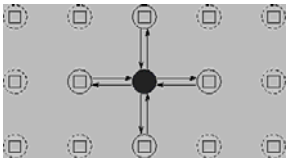
Communication (cont.)

- In *local* communication, each task communicates with a small set of other tasks (its ``neighbors'');
- *global* communication requires each task to communicate with many tasks.

- In *structured* communication, a task and its neighbors form a regular structure, such as a tree or grid;
- *unstructured* communication networks may be arbitrary graphs.

Local Communication

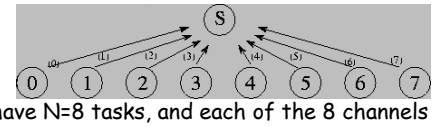
- A local communication structure is obtained when an operation requires data from a small number of other tasks.
- For illustrative purposes, we consider the communication requirements associated with a Jacobi finite difference method, using a five-point stencil to update each element of a 2-D grid.



$$X_{i,j}^{(t+1)} = \frac{4X_{i,j}^{(t)} + X_{i-1,j}^{(t)} + X_{i+1,j}^{(t)} + X_{i,j-1}^{(t)} + X_{i,j+1}^{(t)}}{8}.$$

Global Communication

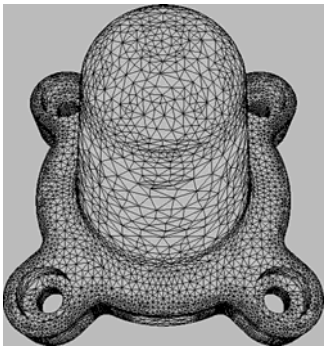
- Many tasks must participate. When such operations are implemented, it may not be sufficient simply to identify individual producer/consumer pairs. Such an approach may result in too many communications or may restrict opportunities for concurrent execution.
- For example, consider the problem of performing a parallel reduction operation, a centralized sum in S.



- We have N=8 tasks, and each of the 8 channels are connected to S (labels denotes the number of step). This approach takes O(N) steps, not good!

Unstructured and Dynamic Communication

- Example of a problem requiring unstructured communication.
- In this finite element mesh generated for an assembly part, each vertex is a grid point.
- Notice that different vertices have varying numbers of neighbours.



Communication (cont.)

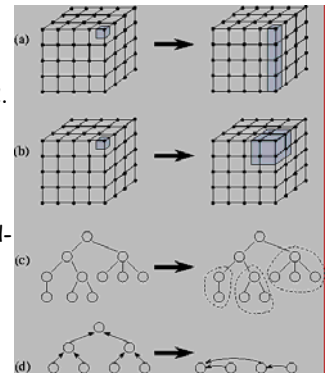
- In *synchronous* communication, producers and consumers execute in a coordinated fashion, with producer/consumer pairs cooperating in data transfer operations;
- in contrast, *asynchronous* communication may require that a consumer obtain data without the cooperation of the producer.

Agglomeration

- In the first two stages of the design process, we partitioned the computation to be performed into a set of tasks and introduced communication to provide data required by these tasks.
- The resulting algorithm is still abstract it is not specialized for efficient execution on any particular parallel computer. It may creates many more tasks than there are processors, or the computer is not designed for efficient execution of small tasks.
- In the third stage, *agglomeration*, we move to the concrete. We consider whether it is useful to combine, or agglomerate, tasks (smaller number).
- We also determine whether it is worthwhile to replicate data and/or computation.

Agglomeration (exm.)

(a) the size of tasks is increased by reducing the dimension of the decomposition from 3->2.
(b) adjacent tasks are combined to yield a decomposition of higher granularity.
(c) subtrees in a divide-and-conquer structure are merged.
(d) nodes in a tree algorithm are combined.



Agglomeration Goals

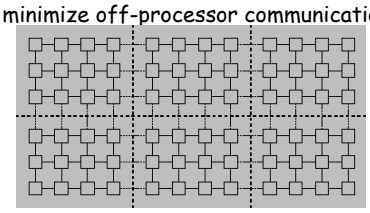
- Three sometimes-conflicting goals guide decisions concerning agglomeration and replication:
- *reducing communication* costs by increasing computation and communication granularity (communication costs, task creation costs), by replicated computation (trade off), or by agglomeration of tasks that cannot execute concurrently.
- *preserving flexibility* with larger number of tasks than the number of processors (scalability and mapping) to preserve portability on computers with different number of processors.
- and *reducing software engineering costs*, small changes when parallelizing existing sequential codes.

Mapping

- In the fourth and final stage of the parallel algorithm design process, we specify where each task is to execute.
- The mapping problem does not arise on uniprocessors or on shared-memory computers that provide automatic task scheduling by operating system and associated communication by shard memory.
- Unfortunately, general-purpose mapping mechanisms is not developed yet for scalable parallel computers. In general, mapping remains a difficult problem that must be explicitly addressed when designing parallel algorithms.

Mapping (exm. 1)

- Mapping in a grid problem in which each task performs the same amount of computation and communicates only with its four neighbors is straightforward. The heavy dashed lines delineate processor boundaries. The grid and associated computation is partitioned to give each processor the same amount of computation and to minimize off-processor communication.



Load Balancing Algorithms

- More complex domain decomposition-based algorithms with variable amounts of work per task and/or unstructured communication patterns. We have to use load balancing algorithms that seek to identify efficient agglomeration and mapping strategies, typically by using heuristic techniques.
- The time required to execute these algorithms must be weighed against the benefits of reduced execution time.
- Probabilistic load-balancing methods have sometimes lower overhead.
- The most complex problems needs dynamic load-balancing strategy in which a load-balancing algorithm is executed periodically.

Load Balancing (exm.)

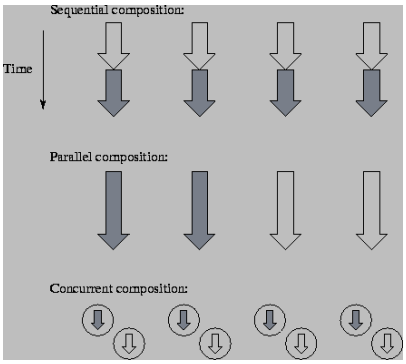
- A final result of a load balancing algorithm of the object analysed by finite elements (PP cover).
- Recursive bisection techniques are used to partition a domain into subdomains of approximately equal computational cost while attempting to minimize communication costs (number of channels crossing task boundaries).
- Many other techniques.

Composition

- We distinguished three general forms of composition that can be used for the modular construction of parallel programs:
- *sequential composition* - two program components execute in sequence on the same set of processors
- *parallel composition* - two program components execute concurrently on disjoint sets of processors
- *concurrent composition* - two program components execute on potentially non disjoint sets of processors.
- MPI's MPMD programming model supports well first two compositions, the full generality of concurrent composition is not generally available.

Composition - Figure

- A program composed of two different components (grey, dark grey).
- It is executing on four processors, with each arrow representing a separate thread of control.



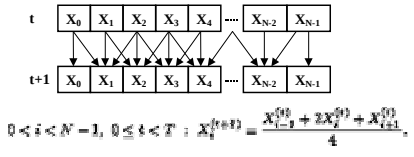
Parallel Algorithm Examples

- In order to introduce Task-Channel model and all other issues mentioned, we present four typical parallel algorithms:

- Finite differences (fixed number of tasks with the same function - SPMD structure),
- Pairwise Interactions (SPMD structure),
- Parallel Search (dynamic creation of tasks), and
- Parameter Study (fixed number of tasks with different functions).

Finite Differences

- Finite differences are a fundamental tool for the solution of partial differential equations.
- A one-dimensional finite difference example, in which we have an initial state represents by vector X^0 of size N and must compute the solution X^T with step-by-step updating of X^t by:



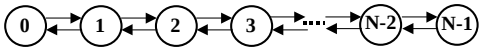
$$0 < i < N-1,\ 0 \le t < T\ :\ X_i^{(t+1)} = \frac{X_{i-1}^{(t)} + 2X_i^{(t)} + X_{i+1}^{(t)}}{4}$$

Finite Differences (cont.)

- The new value of X^{t+1} can be calculated after all tasks calculate their own value for X^t, and receive values for X^t from the left and the right neighbour.
- Values X_0 and X_{N-1} are boundary values. Boundary conditions have to be devised for the boundary values.
- Let say that the boundary values has fixed values that are equal to the initial values X^0_0 and X^0_{N-1}.
- Communication between nearest neighbours is necessary.

Finite Differences-Parallel Model

- We have N tasks, each responsible for computing X_0, X_1, ..., X_{N-1}, in each of T calculation steps.
- Tasks 0 and N-1 are boundary tasks (with i.e.: fixed values), and have a slightly different calculation than other tasks.
- Data transfer is implemented with two bi-directional channels to the right and to the left neighbours.



Finite Differences-Performance Analysis

- Assume that we distribute N tasks (points) among P processors, each responsible for equal number N/P points. Each processor performs the same computation on each grid point and at each time step. Because the parallel algorithm does not replicate computation, we can model computation time in a single time step as: Tcomp = tc*N
- Each processor must exchange a single data point on each boundary (two messages received two sent). The number of all messages is: Tcomm = 2*P*(ts + tw)
- The total execution time Tp = tc*N/P + 2*(ts + tw)

Finite Differences - Algorithm

- Each task i performs the following step algorithm:

```
if (taskID not 0 or N-1) {
   send local data X^t to left and right outports;
   receives X^t from its left and right inports;
   use these values to compute X^t+1;}
else X^t+1 = X^t ;
```

- Single Program Multiple Data algorithm.
- All tasks can execute independently between steps and within a single step.
- Execution order is synchronised by the receive operations (no data value is updated at step t+1 until the data values in neighbouring tasks have been updated at step t).