Parallel design patterns

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Contents

Parallel computing

The problem

- Solve a problem using n_w processing resources
- Obtaining a (close to) n_w speedup with respect to time spent sequentially

Parallel computing

The problem

- Solve a problem using n_w processing resources
- Obtaining a (close to) n_w speedup with respect to time spent sequentially

$$s(n) = \frac{T_{seq}}{T_{par}(n)} \quad (speedup)$$

$$\epsilon(n) = \frac{T_i d}{T_{par}(n)} = \frac{T_{seq}}{n \times T_{par}(n)} \quad (efficiency)$$

$$s(n) = \frac{1}{f + \frac{1-f}{n}} \quad (Amdhal\ law)$$

The problems

Find potentially concurrent activities

- alternative decompositions
- with possibly radically differences

The problems

Find potentially concurrent activities

- alternative decompositions
- with possibly radically differences

Parallelism exploitation

- program activities (threads, processes)
- program interactions (communications, sycnhronizations)

  $\rightarrow$ *overhead*

Structured parallel programming

Structured parallel programming

Algorithmic skeletons

- Cole 1988 → common, parametric, reusable parallelism exploitation pattern
- languages & libraries since '90 (P3L, Skil, eSkel, ASSIST, Muesli, SkeTo, Mallba, Muskel, Skipper, BS, ...)
- high level parallel abstractions (parallel programming community)
  - hiding most of the technicalities related to parallelism exploitation
  - directly exposed to application programmers

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Parallel design patterns

- Massingill, Mattson, Sanders 2000 → "Patterns for parallel programming" book (2006) (software engineering community)
- design patterns à la Gamma book
  - name, problem, solution, use cases, etc.
- concurrency, algorithms, implementation, mechanisms

Concept evolution

Parallelism

- parallelism exploitation patterns shared among applications
- separation of concerns:
  - system programmers → efficient implementation of parallel patterns
  - application programmers → application specific details

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New architectures

- *Heterogeneous* in Hw & Sw
- *Multicore* NUMA, cache coherent architectures

Concept evolution

Parallelism

- parallelism exploitation patterns shared among applications
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New architectures

- *Heterogeneous* in Hw & Sw
- *Multicore* NUMA, cache coherent architectures

Further non functional concerns

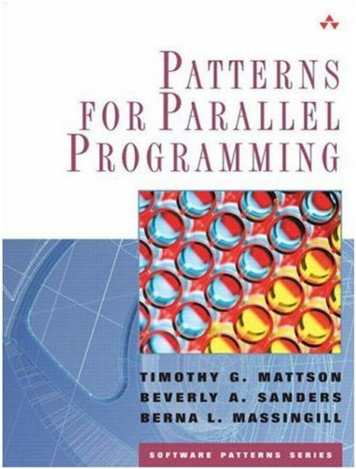
- security, fault tolerance, power management, ...

Parallel design patterns

Researchers active since beginning of the century

- S. MacDonald, J. Anvik, S. Bromling, J. Schaeffer, D. Szafron, and K. Tan. 2002. From patterns to frameworks to parallel programs. Parallel Comput. 28, 12 (December 2002), 1663-1683.
- Berna L. Massingill, Timothy G. Mattson, Beverly A. Sanders: A Pattern Language for Parallel Application Programs (Research Note). Euro-Par 2000, LNCS, pp. 678-681, 2000
- Berna L. Massingill, Timothy G. Mattson , Beverly A. Sanders, Parallel programming with a pattern language, Springer Verlag, Int. J. STTT 3:1-18, 2001
- Berna L. Massingill, Timothy G. Mattson , Beverly A. Sanders, Patterns for Finding Concurrency for Parallel Application Programs, (pre-book)
- Timothy G. Mattson, Beverly A. Sanders, Berna L. Massingill, Patterns for parallel programming, Addison Wesley, Pearson Education, 2005

Parallel design patterns



The pattern framework

Four patter classes:

1. Finding concurrency
2. Algorithm structure
3. Supporting structure
4. Implementation mechanisms

These are "design spaces"

- different concerns
- different "kind of programmers" involved
  - upper layers → application programmers
  - lower layers → system programmers

Finding concurrency design space

Three main blocks

1. Decomposition

   → Decomposition of problems into pieces that can be computed concurrently

2. Dependency analysis

   → support task grouping and dependency analysis

3. Design evaluation

   → aimed at supporting evaluation of alternatives

Used in an iterative process:
design → evaluate → redesign → ...

Finding concurrency design space

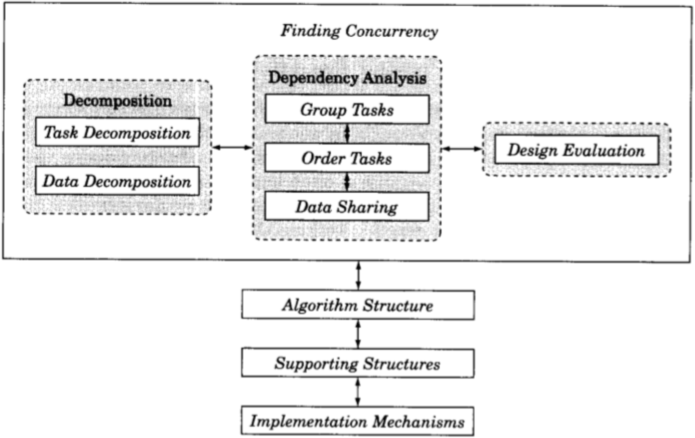


Figure 3.1: Overview of the *Finding Concurrency* design space and its place in the pattern language

Decomposition patterns

Task decomposition

How can a problem be decomposed into tasks that can execute concurrently ?

Data decomposition

How can a problem's date be decomposed into units that can be operated on relatively independently?

Forces:

- Flexibility
- Efficiency
- Simplicity

Dependency analysis patterns

Group tasks

How can the tasks make up a problem be grouped to simplify the job of managing dependencies?

Order tasks

Given a way of decomposing a problem into tasks and a way of collecting these tasks into logically related groups, how must these groups of tasks be ordered to satisfy constrains among tasks?

Data sharing

Given a data and task decomposition for a problem, how is data shared among the tasks?

Design evaluation pattern

Design evaluation pattern

Is the decomposition and dependency analysis so far good to move on to the next design space, or should the design be revisited?

Forces:

- Suitability for the target platform (PE available, sharing support, coordination of PE activities, overheads)
- Design quality (flexibility, efficiency, simplicity)
- Preparation for the next phase of the design (regularity of the solution, synchronous/asynchronous interactions, task grouping)

Algorithm structure

Three main blocks

1. Organize by task

   → when execution by tasks is the best organizing principle
2. Organize by data decomposition

   → when main source of parallelisms is data
3. Organize by flow analysis

   → flow of data imposing ordering on (groups of) tasks

Algorithm structure

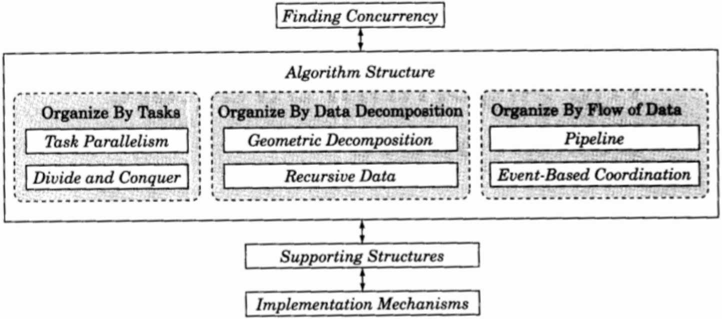


Figure 4.1: Overview of the *Algorithm Structure* design space and its place in the pattern language

Organize by task

Task parallelism

When the problem is best decomposed into a collection of tasks that can execute concurrently, how can this concurrency be exploited efficiently?

$\rightarrow$ dependency analysis, scheduling, ...

Divide & conquer

Suppose the problem is formulated using the sequential divide&conquer strategy. How can the potential concurrency be exploited?

$\rightarrow$ dependency analysis, communication costs, ...

Organize by data decomposition

Geometric decomposition

How can an algorithm be organized around a data structure that has been decomposed into concurrently updatable "chuncks"?

Recursive data

Suppose the problem involves an operation on a recursive data structure (such as a list, tree or graph) that appears to require sequential processing. How can operations on these data structures be performed in parallel?

Organize by flow of data

Pipeline

Suppose that the overall computation involves performing a calculation on many sets of data, where the calculation can be viewed in terms of data flowing through a sequence of stages. How can potential concurrency be exploited ?

Event based coordination

Suppose th application can be decomposed into groups of semi-independent tasks interacting in an irregular fashion. The interaction is determined by the flow of data between them which implies ordering constraints between the tasks. How can these tasks and their interaction be implemented so they can execute concurrently?

Supporting structures

Two main blocks:

1. Program structures

   → approaches for structuring source code

2. Data structures

   → data dependency management

Forces:

- Clarity of abstraction
- Scalability
- Efficiency
- Maintainability
- Environmental affinity
- Sequential equivalence

Supporting structures

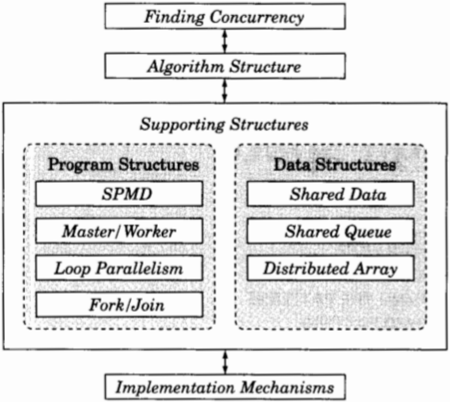


Figure 5.1: Overview of the *Supporting Structures* design space and its place in the pattern language

Program structures

SPMD (Single Program Multiple Data)

The interactions between the various UEs cause most of the problems when writing correct and efficient parallel programs. How can programmers structure their parallel programs to make these interactions more manageable and easier to integrate with the core computations?

Master/worker

How should a program be organized when the design is dominated by the need to dynamically balance the work on a set of tasks among the UEs?

Program structures (2)

Loop parallelism

Given a serial program whose runtime is dominated by a set of computationally intensive loops, how can it be translated into a parallel program?

Fork/join

In some programs the number of concurrent tasks varies as the program executes, and the way these tasks are related prevents the use of simple control structures such as parallel loops. How can a parallel program be constructed around such complicated sets of dynamic tasks?

Data Structures

Shared data

How toes one explicitly manage shared data inside a set of concurrent tasks?

Shared queue

How can concurrenty-executing UEs safely share a queue data structure?

Distributed array

Arrays often need to be partitioned between multiple UEs. How can we do this so the resulting program is both readable and efficient?

Implementation mechanisms

Directly related to the target architecture:

1. to provide mechanisms suitable to create a set of concurrent activities (UE Units of Execution)

   → threads, processes (creation, destruction)

2. to support interactions among the UEs

   → locks, mutexes, semaphores, memory fences, barriers, monitors, ...

3. to support data exchange among the UEs

   → communication channels, queues, shared memory, collective operations (broadcasts, multicast, barrier, reduce) ...

Implementation mechanisms

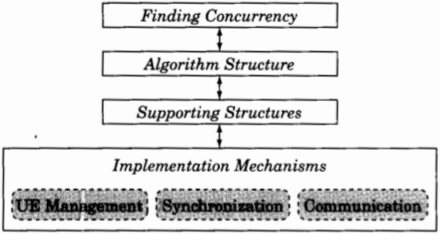


Figure 6.1: Overview of the *Implementation Mechanisms* design space and its place in the pattern language

Design patterns vs. algorithmic skeletons

Sw engineering vs. HPC community

SwEng Focus on efficiency of the programming process

HPC Focus on performance (and programmer productivity)

Design patterns vs. algorithmic skeletons

Sw engineering vs. HPC community

SwEng Focus on efficiency of the programming process

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Then:

Design patterns "recipes" to be implemented in order to get a working program

Algorithmic skeletons predefined program constructs (language constructs, classes, library entries) implementing parallel patterns

Typical skeleton based program development

1. Figure out which skeleton (composition) models your problem
2. Instantiate skeletons
   - functional parameters (e.g. code, data types) & non functional ones (e.g parallelism degree)
3. Fine tune program performance
   - parameter sweeping, bottleneck analysis *or* skeleton restructuring

→ no parallel debugging, correctness guaranteed

→ no possibility to use parallel patterns not supported by the skeleton set

Typical algorithmic skeleton frameworks

Muesli (H. Kuchen, Munster Univ. D)

- C++ class library
- stream parallel skeletons
  - Pipeline, Farm, Branch&Bound, Divide&Conquer (Atomic, Filter, Final, Initial)
- data parallel skeletons
  - DistributedXXX (XXX $\in$ { Array, Matrix, SparseMatrix}) + fold, map, scan, zip
- target architecture: C++ (MPI + OpenMP)
- all communication, synchronization, shared access problems solved in the skeleton implementation
- program declaration separated from execution

Parallel design patterns in perspective

DOI:10.1145/1562764.1562783

Writing programs that scale with increasing numbers of cores should be as easy as writing programs for sequential computers.

BY KRSTE ASANOVIC, RASTISLAV BODIK, JAMES DEMMEL, TONY KEAVENY, KURT KEUTZER, JOHN KUBIATOWICZ, NELSON MORGAN, DAVID PATTERSON, KOUSHIK SEN, JOHN WAWRZYNEK, DAVID WESSEL, AND KATHERINE YELICK

A View of the Parallel Computing Landscape

INDUSTRY NEEDS HELP from the research community to succeed in its recent dramatic shift to parallel computing. Failure could jeopardize both the IT industry and the portions of the economy that depend on rapidly improving information technology. Here, we review the issues and, as an example, describe an integrated approach we're developing at the Parallel Computing Laboratory, or Par Lab, to tackle the parallel challenge.

Principles

- Architecting parallel software with design patterns, not just parallel programming languages
- Split productivity and efficiency layers, not just a single general-purpose layer
- Generating code with search-based autotuners, not compilers
- Synthesis with sketching
- Verification and testing, not one or the other
- ...

Parallel design patterns in perspective (2)

TBB (Thread Building Block library by Intel,2005)

- C++ library
- currently version 3.0 (since late 2010)
- base building blocks for parallel programming with thread
  - parallel loop, reduce, pipeline
  - tasks
  - parallel containers
  - mutexes
- since 3.0 → TBB Design patterns
  - Agglomeration, Elementwise, Odd-even communication, Wavefront, Reduction, Divide&Conquer, GUI thread, Non-preemptive priorities, Local serializer, Fenced data transfer, Lazy initialization, Reference counting, Compare-and-swap loop.

Sample TBB pattern: D&C

Intel® Threading Building Blocks Design Patterns

7 Divide and Conquer

Problem

Parallelize a divide and conquer algorithm.

Context

Divide and conquer is widely used in serial algorithms. Common examples are quicksort and mergesort.

Forces

- Problem can be transformed into subproblems that can be solved independently.
- Splitting problem or merging solutions is relatively cheap compared to cost of solving the subproblems.

Solution

There are several ways to implement divide and conquer in Intel®Threading Building Blocks (Intel® TBB). The best choice depends upon circumstances.

- If division always yields the same number of subproblems, use recursion and `tbb::parallel_invoke`.
- If the number of subproblems varies, use recursion and `tbb::task_group`.
- If ultimate efficiency and scalability is important, use `tbb::task` and continuation passing style.

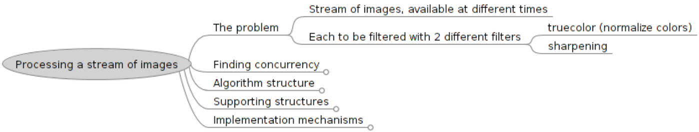
Sample TBB pattern: D&C

Example

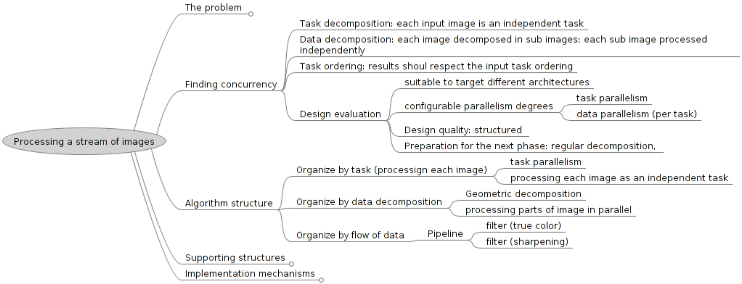
The number of subsorts is fixed at two, so `tbb::parallel_invoke` provides a simple way to parallelize it. The parallel code is shown below:

```
void ParallelQuicksort( T* begin, T* end ) {
    if( end-begin>1 ) {
        using namespace std;
        T* mid = partition( begin+1, end, bind2nd(less<T>(),*begin) );
        swap( *begin, mid[-1] );
        tbb::parallel_invoke( [=]{ParallelQuicksort( begin, mid-1 );},
                              [=]{ParallelQuicksort( mid, end );} );
    }
}
```

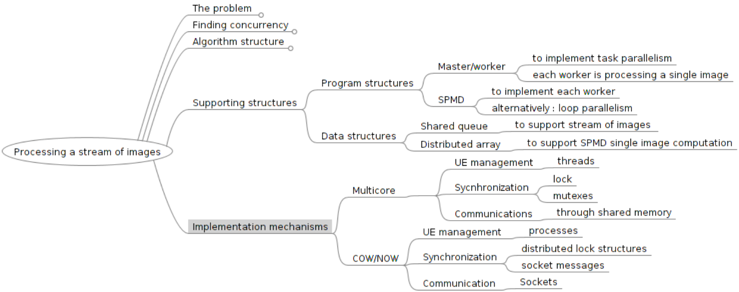
Sample APPL


Processing a stream of images
The problem
Stream of images, available at different times
Each to be filtered with 2 different filters
truecolor (normalize colors)
sharpening
Finding concurrency
Algorithm structure
Supporting structures
Implementation mechanisms

Sample APPL


Processing a stream of images
The problem
Finding concurrency
Task decomposition: each input image is an independent task
Data decomposition: each image decomposed in sub images: each sub image processed independently
Task ordering: results shoul respect the input task ordering
Design evaluation
suitable to target different architectures
configurable parallelism degrees
task parallelism
data parallelism (per task)
Design quality: structured
Preparation for the next phase: regular decomposition,
Algorithm structure
Organize by task (processign each image)
task parallelism
processing each image as an independent task
Organize by data decomposition
Geometric decomposition
processing parts of image in parallel
Organize by flow of data
Pipeline
filter (true color)
filter (sharpening)
Supporting structures
Implementation mechanisms

Sample APPL


Processing a stream of images
The problem
Finding concurrency
Algorithm structure
Supporting structures
Program structures
Master/worker
to implement task parallelism
each worker is processing a single image
SPMD
to implement each worker
alternatively : loop parallelism
Data structures
Shared queue
to support stream of images
Distributed array
to support SPMD single image computation
Implementation mechanisms
Multicore
UE management
threads
Sycnhronization
lock
mutexes
Communications
through shared memory
COW/NOW
UE management
processes
Synchronization
distributed lock structures
socket messages
Communication
Sockets

Conclusions

Become an expert in parallel computing

→ by studying and applying parallel design patterns !!!

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$\rightarrow$ by studying and applying parallel design patterns !!!

You will need it

also to program iPhone applications!