Researchers Give Update on Road to Parallelism

EE Times (03/19/10) Merritt, Rick

University of Illinois researchers have taken several small steps toward developing new parallel programming models to tap the many-core processors of the future. The DeNovo project attempts to define a new and more rigorous way of utilizing shared memory. It is working concurrently with a separate effort to define a deterministic, parallel language primarily based on a parallel version of Java and eventually migrating to a parallel version of C++. The chip project that is nearest to testing is the 1,024-core Rigel processor architecture targeting high density, high throughput computing, which would be programmed through a task-level applications programming interface aimed at chores in imaging, computer vision, physics, and simulations. The Bulk Architecture chip design is testing the notion of atomic transactions.

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Titan has AMD Opteron CPUs in conjunction with Nvidia Tesla GPUs to improve energy efficiency while providing an order of magnitude increase in computational power over Jaguar. It uses 18,688 CPUs paired with an equal number of GPUs to perform at a theoretical peak of 27 petaFLOPS; however, in the LINPACK benchmark used to rank supercomputers’ speed, it performed at 17.59 petaFLOPS. This was enough to take first place in the November 2012 list by the TOP500 organisation.
Instruction-level parallelism

A canonical five-stage pipeline in a RISC machine (IF = Instruction Fetch, ID = Instruction Decode, EX = Execute, MEM = Memory access, WB = Register write back)

A five-stage pipelined superscalar processor, capable of issuing two instructions per cycle. It can have two instructions in each stage of the pipeline, for a total of up to 10 instructions (shown in green) being simultaneously executed.

TÜ HPC – v1, Feb 2, 2009

- 42 nodes, 2x4-core = 336 core
- 32GB RAM / node
- Infiniband fast interconnect

http://www.hpc.ut.ee/
- Job scheduling (Torque)
- MPI

Latency

The single data rate switch chips have a latency of 200 nanoseconds, and DDR switch chips have a latency of 140 nanoseconds. The end-to-end latency range is from 1.07 microseconds MPI latency to 2.6 microseconds.

Compare:

The speed of a normal ethernet ping/pong (request and response) is roughly 350us (microseconds) or about .35 milliseconds or .00035 seconds.
Grace Hopper - Nanosecods

http://www.youtube.com/watch?v=JEpsKnWZrl8

Anno 2013

• HPC: 2.5GHz, 4-op-parallel (v1.)

• Vedur: klots1-klots80 (ProLiant DL165 G7):
  — 2 x AMD Opteron(TM) Processor 6276 CPU (32 cores)
  — 48GB RAM
  — 500GB HDD
  — 4x QDR Infiniband
  — $2.5e+9 \times 80*32*4 = 2.56e+13 \Rightarrow 25$ TFLOP?

Single large-memory machines @TartuUniversity

• 80-core, 256GB RAM
• HPC: 512GB,
• EXCS: 160-core cpu, 1TB RAM fall 2011
• Buying 2TB RAM machine

Drivers for parallel computing

• Multi-core processors (2, 4, …, 64 …)
• Computer clusters (and NUMA)
• Specialised computers (e.g. vector processors, massively parallel, …)
• Distributed computing: GRID, cloud, …
• Need to create computer systems from cheaper (and weaker) components, but many …
• One of the major challenges of modern IT

Slides based on materials from

• Joe Davey
• Matt Maul
• Ashok Srinivasan
• Edward Chorzanowski
• Ananth Grama, Anshul Gupta, George Karypis, and Vipin Kumar
• Dr. Amitava Datta and Prof. Dr. Thomas Ottmann
  • http://en.wikipedia.org/wiki/Parallel_computing
• … and many others
What is a Parallel Algorithm?

- Imagine you needed to find a lost child in the woods.
- Even in a small area, searching by yourself would be very time consuming.
- Now if you gathered some friends and family to help you, you could cover the woods in much faster manner.

Textbooks

- CLRS: (3rd edition) pp 772-812 (Chapter 27)

Terms (CLRS)

- work, span

Parallel complexity

- Schedule on p processors
- schedule depth – max /longest path in schedule/
- N – set of nodes on DAG
- time ti – assigned for each DAG node
- \( T_p(n) = \min \{ \max_{i \in N} t_i \} \)
- Length of the longest (critical) path!

Boolean circuits, bit-level parallelism

- (Micro)processors
- Basic building blocks,
- bit-level operations
- combine into word-level operations

A simple parallel algorithm

Adding n numbers in parallel
Circuit complexity

- Longest path (= time)
- Nr or elements (= size)

Most of the available algorithms to compute $P_i$, on the other hand, cannot be easily split up into parallel portions. They require the results from a preceding step to effectively carry on with the next step. Such problems are called inherently serial problems.
Background

- Terminology
  - Time complexity
  - Speedup
  - Efficiency
  - Scalability
- Communication cost model

Time complexity

- Parallel computation
  - A group of processors work together to solve a problem
  - Time required for the computation is the period from when the first processor starts working until when the last processor stops

Other terminology

- Speedup: \( S = \frac{T_1}{T_P} \)
- Efficiency: \( E = \frac{S}{P} \)
- Work: \( W = P \cdot T_P \)
- Scalability
  - How does \( T_P \) decrease as we increase \( P \) to solve the same problem?
  - How should the problem size increase with \( P \), to keep \( E \) constant?

Notation

- \( P \) = Number of processors
- \( T_1 \) = Time on one processor
- \( T_P \) = Time on \( P \) processors

- Sometimes a speedup of more than \( N \) when using \( N \) processors is observed in parallel computing, which is called super linear speedup. Super linear speedup rarely happens and often confuses beginners, who believe the theoretical maximum speedup should be \( N \) when \( N \) processors are used.

- One possible reason for a super linear speedup is the cache effect

- Super linear speedups can also occur when performing backtracking in parallel: One thread can prune a branch of the exhaustive search that another thread would have taken otherwise.

Amdahl law

is used to find the maximum expected improvement to an overall system when only part of the system is improved

- Amdahl’s Law
  - Parallel Fraction
  - 75%
  - 50%
  - 25%
• e.g. 5% non parallelizable => speedup can not be more than 20x!

• http://en.wikipedia.org/wiki/Amdahl%27s_law

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Sequential programme

<table>
<thead>
<tr>
<th>Two independent parts</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make B 5x faster</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make A 2x faster</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Communication cost model

• Processes spend some time doing useful work, and some time communicating
• Model communication cost as
  – \( T_c = t_s + L \bar{t}_b \)
  – \( L \) = message size
  – Independent of location of processes
  – Any process can communicate with any other process
  – A process can simultaneously send and receive one message

Simple model for analyzing algorithm performance:

\[ t_{\text{comm}} = t_{\text{startup}} + (\text{words} \times \frac{t_{\text{data}}}{\text{words/second}}) \]

\[ = \text{ latency} + (\text{words} \times \frac{1}{\text{words/second}}) \]

\[ = \alpha + w^* \beta \]

\( \text{latency} \) and \( \text{bandwidth} \)

---

I/O model

• We will ignore I/O issues, for the most part
• We will assume that input and output are distributed across the processors in a manner of our choosing
• Example: Sorting
  – Input: \( x_1, x_2, \ldots, x_n \)
    • Initially \( x_i \) on processor \( i \)
  – Output \( x_{p1}, x_{p2}, \ldots, x_{pn} \)
    • \( x_{pi} \) on processor \( i \)
    • \( x_{pi} \leq x_{pi+1} \)
Important points

- Efficiency
  - Increases with increase in problem size
  - Decreases with increase in number of processors
- Aggregation of tasks to increase granularity
  - Reduces communication overhead
- Data distribution
  - 2-dimensional may be more scalable than 1-dimensional
  - Has an effect on load balance too
- General techniques
  - Divide and conquer
  - Pipelining

Parallel Architectures

- Single Instruction Stream, Multiple Data Stream (SIMD)
  - One global control unit connected to each processor
- Multiple Instruction Stream, Multiple Data Stream (MIMD)
  - Each processor has a local control unit

Parallel Computing Architectures
Flynn’s Taxonomy

<table>
<thead>
<tr>
<th>Single Instruction Stream</th>
<th>Single Data Stream</th>
<th>Multiple Data Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>SISD uniprocessors</td>
<td>SIMD Processor arrays</td>
<td></td>
</tr>
<tr>
<td>MIMD Systolic arrays</td>
<td>MIMD Multiprocessors multicomputers</td>
<td></td>
</tr>
</tbody>
</table>

Architecture (continued)

- Shared-Address-Space
  - Each processor has access to main memory
  - Processors may be given a small private memory for local variables
- Message-Passing
  - Each processor is given its own block of memory
  - Processors communicate by passing messages directly instead of modifying memory locations

Parallel Computing Architectures
Memory Model

<table>
<thead>
<tr>
<th>Centralized memory</th>
<th>SMP (Symmetric Multiprocessor)</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed memory</td>
<td>NUMA (Non-Uniform Memory Access)</td>
<td>MPP (Massively Parallel Processors)</td>
</tr>
</tbody>
</table>

NUMA architecture

- Distributed shared memory network with directory
### SMP - Symmetric multiprocessing

- **Shared Memory**
  - All processes share the same address space
  - Easy to program; also easy to program poorly
  - Performance is hardware dependent; limited memory bandwidth can create contention for memory
- **MIMD (multiple instruction multiple data)**
  - Each parallel computing unit has an instruction thread
  - Each processor has local memory
  - Processors share data by message passing
  - Synchronization must be explicitly programmed into a code
- **NUMA (non-uniform memory access)**
  - Distributed memory in hardware, shared memory in software, with hardware assistance (for performance)
  - Better scalability than SMP, but not as good as a full distributed memory architecture

### MPP – Massively Parallel

- Each node is an independent system having its own:
  - Physical memory
  - Address space
  - Local disk and network connections
  - Operating system

### MPP

- Short for **massively parallel processing**, a type of computing that uses many separate CPUs running in parallel to execute a single program. MPP is similar to **symmetric processing (SMP)**, with the main difference being that in SMP systems all the CPUs share the same memory, whereas in MPP systems, each CPU has its own memory. MPP systems are therefore more difficult to program because the application must be divided in such a way that all the executing segments can communicate with each other. On the other hand, MPP don’t suffer from the bottleneck problems inherent in SMP systems when all the CPUs attempt to access the same memory at once.

### Interconnection Networks

- **Static**
  - Each processor is hard-wired to every other processor
  - Completely Connected
  - Star-Connected
  - Bounded-Degree (Degree 4)
- **Dynamic**
  - Processors are connected to a series of switches
Why Do Parallel Computing

- Time: Reduce the turnaround time of applications
- Performance: Parallel computing is the only way to extend performance toward the TFLOP realm
- Cost/Performance: Traditional vector computers become too expensive as one pushes the performance barrier
- Memory: Applications often require memory that goes beyond that addressable by a single processor

Some Misconceptions

- Requires new parallel languages?
  - No. Uses standard languages and compilers (Fortran, C, C++, Java, Occam)
  - However, there are some specific parallel languages such as Qlisp, Mul-T and others – check out: http://ceu.fi.udc.es/SAL/C/1/index.shtml
- Requires new code?
  - No. Most existing code can be used. Many production installations use the same code base for serial and parallel code.

Cont...

- Whole classes of important algorithms are ideal for parallel execution. Most algorithms can benefit from parallel processing such as Laplace equation, Monte Carlo, FFT (signal processing), image processing
- Life itself is a set of concurrent processes
  - Scientists use modelling so why not model systems in a way closer to nature
Cont...

• Requires confusing parallel extensions?
  – No. They are not that bad. Depends on how complex you want to make it. From nothing at all (letting the compiler do the parallelism) to installing semaphores yourself
• Parallel computing is difficult:
  – No. Just different and subtle. Can be akin to assembler language programming 😊

The PRAM Model

• **Parallel Random Access Machine**
  – Theoretical model for parallel machines
  – p processors with uniform access to a large memory bank
  – MIMD
  – UMA (uniform memory access) – Equal memory access time for any processor to any address

Memory Protocols

• Exclusive-Read Exclusive-Write
• Exclusive-Read Concurrent-Write
• Concurrent-Read Exclusive-Write
• Concurrent-Read Concurrent-Write

• If concurrent write is allowed we must decide which value to accept

Example: Merge Sort

```
P1  P2  P3  P4
| 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 |

P1  P2
| 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 |
```

Merge Sort Analysis

• Number of compares
  – $1 + 3 + ... + (2^{i-1}) + ... + (n-1)$
  – $\sum_{i=1}^{\lg n} 2^{i-1} = 2n-2\lg n = \Theta(n)$

• We have improved from $n\lg(n)$ to $n$ simply by applying the old algorithm to parallel computing, by altering the algorithm we can further improve merge sort to $(\lg n)^2$
Parallel loops

Mat-Vec( A, x )
1 n= A.rows
2 let y be a new vector of length n
3 parallel for i=1 to n
4 yi = 0
5 parallel for i=1 to n
6 for j=1 to n
7 yi = yi + aij xj
8 return y

Parallel Design and Dynamic Programming

- Often in a dynamic programming algorithm a given row or diagonal can be computed simultaneously
- This makes many dynamic programming algorithms amenable for parallel architectures

Current Applications that Utilize Parallel Architectures

- Computer Graphics Processing
- Video Encoding
- Accurate weather forecasting
- Scientific computing, modelling
- …
**Parallel addition features**

- If $n \gg P$
  - Each processor adds $n/P$ distinct numbers
  - Perform parallel reduction on $P$ numbers
  - $T_p \sim n/P + (1 + t_s + t_b) \log P$
  - Optimal $P$ obtained by differentiating wrt $P$
    - $P_{opt} \sim n/(1 + t_s + t_b)$
  - If communication cost is high, then fewer processors ought to be used
    - $E = \left[1 + (1 + t_s + t_b) P \log P/n\right]^{-1}$
  - As problem size increases, efficiency increases
  - As number of processors increases, efficiency decreases

**Some common collective operations**

- **Broadcast**
  - $T \sim (t_s + L_t) \log P$
    - $L$: Length of data

- **Gather/Scatter**
  - Gather: Data move towards the root
  - Scatter: Review question
  - $T \sim t_s P + PL_b$

- **All gather**
  - Equivalent to each processor broadcasting to all the processors
Matrix-vector multiplication

- \( c = A \cdot b \)
  - Often performed repeatedly
    - \( b_i = A \cdot b_{i-1} \)
  - We need same data distribution for \( c \) and \( b \)
- One dimensional decomposition
  - Example: row-wise block striped for \( A \)
    - \( b \) and \( c \) replicated
  - Each process computes its components of \( c \) independently
  - Then all-gather the components of \( c \)

2-D matrix-vector multiplication

- Processes \( P_{ij} \) sends \( b_i \) to \( P_{0j} \)
  - Time: \( t_s + t_b \frac{n}{P^{0.5}} \)
- Processes \( P_{0j} \) broadcast \( b_j \) to all \( P_{ij} \)
  - Time: \( t_s \log P + t_b \frac{n \log P}{P^{0.5}} \)
- Processes \( P_{ij} \) compute \( c_{ij} = A_{ij} \cdot b_j \)
  - Time: \( \Theta \left( \frac{n^2}{P} \right) \)
- Processes \( P_{0j} \) reduce \( c_j \) on to \( P_{00} \), \( 0 \leq j \leq P^{0.5} \)
  - Time: \( t_s \log P + t_b \frac{n \log P}{P^{0.5}} \)
- Total time: \( \Theta \left( \frac{n^2}{P} + t_s \log P + t_b \frac{n \log P}{P^{0.5}} \right) \)
  - \( P \leq n \)
  - More scalable than 1-dimensional decomposition

1-D matrix-vector multiplication

- Each process computes its components of \( c \) independently
  - Time: \( \Theta \left( \frac{n \log P}{P^{0.5}} \right) \)
- Then all-gather the components of \( c \)
  - Time: \( t_s \log P + t_b n \)
- Note: \( P \leq n \)
• 31.2 Strassen's algorithm for matrix multiplication
• This section presents Strassen's remarkable recursive algorithm for multiplying $n \times n$ matrices that runs in $(n \log_2 7)$ time. For sufficiently large $n$, therefore, it outperforms the naive ($n^3$) matrix-multiplication algorithm MATRIX-MULTIPLY from Section 26.1.

Strassen discovered a different recursive approach that requires only 7 recursive multiplications of $n/2 \times n/2$ submatrices, yielding the recursive formula:

$$T(n) = 8T(n/2) + O(n^2).$$

C = AB

\[
\begin{pmatrix} r & s \\ t & u \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} e & g \\ f & h \end{pmatrix}
\]

• $r = ae + bf$
• $s = ag + bh$
• $t = ce + df$
• $u = cg + dh$

Matrix operations are parallelizable

• Problems that are expressed in forms of matrix operations are often easy to automatically parallelise

• Fortran, etc – programming languages can achieve that at no extra effort

The Process

- A running executable of a (compiled and linked) program written in a standard sequential language (i.e. F77 or C) with library calls to implement the message passing.
- A process executes on a processor.
- Processes are assigned to processors in a one-to-one mapping (simplest model of parallel programming).
- Other processes may execute on other processors.
- A process communicates and synchronizes with other processes via messages.
- A process is uniquely identified by:
  - The node on which it is running.
  - Its process id (PID).
- A process does not migrate from node to node (though it is possible for it to migrate from one processor to another within a SMP node).

Solving Problems in Parallel

- It is true that the hardware defines the parallel computer. However, it is the software that makes it usable.
- Parallel programmers have the same concern as any other programmer:
  - Algorithm design,
  - Efficiency,
  - Debugging ease,
  - Code reuse, and
  - Lifecycle.
However, they are also concerned with:
- Concurrency and communication
- Need for speed (nee high performance), and
- Plethora and diversity of architecture

Fosters Four step Process for Designing Parallel Algorithms

1. Partitioning – process of dividing the computation and the data into many small pieces – decomposition
2. Communication – local and global (called overhead) minimizing parallel overhead is an important goal and the following check list should help the communication structure of the algorithm
   1. The communication operations are balanced among tasks
   2. Each task communicates with only a small number of neighbours
   3. Tasks can perform their communications concurrently
   4. Tasks can perform their computations concurrently

Solving Problems in Parallel

- Decomposition determines:
  - Data structures
  - Communication topology
  - Communication protocols
- Must be looked at early in the process of application development
- Standard approaches

Decomposition methods

- Perfectly parallel
- Domain
- Control
- Object-oriented
- Hybrid[layered (multiple uses of the above)]

For the program

- Choose a decomposition
  - Perfectly parallel, domain, control etc.
- Map the decomposition to the processors
  - Ignore topology of the system interconnect
  - Use natural topology of the problem
- Define the inter-process communication protocol
  - Specify the different types of messages which need to be sent
  - See if standard libraries efficiently support the proposed message patterns
Perfectly parallel

- Applications that require little or no inter-processor communication when running in parallel
- Easiest type of problem to decompose
- Results in nearly perfect speed-up

Domain decomposition

- In simulation and modelling this is the most common solution
  - The solution space (which often corresponds to the real space) is divided up among the processors. Each processor solves its own little piece
  - Finite-difference methods and finite-element methods lend themselves well to this approach
  - The method of solution often leads naturally to a set of simultaneous equations that can be solved by parallel matrix solvers
  - Sometimes the solution involves some kind of transformation of variables (i.e. Fourier Transform). Here the domain is some kind of phase space. The solution and the various transformations involved can be paralleled

Output Data Decomposition: Example

Consider the problem of multiplying two $m \times m$ matrices $A$ and $B$ to yield matrix $C$. The output matrix $C$ can be partitioned into four tasks as follows:

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

Task 1: $C_{1,1} = A_{1,1}B_{1,1} + A_{1,2}B_{2,1}$

Task 2: $C_{1,2} = A_{1,1}B_{1,2} + A_{1,2}B_{2,2}$

Task 3: $C_{2,1} = A_{2,1}B_{1,1} + A_{2,2}B_{2,1}$

Task 4: $C_{2,2} = A_{2,1}B_{1,2} + A_{2,2}B_{2,2}$

Control decomposition

- If you cannot find a good domain to decompose, your problem might lend itself to control decomposition
  - Good for:
    - Unpredictable workloads
    - Problems with no convenient static structures
  - One set of control decomposition is functional decomposition
    - Problem is viewed as a set of operations. It is among operations where parallelization is done
    - Many examples in industrial engineering (i.e. modelling an assembly line, a chemical plant, etc.)
    - Many examples in data processing where a series of operations is performed on a continuous stream of data

Output Data Decomposition: Example

A partitioning of output data does not result in a unique decomposition into tasks. For example, for the same problem as in previous foil, with identical output data distribution, we can derive the following two (other) decompositions:

Decomposition I

- Task 1: $C_{1,1} = A_{1,1}B_{1,1}$
- Task 2: $C_{1,1} = A_{1,1}B_{1,1} + A_{1,2}B_{2,1}$
- Task 3: $C_{1,2} = A_{1,2}B_{2,2}$
- Task 4: $C_{1,2} = C_{1,2} + A_{1,1}B_{1,2}$
- Task 5: $C_{2,1} = A_{2,1}B_{1,1}$
- Task 6: $C_{2,1} = A_{2,1}B_{1,1} + A_{2,2}B_{2,1}$
- Task 7: $C_{2,2} = A_{2,2}B_{2,2}$
- Task 8: $C_{2,2} = C_{2,2} + A_{2,2}B_{2,2}$

Decomposition II

- Task 1: $C_{1,1} = A_{1,1}B_{1,1}$
- Task 2: $C_{1,1} = C_{1,1} + A_{1,2}B_{2,1}$
- Task 3: $C_{1,2} = A_{1,1}B_{1,2}$
- Task 4: $C_{1,2} = C_{1,2} + A_{1,1}B_{1,2}$
- Task 5: $C_{2,1} = A_{2,2}B_{2,1}$
- Task 6: $C_{2,1} = A_{2,1}B_{1,1}$
- Task 7: $C_{2,2} = A_{2,2}B_{2,2}$
- Task 8: $C_{2,2} = C_{2,2} + A_{2,2}B_{2,2}$

Control is distributed, usually with some distribution of data structures

- Some processes may be dedicated to achieve better load balance

Examples

- Image processing: given a series of raw images, perform a series of transformations that yield a final enhanced image. Solve this in a functional decomposition (each process represents a different function in the problem) using data pipelining
- Game playing: games feature an irregular search space. One possible move may lead to a rich set of possible subsequent moves to search. Need an approach where work can be dynamically assigned to improve load balancing. May need to assign multiple processes to work on a particularly promising lead
Any problem that involve search (or computations) whose scope cannot be determined a priori, are candidates for control decomposition.

Calculations involving multiple levels of recursion (i.e. genetic algorithms, simulated annealing, artificial intelligence)

Discrete phenomena in an otherwise regular medium (i.e. modeling localized storms within a weather model)

Design-rule checking in micro-electronic circuits

Simulation of complex systems

Game playing, music composing, etc..

Object-oriented decomposition

Object-oriented decomposition is really a combination of functional and domain decomposition.

Rather than thinking about a dividing data or functionality, we look at the objects involved.

The object can be decomposed as a set of data structures plus the procedures that act on those data structures.

The goal of object-oriented parallel programming is distributed objects.

Works best for fine-grained problems and in environments where having functionally ready-at-the-call is more important than worrying about under-worked processors (i.e. battlefield simulation).

Object-oriented decomposition is explicit (no standard C++ compiler automatically parallelizes over objects).

Partitioning the Graph of Lake Superior

Random Partitioning

Partitioning for minimum edge-cut.

Partitioning summary

A good decomposition strategy is

Key to potential application performance

Key to programmability of the solution

There are many different ways of thinking about decomposition

Decomposition models (domain, control, object-oriented, etc.) provide standard templates for thinking about the decomposition of a problem

Decomposition should be natural to the problem rather than the computer architecture

Communication does no useful work; keep it to a minimum

Always wise to see if a library solution already exists for your problem

Don’t be afraid to use multiple decompositions in a problem if it seems to fit

Summary of Software

- Compilers
  - Moderate (4-10) parallelism
  - Not concerned with availability
  - Moderate (4-10) parallelism
  - Not available
  - All platforms come with built-in libraries
  - Required to be used in some settings
  - Use C++-like facilities to provide a data-parallel implicit programming model
  - Not recommended
  - Difficult to resolve and maintain programs
  - Not available in large number of cases
  - Moderate (4-10) parallelism
  - Library is available and it addresses a specific problem

- OpenMP
  - Moderate (4-10) parallelism
  - Not available
  - Good quality implementation exists on the platform
  - Not available
  - All platforms come with built-in libraries
  - Required to be used in some settings
  - Use C++-like facilities to provide a data-parallel implicit programming model
  - Not recommended
  - Difficult to resolve and maintain programs
  - Not available in large number of cases
  - Moderate (4-10) parallelism
  - Library is available and it addresses a specific problem

- Pthreads
  - Moderate (4-10) parallelism
  - Not available
  - Good quality implementation exists on the platform
  - Not available
  - All platforms come with built-in libraries
  - Required to be used in some settings
  - Use C++-like facilities to provide a data-parallel implicit programming model
  - Not recommended
  - Difficult to resolve and maintain programs
  - Not available in large number of cases
  - Moderate (4-10) parallelism
  - Library is available and it addresses a specific problem

- High Performance Fortran (HPF)
  - Moderate (4-10) parallelism
  - Not available
  - Good quality implementation exists on the platform
  - Not available
  - All platforms come with built-in libraries
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  - Not recommended
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