Computação Paralela

Mest. Int. Engenharia Computacional

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Designing Parallel Programs

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Agenda

- Automatic vs. Manual Parallelization
- Understand the Problem and the Program
- Partitioning
- Communications
- Synchronization
- Data Dependencies
- Load Balancing
- Granularity
- I/O
- Limits and Costs of Parallel Programming
- Performance Analysis and Tuning

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- Designing and developing parallel programs has characteristically been a very manual process. The programmer is typically responsible for both identifying and actually implementing parallelism.
- Very often, manually developing parallel codes is a time consuming, complex, error-prone and ***iterative*** process.
- For a number of years now, various tools have been available to assist the programmer with converting serial programs into parallel programs. The most common type of tool used to automatically parallelize a serial program is a parallelizing compiler or pre-processor.

- A parallelizing compiler generally works in two different ways:
  - Fully Automatic
    - The compiler analyses the source code and identifies opportunities for parallelism.
    - The analysis includes identifying inhibitors to parallelism and possibly a cost weighting on whether or not the parallelism would actually improve performance.
    - Loops (do, for) loops are the most frequent target for automatic parallelization.
  - Programmer Directed
    - Using "compiler directives" or possibly compiler flags, the programmer explicitly tells the compiler how to parallelize the code.
    - May be able to be used in conjunction with some degree of automatic parallelization also.

- If you are beginning with an existing serial code and have time or budget constraints, then automatic parallelization may be the answer. However, there are several important caveats that apply to automatic parallelization:
  - Wrong results may be produced
  - Performance may actually degrade
  - Much less flexible than manual parallelization
  - Limited to a subset (mostly loops) of code
  - May actually not parallelize code if the analysis suggests there are inhibitors or the code is too complex
  - Most automatic parallelization tools are for Fortran
- The remainder of this section applies to the manual method of developing parallel codes.

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- Undoubtedly, the first step in developing parallel software is to first understand the problem that you wish to solve in parallel. If you are starting with a serial program, this necessitates understanding the existing code also.
- Before spending time in an attempt to develop a parallel solution for a problem, determine whether or not the problem is one that can actually be parallelized.

Example of Parallelizable Problem

Calculate the potential energy for each of several thousand independent conformations of a molecule. When done, find the minimum energy conformation.

- This problem is able to be solved in parallel. Each of the molecular conformations is independently determinable. The calculation of the minimum energy conformation is also a parallelizable problem.

Example of a Non-parallelizable Problem

Calculation of the Fibonacci series (1,1,2,3,5,8,13,21,...) by use of the formula:

```
F(k + 2) = F(k + 1) + F(k)
```

- This is a non-parallelizable problem because the calculation of the Fibonacci sequence as shown would entail dependent calculations rather than independent ones. The calculation of the k + 2 value uses those of both k + 1 and k. These three terms cannot be calculated independently and therefore, not in parallel.

Identify the program's ***hotspots***

- Know where most of the real work is being done. The majority of scientific and technical programs usually accomplish most of their work in a few places.
- Profilers and performance analysis tools can help here
- Focus on parallelizing the hotspots and ignore those sections of the program that account for little CPU usage.

Identify ***bottlenecks*** in the program

- Are there areas that are disproportionately slow, or cause parallelizable work to halt or be deferred? For example, I/O is usually something that slows a program down.
- May be possible to restructure the program or use a different algorithm to reduce or eliminate unnecessary slow areas

Other considerations

- Identify inhibitors to parallelism.
  - One common class of inhibitor is *data dependence*, as demonstrated by the Fibonacci sequence above.
  - Data dependences
    - RAW – Read after Write;
    - WAR – Write after Read;
    - WAW – Write after Write
- Investigate other algorithms if possible.
  - This may be the single most important consideration when designing a parallel application.

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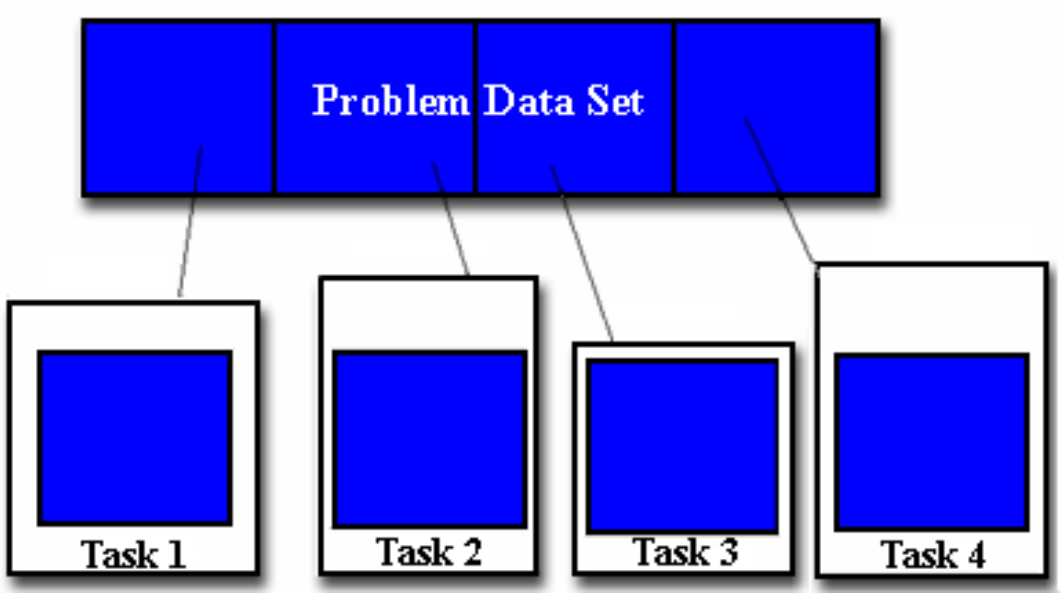
- One of the first steps in designing a parallel program is to break the problem into discrete "chunks" of work that can be distributed to multiple tasks. This is known as decomposition or partitioning.
- There are two basic ways to partition computational work among parallel tasks:
  - ***Domain decomposition***
  - ***Functional decomposition***

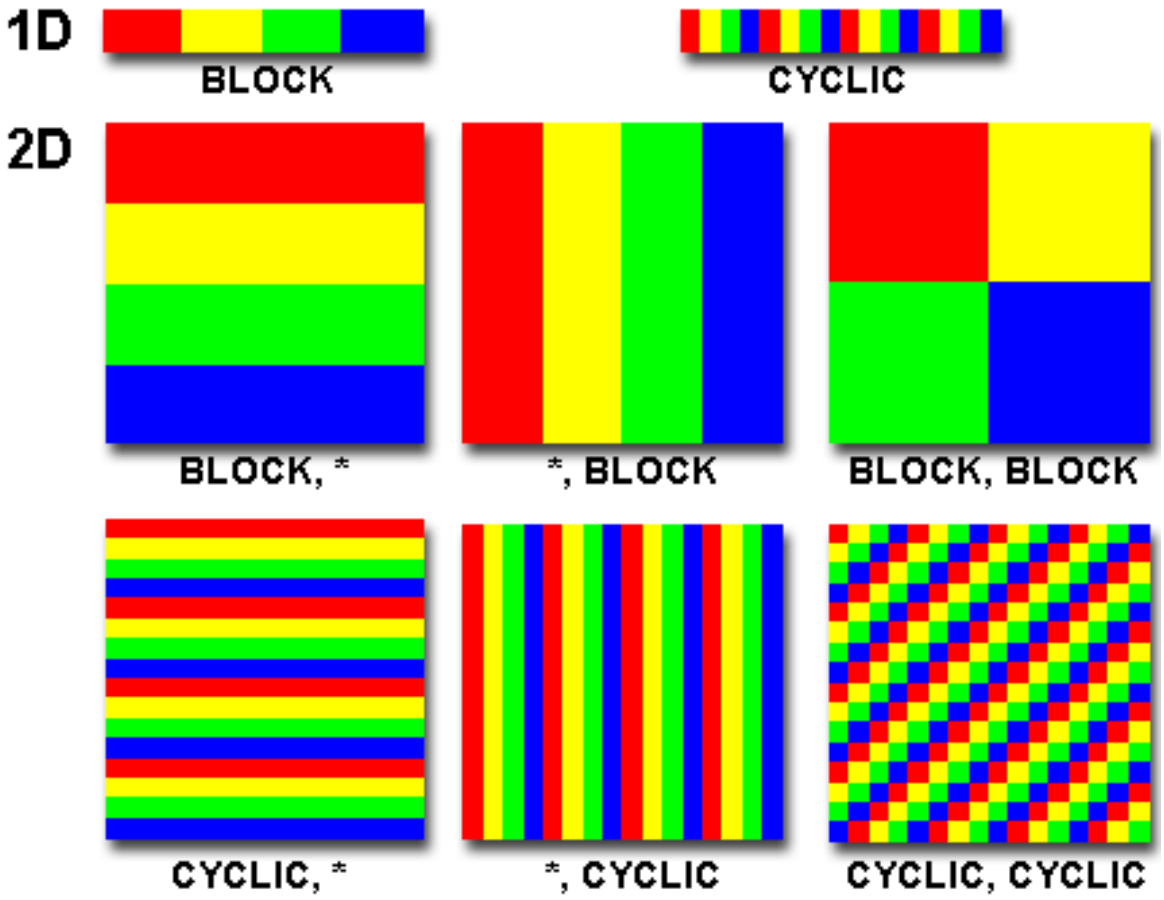
Domain Decomposition

- In this type of partitioning, the data associated with a problem is decomposed. Each parallel task then works on a portion of of the data.



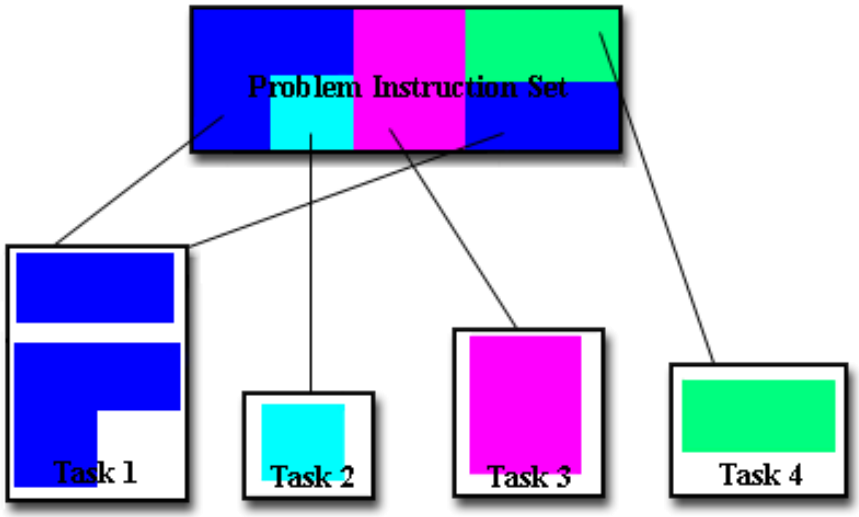
Partitioning Data

- There are different ways to partition data



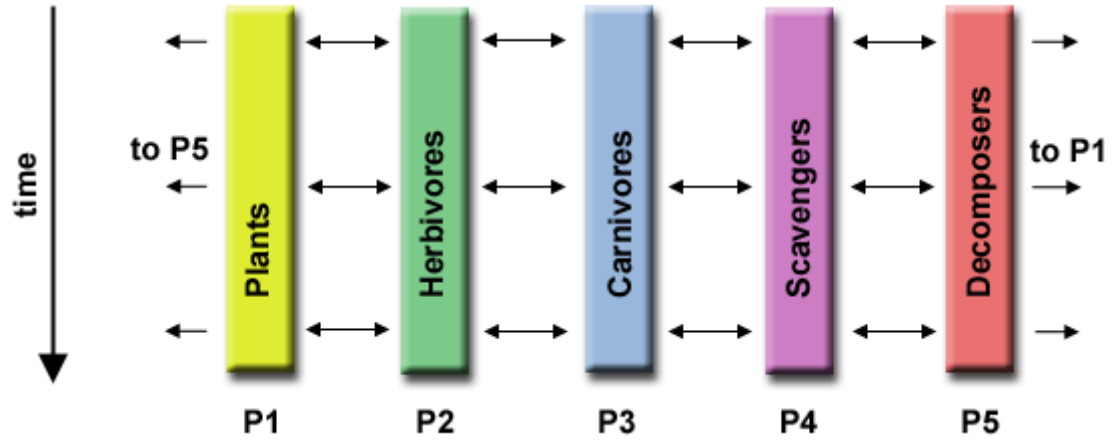
Functional Decomposition

- In this approach, the focus is on the computation that is to be performed rather than on the data manipulated by the computation. The problem is decomposed according to the work that must be done. Each task then performs a portion of the overall work.
- Functional decomposition lends itself well to problems that can be split into different tasks. For example
  - Ecosystem Modeling
  - Signal Processing
  - Climate Modeling



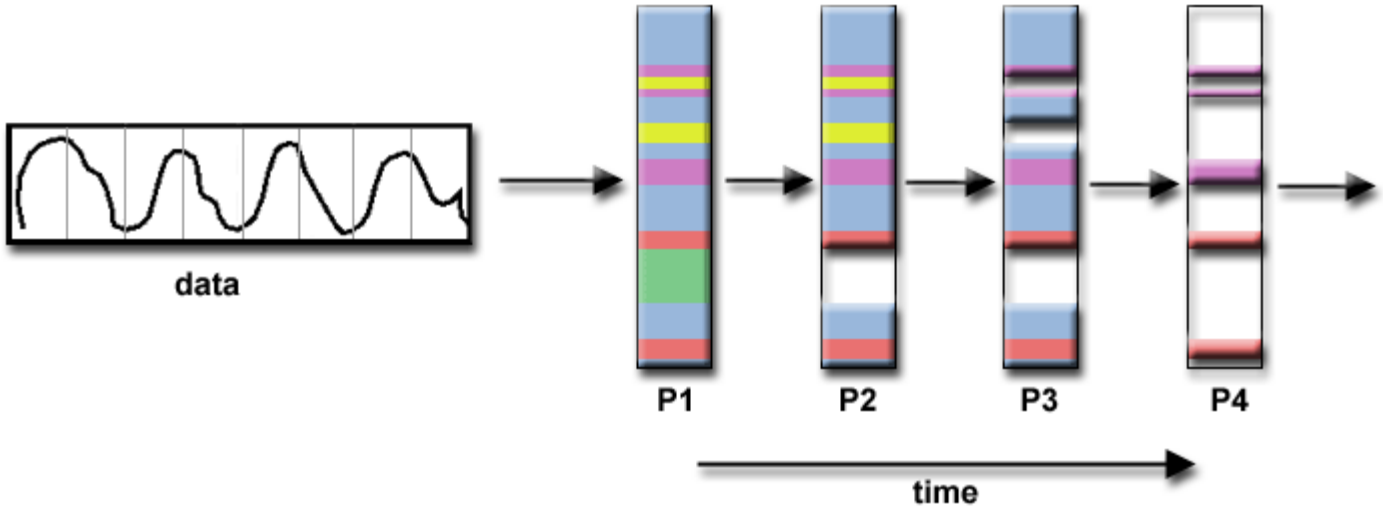
Ecosystem Modeling

- Each program calculates the population of a given group, where each group's growth depends on that of its neighbours. As time progresses, each process calculates its current state, then exchanges information with the neighbour populations. All tasks then progress to calculate the state at the next time step.



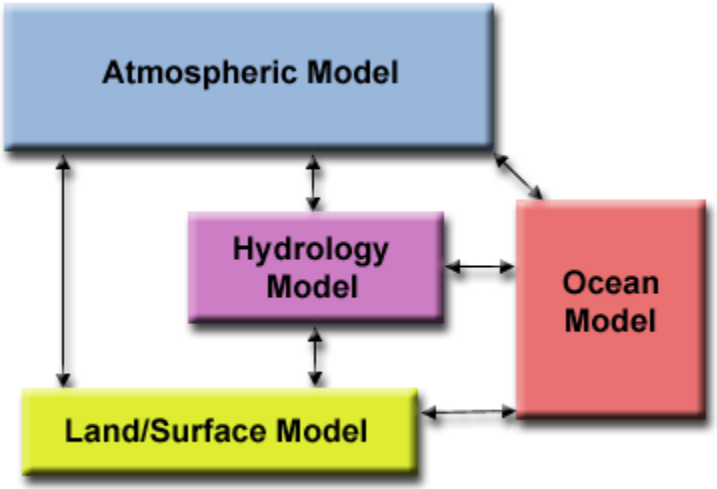
Signal Processing

- An audio signal data set is passed through four distinct computational filters. Each filter is a separate process. The first segment of data must pass through the first filter before progressing to the second. When it does, the second segment of data passes through the first filter. By the time the fourth segment of data is in the first filter, all four tasks are busy.



Climate Modeling

- Each model component can be thought of as a separate task. 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.



- Combining these two types of problem decomposition is common and natural.

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Who Needs Communications?

- The need for communications between tasks depends upon your problem
- **You DON'T need communications**
  - Some types of problems can be decomposed and executed in parallel with virtually no need for tasks to share data. For example, imagine an image processing operation where every pixel in a black and white image needs to have its color reversed. The image data can easily be distributed to multiple tasks that then act independently of each other to do their portion of the work.
  - These types of problems are often called ***embarrassingly parallel*** because they are so straight-forward. Very little inter-task communication is required.
- **You DO need communications**
  - Most parallel applications are not quite so simple, and do require tasks to share data with each other. For example, a 3-D heat diffusion problem requires a task to know the temperatures calculated by the tasks that have neighboring data. Changes to neighboring data has a direct effect on that task's data.

Factors to Consider (1)

- There are a number of important factors to consider when designing your program's inter-task communications
- **Cost of communications**
  - Inter-task communication virtually always implies overhead.
  - Machine cycles and resources that could be used for computation are instead used to package and transmit data.
  - Communications frequently require some type of synchronization between tasks, which can result in tasks spending time "waiting" instead of doing work.
  - Competing communication traffic can saturate the available network bandwidth, further aggravating performance problems.

Factors to Consider (2)

- **Latency vs. Bandwidth**
  - ***latency*** is the time it takes to send a minimal (0 byte) message from point A to point B. Commonly expressed as microseconds.
  - ***bandwidth*** is the amount of data that can be communicated per unit of time. Commonly expressed as megabytes/sec.
  - Sending many small messages can cause latency to dominate communication overheads. Often it is more efficient to package small messages into a larger message, thus increasing the effective communications bandwidth.

Factors to Consider (3)

- **Visibility of communications**
  - With the Message Passing Model, communications are explicit and generally quite visible and under the control of the programmer.
  - With the Data Parallel Model, communications often occur transparently to the programmer, particularly on distributed memory architectures. The programmer may not even be able to know exactly how inter-task communications are being accomplished.

Factors to Consider (4)

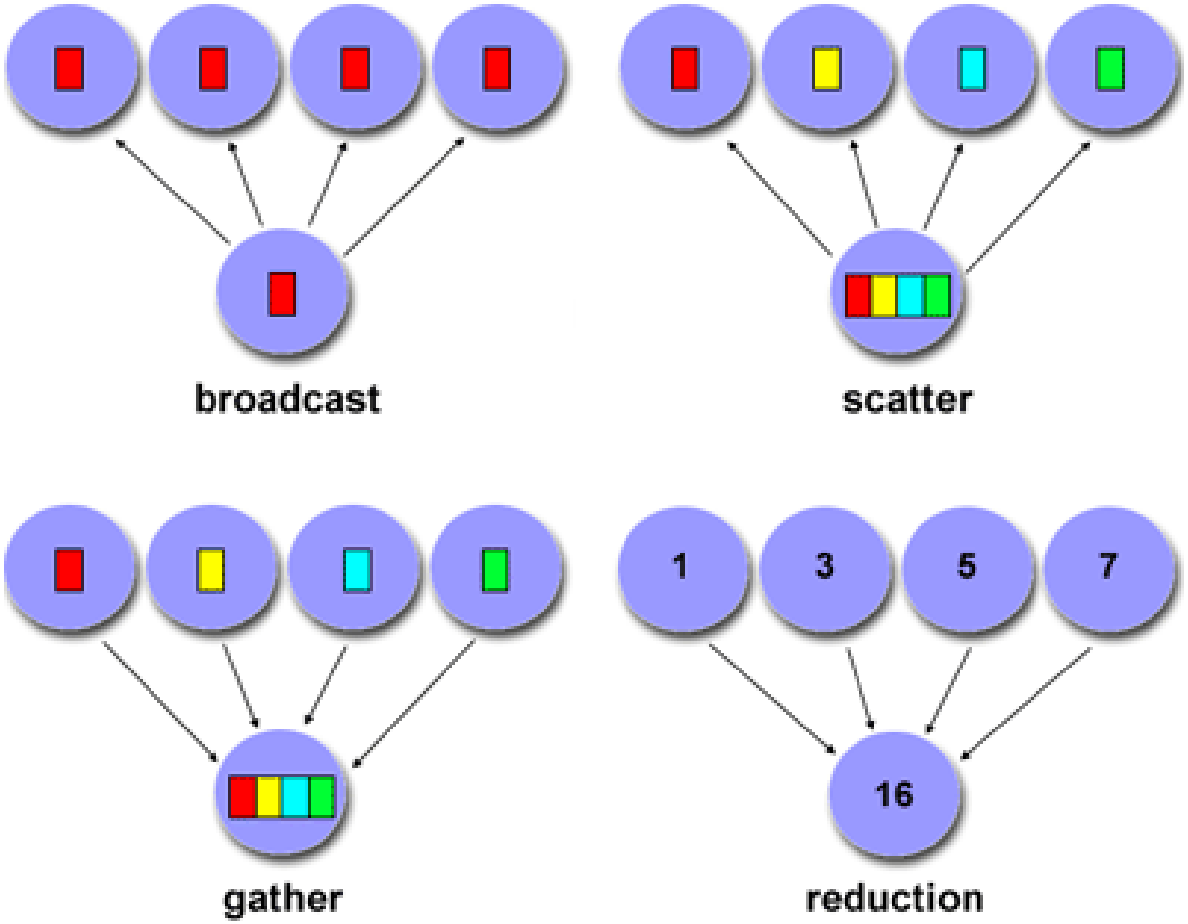
- **Synchronous vs. Asynchronous communications**
  - Synchronous communications require some type of "handshaking" between tasks that are sharing data. This can be explicitly structured in code by the programmer, or it may happen at a lower level unknown to the programmer.
  - Synchronous communications are often referred to as ***blocking*** communications since other work must wait until the communications have completed.
  - Asynchronous communications allow tasks to transfer data independently from one another. For example, task 1 can prepare and send a message to task 2, and then immediately begin doing other work. When task 2 actually receives the data doesn't matter.
  - Asynchronous communications are often referred to as ***non-blocking*** communications since other work can be done while the communications are taking place.
  - Interleaving computation with communication is the single greatest benefit for using asynchronous communications.

Factors to Consider (5)

- **Scope of communications**
  - Knowing which tasks must communicate with each other is critical during the design stage of a parallel code. Both of the two scopings described below can be implemented synchronously or asynchronously.
  - ***Point-to-point*** - involves two tasks with one task acting as the sender/producer of data, and the other acting as the receiver/consumer.
  - ***Collective*** - involves data sharing between more than two tasks, which are often specified as being members in a common group, or collective.

Collective Communications

- **Examples**

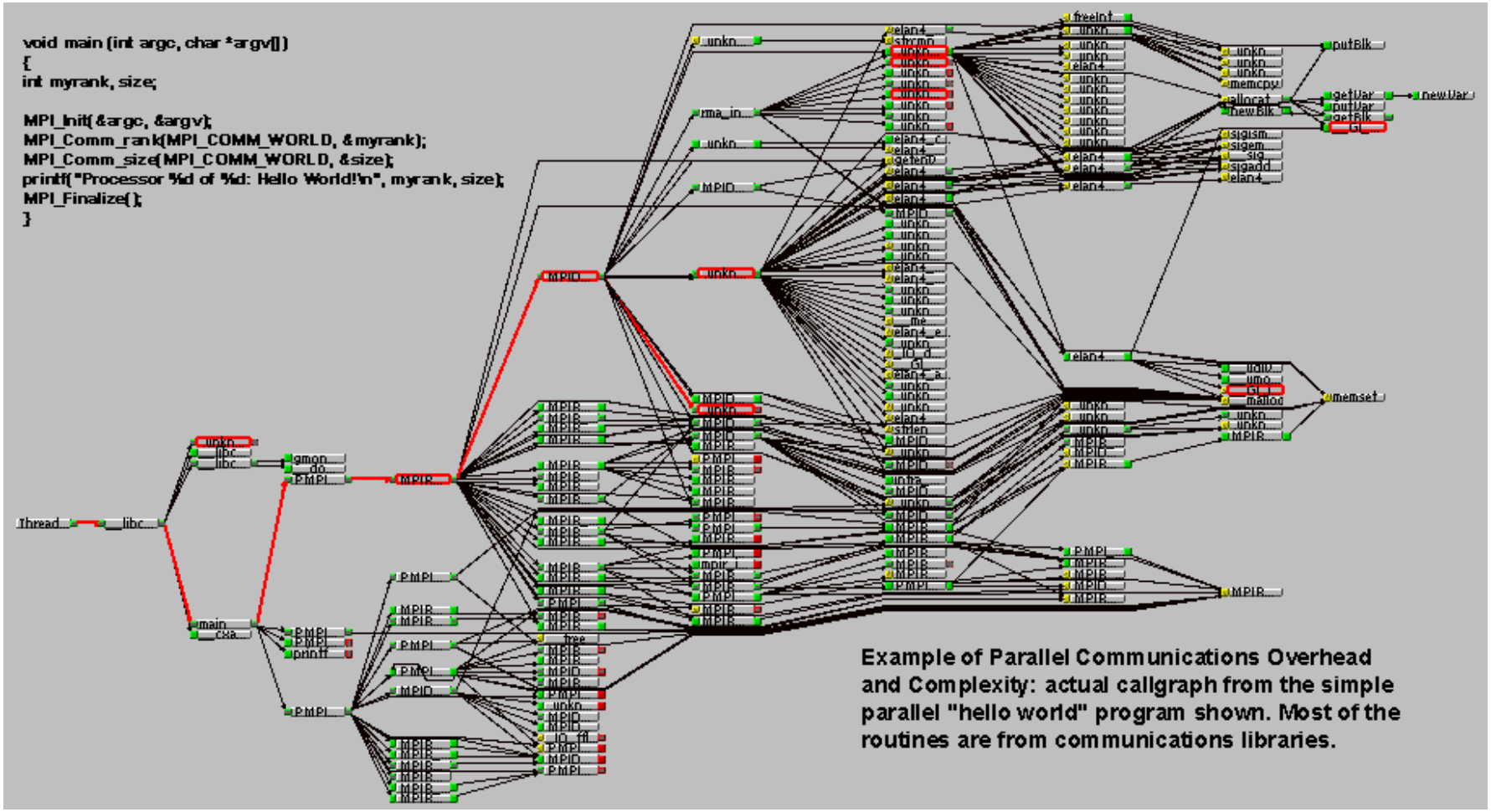


Factors to Consider (6)

- **Efficiency of communications**
  - Very often, the programmer will have a choice with regard to factors that can affect communications performance. Only a few are mentioned here.
  - Which implementation for a given model should be used? Using the Message Passing Model as an example, one MPI implementation may be faster on a given hardware platform than another.
  - What type of communication operations should be used? As mentioned previously, asynchronous communication operations can improve overall program performance.
  - Network media - some platforms may offer more than one network for communications. Which one is best?

Factors to Consider (7)

- **Overhead and Complexity**



Factors to Consider (8)

- **Finally, realize that this is only a partial list of things to consider!!!**

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Types of Synchronization

- **Barrier**
  - Usually implies that all tasks are involved
  - Each task performs its work until it reaches the barrier. It then stops, or "blocks".
  - When the last task reaches the barrier, all tasks are synchronized.
  - What happens from here varies. Often, a serial section of work must be done. In other cases, the tasks are automatically released to continue their work.

Types of Synchronization

- **Lock / semaphore**
  - Can involve any number of tasks
  - Typically used to serialize (protect) access to global data or a section of code. Only one task at a time may use (own) the lock / semaphore / flag.
  - The first task to acquire the lock "sets" it. This task can then safely (serially) access the protected data or code.
  - Other tasks can attempt to acquire the lock but must wait until the task that owns the lock releases it.
  - Can be blocking or non-blocking

Types of Synchronization

- **Synchronous communication operations**
  - Involves only those tasks executing a communication operation
  - When a task performs a communication operation, some form of coordination is required with the other task(s) participating in the communication. For example, before a task can perform a send operation, it must first receive an acknowledgment from the receiving task that it is OK to send.
  - Discussed previously in the Communications section.

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Definitions

- A ***dependence*** exists between program statements when the order of statement execution affects the results of the program.
- A ***data dependence*** results from multiple use of the same location(s) in storage by different tasks.
- Dependencies are important to parallel programming because they are one of the primary inhibitors to parallelism.

Examples (1): Loop carried data dependence

```
for (j = START; j<END; j++)
  A(j) = A(j-1) * 2.0500
CONTINUE
```

- The value of A(J-1) must be computed before the value of A(J), therefore A(J) exhibits a data dependency on A(J-1). Parallelism is inhibited.
- If Task 2 has A(J) and task 1 has A(J-1), computing the correct value of A(J) necessitates:
  - Distributed memory architecture - task 2 must obtain the value of A(J-1) from task 1 after task 1 finishes its computation
  - Shared memory architecture - task 2 must read A(J-1) after task 1 updates it

Examples (2): **Loop independent data dependence**

```
task 1          task 2
------          ------
X = 2           X = 4
.               .
.               .
Y = X**2        Y = X**3
```

- As with the previous example, parallelism is inhibited. The value of Y is dependent on:
  - Distributed memory architecture - if or when the value of X is communicated between the tasks.
  - Shared memory architecture - which task last stores the value of X.
- Although all data dependencies are important to identify when designing parallel programs, loop carried dependencies are particularly important since loops are possibly the most common target of parallelization efforts.

How to Handle Data Dependencies?

- Distributed memory architectures
  - communicate required data at synchronization points.
- Shared memory architectures
  - synchronize read/write operations between tasks.