# Parallel Program Design
# (cf. Libro Grama et al.)

# Parallel Program Design

- One of the first steps of the design of a parallel program is to divide the problem into "chunks" of discrete job that can be distributed to multiple tasks. This is called **decomposition** or **partitioning**

- There are two main ways to partition the computational load among parallel tasks: **functional (task / work) decomposition** and **data decomposition**

# Distributing Work & Data

## Work decomposition

- based on loop decomposition

```
do i=1,100
→ i=1,25
  i=26,50
  i=51,75
  i=76,100
```

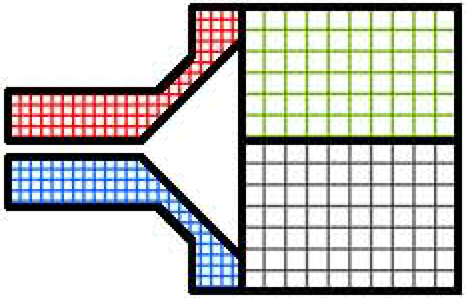
## Data decomposition

- all work for a local portion of the data is done by the local processor

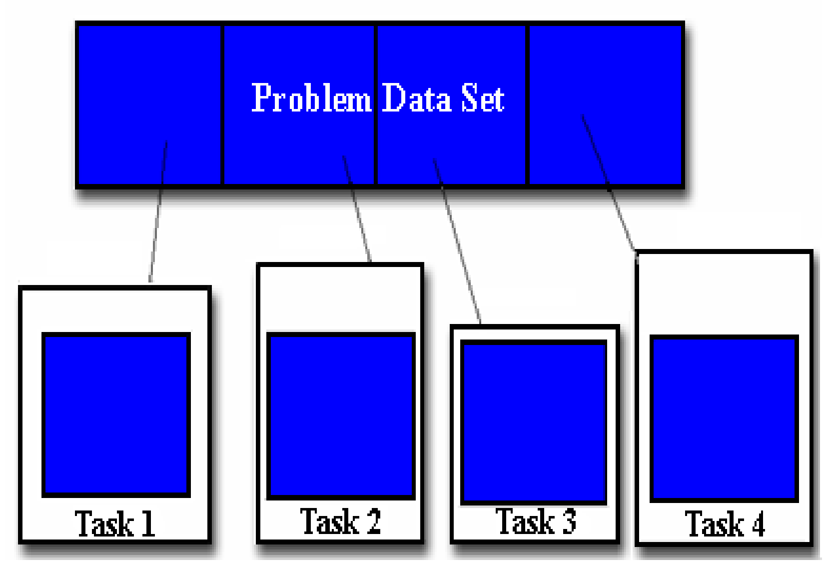
```
A( 1:20,  1:  50)
A( 1:20, 51:100)
A(21:40,  1:  50)
A(21:40, 51:100)
```

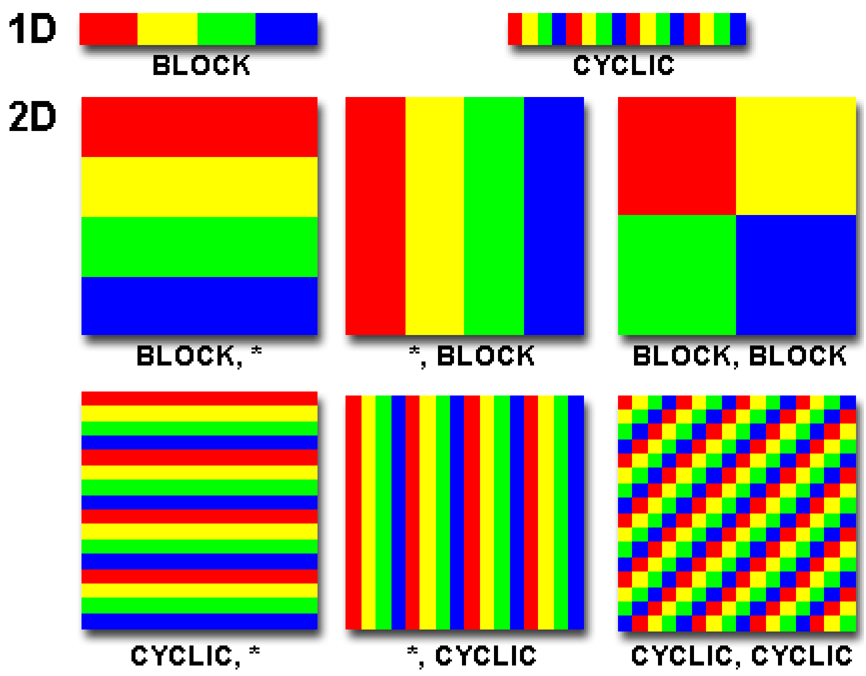
## Domain decomposition

- decomposition of work and data is done in a higher model, e.g. in the reality



# Data Decomposition

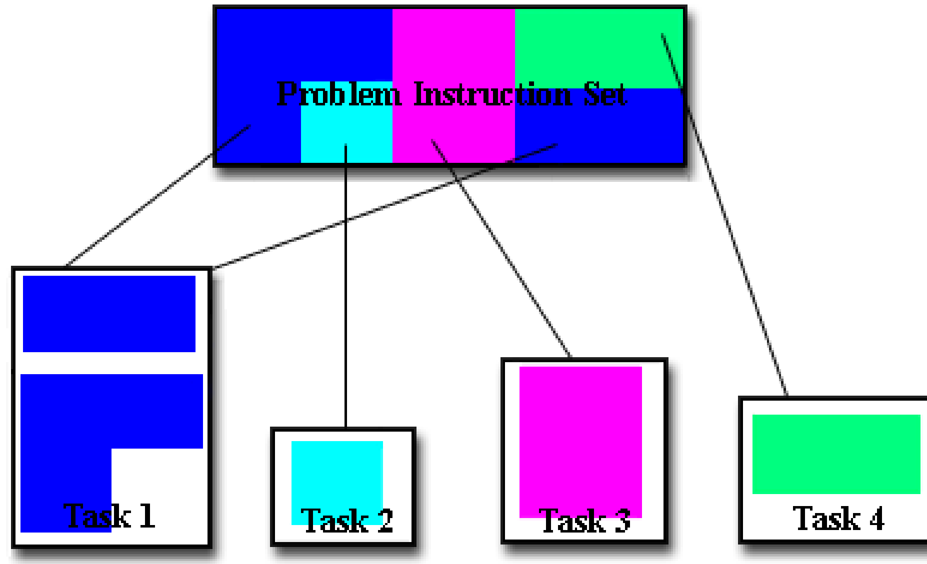


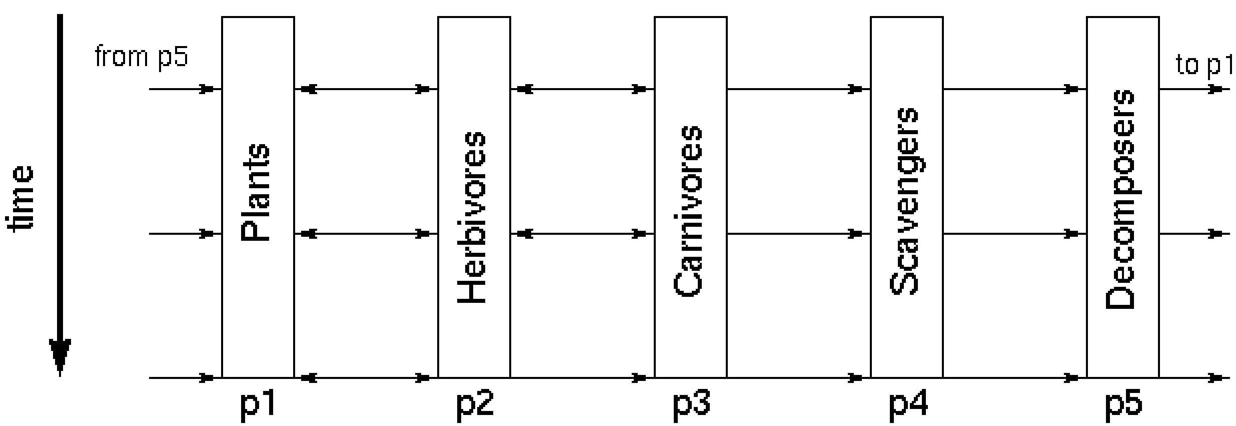




**For example, cellular automata lend themselves well to this type parallelization**

# Task Decomposition

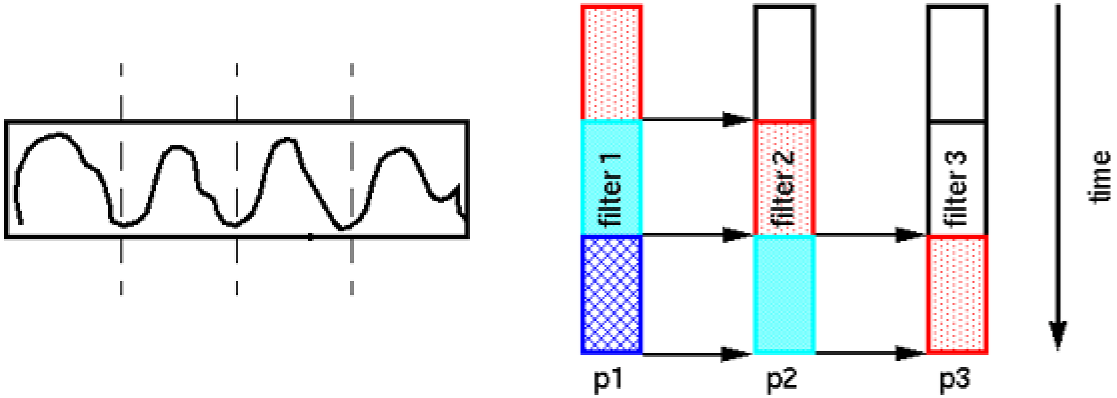
**Functional decomposition works well on those problems that can be divided into different tasks, such as: [Ecosystem Modeling]**



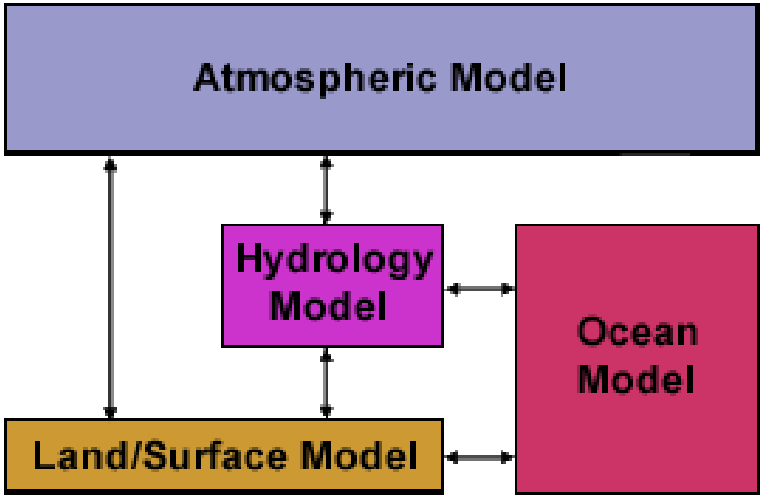



# Task Decomposition

- Signal Processing




Climate Modeling



**… suggestions, advice, etc …**

# Example of Non-Parallelizable Problem

- **Fibonacci series computations**

(1,1,2,3,5,8,13,21,...)

- The formula: F (k + 2) = F (k + 1) + F (k)
- This problem is **<u>not easily parallelizable</u>** because the calculation of the Fibonacci sequence includes dependent calculation, rather than independent
- The calculation of the value of k + 2 uses both value k + 1 and k. These three terms can not be calculated independently and then, not in parallel
- **In Posix/OpenMP? Thanks to recursion!**

# Moral

**Identify the hotspots of the program**

Try to know where the work is done "really‟. Most scientific programs usually run the main part of the work in a few places (typically, **<u>for</u>** loops!)

Focuses on the parallelization of the hotspots and ignore those parts of the program that use little CPU

**Identify bottlenecks in the program**

There are areas that are disproportionately slow, or cause the work parallelized to stop or be delayed? For example, I / O operations usually slows down the execution of the program!

*You may need to restructure the program or use a different algorithm to reduce or eliminate areas that are too "slow"*

# Data Dependencies

- A **data dependency** exists between the instructions of a program when the **order** of execution of instructions **influence** the results of the program
- A data dependence occurs when multiple tasks use several times the same memory locations
- The dependences are important in parallel computing because they are one of the **biggest inhibitors to parallelism**

# Moral - bis

**Identifies inhibitors of parallelism**

A common cause of inhibitor is the data dependence, as demonstrated in the example of the Fibonacci sequence

**Investigate other algorithms if possible**

This might even be the only alternative when designing a parallel application

# How to deal with Data Dependencies

## Simple!

- Distributed memory architectures – Communicate the data in sync points

- Shared memory architectures –

  Synchronizes the read / write operations between tasks

# Data Dependencies

**Example: cycle data dependence**

```
for (i=init; i<end; i++)
  a[j] = a[j-1] * 2.0
```

The value of `a[j-1]` must be calculated before the value of `a[j]`, so `a[j]` shows a date dependency on `a[j-1]`. Parallelism is inhibited. If the Task 2 has `a[j]` and Task 1 has `a[j-1]`, the calculation of the corrected value of `a[j]` requires:

- In **Distributed Memory Architectures** - task 2 must obtain the value of `a[j-1]` from task 1 **<u>after</u>** task 1 has finished computing
- In **Shared Memory Architectures** - Task 2 should read `a[j-1]` **<u>after</u>** task 1 has updated

# Data Dependencies

**Example: Independent-cycle data dependence**

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

**X, Y are shared variables**

As in the previous example, the parallelism is inhibited. The correct value of Y depends on:

In **Distributed Memory Architecture** - If or when the value of X is communicated between tasks

In **Shared Memory Architecture** - which task stores the value of X for last

# Principles of Parallel Algorithm Design

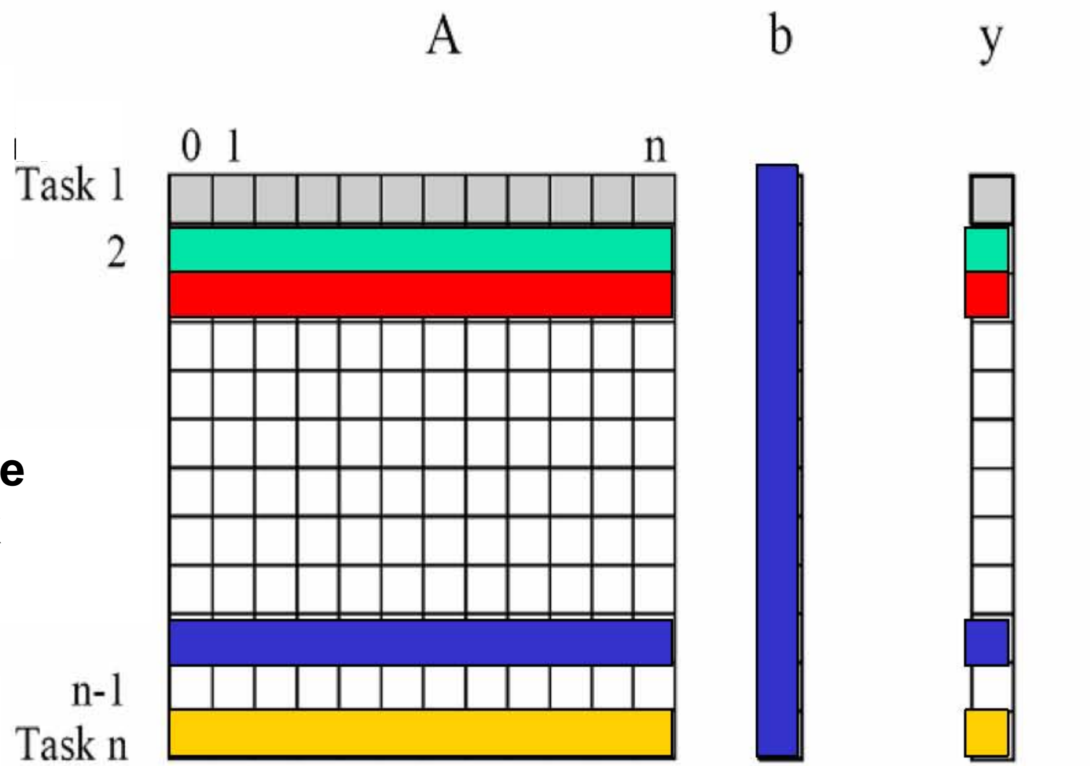
# Task Decomposition

Let's consider a matrix-vector product:

$$y[i]=\sum_{j=1,n} A([i,j] x\ b[j])$$

n tasks are considered, as the number of rows of the matrix

Tasks are independent, and can be computed in any order



# Task Graph Model (Task Parallelism)

- Based on the **task dependency graph**
- Useful to reduce the interaction degree
- Used when the quantity of data a task has to compute is large with respect to the computational cost
- Tasks are statically associated, to minimize data exchange among tasks
- Works better if applied for a shared-memory architecture
- Example: Parallel Quicksort

# Task-Dependency Graph

- The **dependency graph** is used to explicit which tasks need the result of other tasks and their execution order
- It's a DAG
- Nodes represent tasks
- Arcs represent the **dependence** among tasks

What's the dependency graph of the previous example?

- In this case, the graph is disconnected (arc set =0) since all tasks are **independent** from each other

**N.B. DAG = Direct Acyclic Graph**

# Example: Data-Base Query

- **Let's consider a car relational DB:**

| ID# | Model | Year | Color | Dealer | Price |
|---|---|---|---|---|---|
| 4523 | Civic | 2002 | Blue | MN | $18,000 |
| 3476 | Corolla | 1999 | White | IL | $15,000 |
| 7623 | Camry | 2001 | Green | NY | $21,000 |
| 9834 | Prius | 2001 | Green | CA | $18,000 |
| 6734 | Civic | 2001 | White | OR | $17,000 |
| 5342 | Altima | 2001 | Green | FL | $19,000 |
| 3845 | Maxima | 2001 | Blue | NY | $22,000 |
| 8354 | Accord | 2000 | Green | VT | $18,000 |
| 4395 | Civic | 2001 | Red | CA | $17,000 |
| 7352 | Civic | 2002 | Red | WA | $18,000 |

- **Let's consider the query:**
  - **MODEL="civic" AND YEAR="2001" AND (COLOR="Green" OR "COLOR="Withe")**

# Task-Dependency Graph

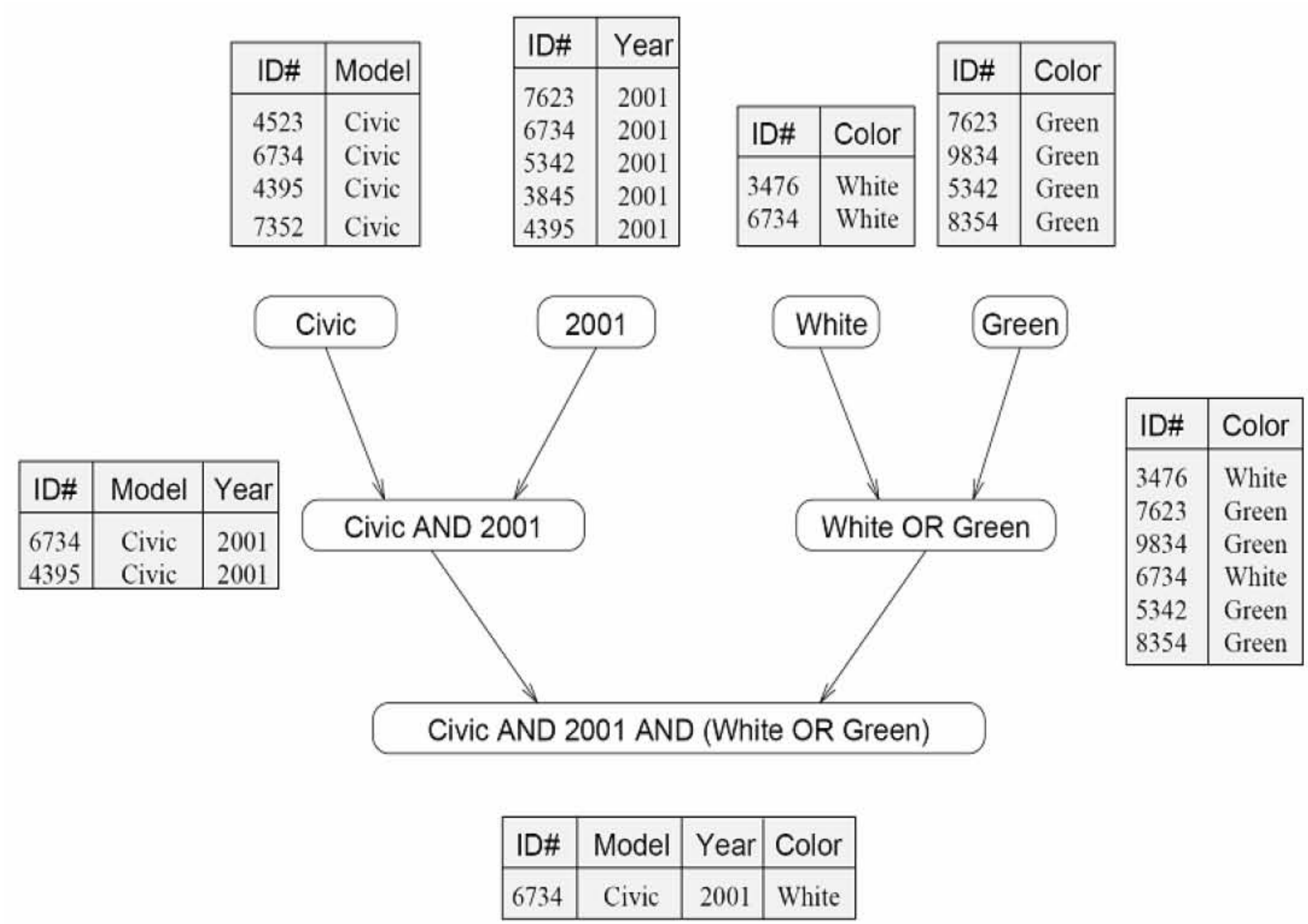
**4 tables**

**All Civics**

**All 2001 models**

**All green models**

**All white models**




| ID# | Model |
|---|---|
| 4523 | Civic |
| 6734 | Civic |
| 4395 | Civic |
| 7352 | Civic |

| ID# | Year |
|---|---|
| 7623 | 2001 |
| 6734 | 2001 |
| 5342 | 2001 |
| 3845 | 2001 |
| 4395 | 2001 |

| ID# | Color |
|---|---|
| 3476 | White |
| 6734 | White |

| ID# | Color |
|---|---|
| 7623 | Green |
| 9834 | Green |
| 5342 | Green |
| 8354 | Green |

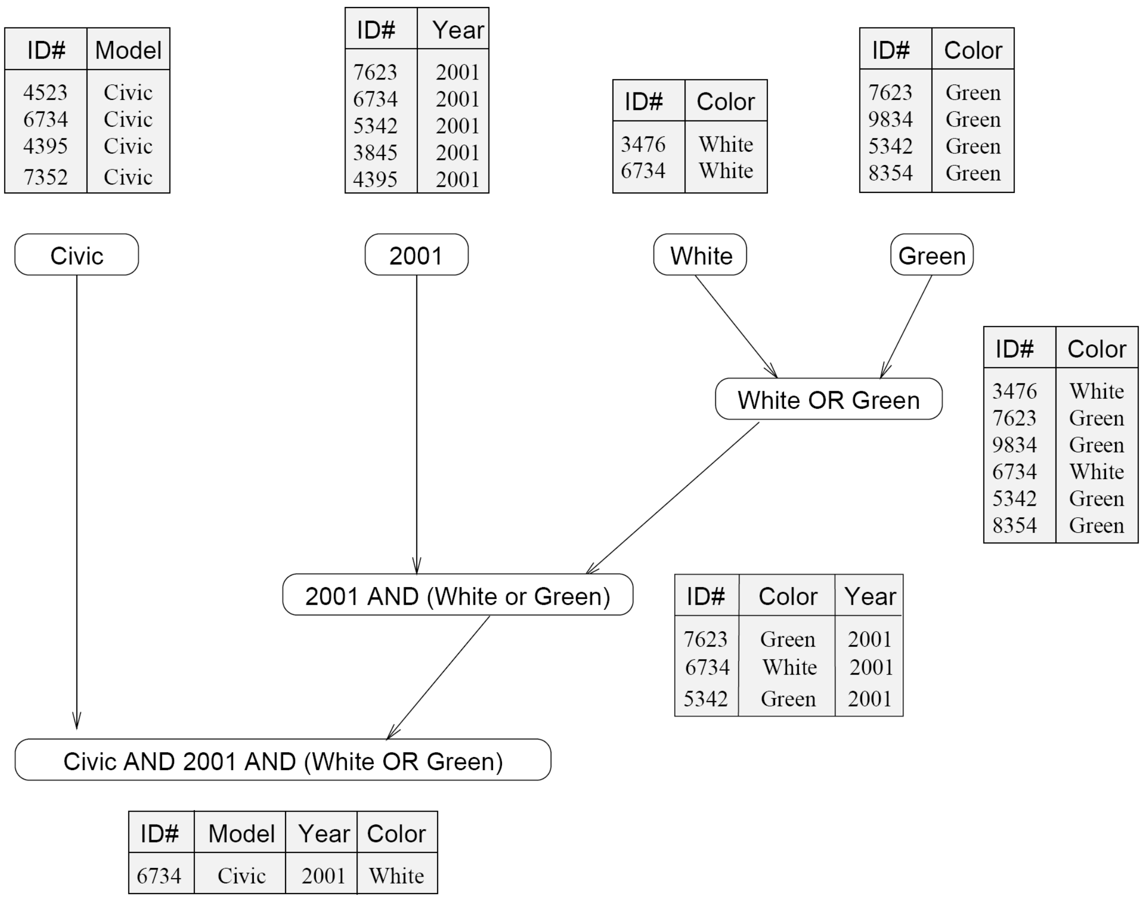
| ID# | Model | Year |
|---|---|---|
| 6734 | Civic | 2001 |
| 4395 | Civic | 2001 |

| ID# | Color |
|---|---|
| 3476 | White |
| 7623 | Green |
| 9834 | Green |
| 6734 | White |
| 5342 | Green |
| 8354 | Green |

| ID# | Model | Year | Color |
|---|---|---|---|
| 6734 | Civic | 2001 | White |

# ... alternative

**…Note that the same problem can be decomposed in other ways ...**




| ID# | Model |
|---|---|
| 4523 | Civic |
| 6734 | Civic |
| 4395 | Civic |
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| ID# | Year |
|---|---|
| 7623 | 2001 |
| 6734 | 2001 |
| 5342 | 2001 |
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| 4395 | 2001 |

| ID# | Color |
|---|---|
| 3476 | White |
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| ID# | Color |
|---|---|
| 7623 | Green |
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| 5342 | Green |
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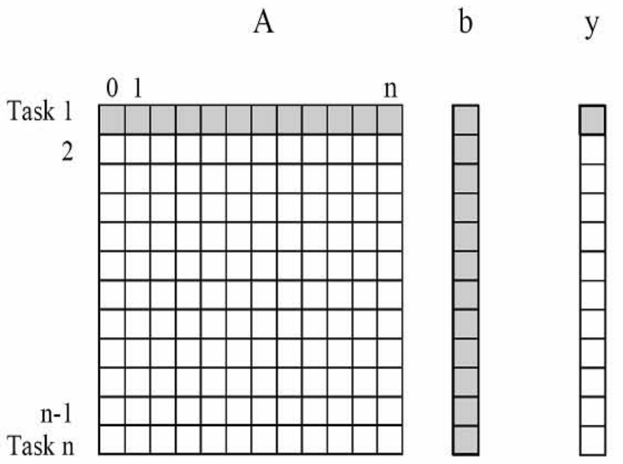
| ID# | Color |
|---|---|
| 3476 | White |
| 7623 | Green |
| 9834 | Green |
| 6734 | White |
| 5342 | Green |
| 8354 | Green |

| ID# | Color | Year |
|---|---|---|
| 7623 | Green | 2001 |
| 6734 | White | 2001 |
| 5342 | Green | 2001 |

| ID# | Model | Year | Color |
|---|---|---|---|
| 6734 | Civic | 2001 | White |

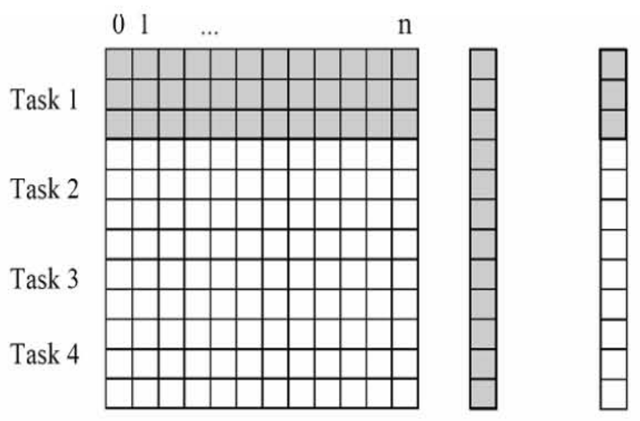
# Granularity

- Granularity of the task decomposition
  - Depends both on the number and size of tasks




- Fine grained

- Coarse grained



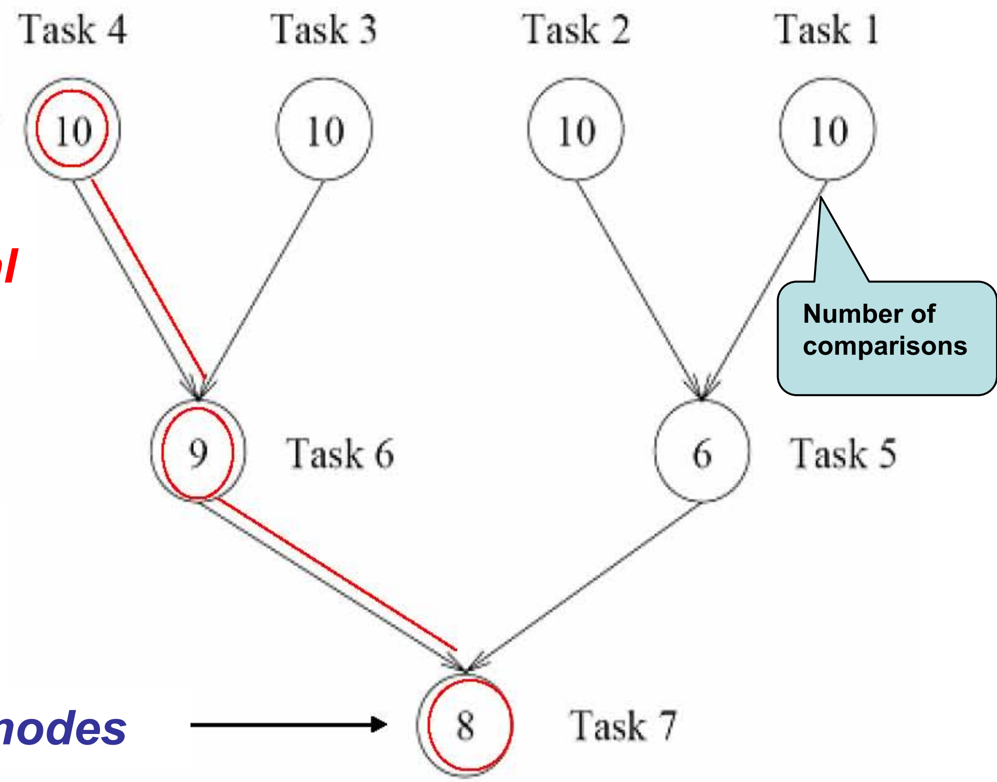
# Concurrency

- It's linked with granularity: when granularity is fine, the concurrency degree among tasks **increases**
- **Maximum concurrency degree**: maximum number of tasks that can be executed simultaneously
- **Average degree of concurrency**: average number of tasks that can be executed simultaneously, computed on the overall duration of the program
- For the same granularity, the concurrency degree is not the same: it depends also on task dependency

# Critical Path

- An aspect of the task dependence that determines the average degree of concurrency for a given granularity
- Suppose that in the dependency graph a *weight* at each node is associated that depends con the quantity of work that a task has to carry out

*Initial nodes*




*The critical path is the longest path between each pair of initial and final nodes in the dependency graph*

**Length of critical path? 27**

**The total work is 63**
**Average concurrency degree is 63/27=2.33**

*Initial nodes*

**NB:** The average concurrency degree for the 2° decomposition is 1.88

# Performance Limits

- It would seem that the parallel time can be reduced in an arbitrary manner by simply making the **granularity finer**
- In practice, there is a lower limit on "how fine" may be the granularity of the computation. For example, in the case of the multiplication of a dense matrix with a vector, <u>it does not make sense to use more than ($n^2$) concurrent tasks.</u>
- In addition, concurrent tasks may also have the need (obvious!) to exchange data with other tasks. This involves a communication overhead.
- <u>The tradeoff between the granularity of a decomposition and the associated overhead will often determine the limits of performance</u>
- In fact ...

# Task Interaction Graphs

- **Task interaction** is a limiting factor for having an **infinite speedup**
- Tasks in which an algorithm is decomposed can **share input, output and other intermediate data**
- Tasks that seem independent may need to share data (in which to write, for instance)
- In the case of the matrix-vector multiplication, all tasks must access vector B, so a suitable data exchange is necessary

**Obs: The set of edges of a task-interaction graph includes that of task-dependency of the graph (eg, in the previous query they are the same)**

# Task Interaction Graphs

- **Captures the pattern of interaction between tasks**
- This graph usually contains the **task-dependency graph** as a **subgraph**
- In fact, there may be interactions between tasks even if there are no dependencies
- These interactions usually occur due to accesses on shared data

# Task Interaction Graphs: An example

Consider the problem of multiplying a **sparse matrix** ***A*** with a vector ***b***. The following observations can be made:

- As before, the computation of each element of the result vector can be viewed as an **independent task**.
- Unlike a dense matrix-vector product though, only non-zero elements of matrix ***A*** participate in the computation.
- If, for memory optimality, we also partition ***b*** across tasks, then one can see that the **task interaction graph of the computation is identical to the graph of the matrix** ***A*** (the graph for which ***A*** represents the adjacency structure).

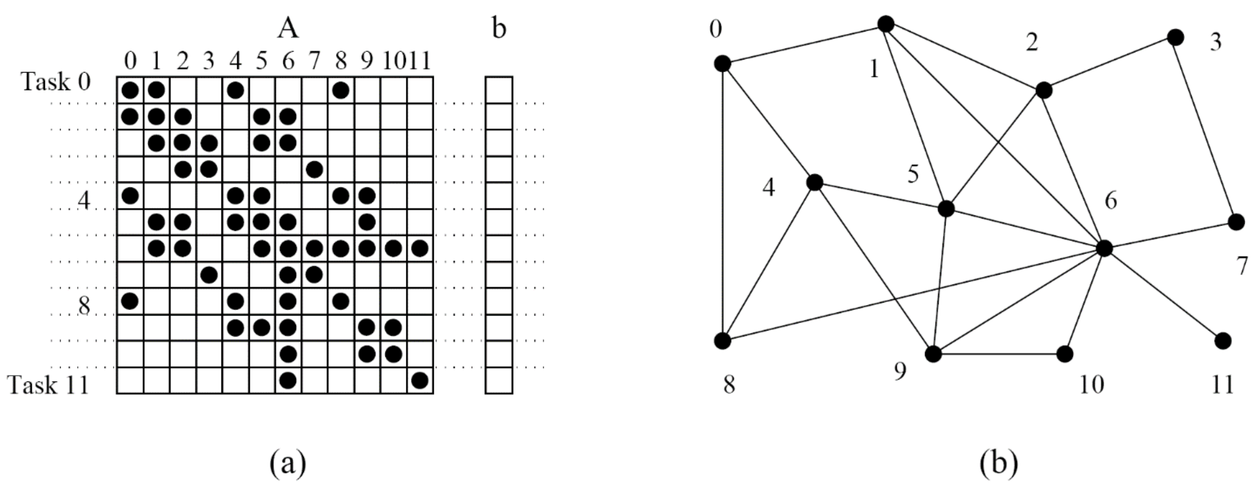



**Figure 3.6** A decomposition for sparse matrix-vector multiplication and the corresponding task-interaction graph. In the decomposition Task $i$ computes $\sum_{0 \le j \le 11, A[i,j] \ne 0} A[i, j].b[j]$.

# Task Interaction Graphs, Granularity, and Communication

*In general, if the granularity of a decomposition is finer, the associated overhead (as a ratio of useful work associated with a task) increases*

**Example:** Consider the sparse matrix-vector product example. Assume that each node takes **1 unit time** of computation and each interaction (edge) causes an overhead of **1 unit time**.

- Viewing node 0 as an independent task involves a useful computation of **one time** unit and overhead (communication) of **three time** units (3/1 ratio)
- Now, if we consider nodes 0, 4, and 5 as one task, then the task has useful computation totaling to three time units and communication corresponding to five time units (five edges). Clearly, this is a **more favorable ratio** than the former case (5/3 ratio)

**Thus, it seems that using <u>less</u> tasks is better?**

At the extreme, one task is **<u>better</u>** than many tasks ?!

# Processors and Mapping

# Processors and Mapping

- Task $\approx$ Process (not Processor or Cores!)
- During its execution, a process can synchronize and communicate with other processes

*The mechanism in which task are assigned to process for their execution is called mapping*

- Task Interaction and dependency graphs are useful to determine a good mapping for a parallel algorithm

# Processors and Mapping

- In general, the number of tasks of a decomposition **exceeds** the number of available processes

- For this reason, a parallel algorithm must also provide a mapping of tasks on processes

- **Note**: Remember that we are referring to the mapping between tasks and processes, and **not to processors**. This is because, on the other hand, typical used APIs (eg OpenMP, MPI) do not allow easy binding of tasks to physical processors. Rather, they seek to aggregate tasks to processes, by giving the **system the task of mapping processes to processors (for efficiency)**.

- We talk about processes, not in the strict sense of UNIX / LINUX, but as a collection of tasks and associated data

# Processors and Mapping

- An appropriate mapping of tasks on processors is **critical** to the performance of a parallel algorithm
- The mappings are determined by both task-dependency and task-interaction graphs

- The **task-dependency graphs** can be used to ensure that the work is **evenly distributed** on the processes at any point (minimum idling and optimal load balance).
- The **task-interaction graphs** can be used to ensure that the processes require **minimal interaction** with other processes (minimum communication).

# Processors and Mapping

An appropriate mapping must minimize the execution and parallel time by:

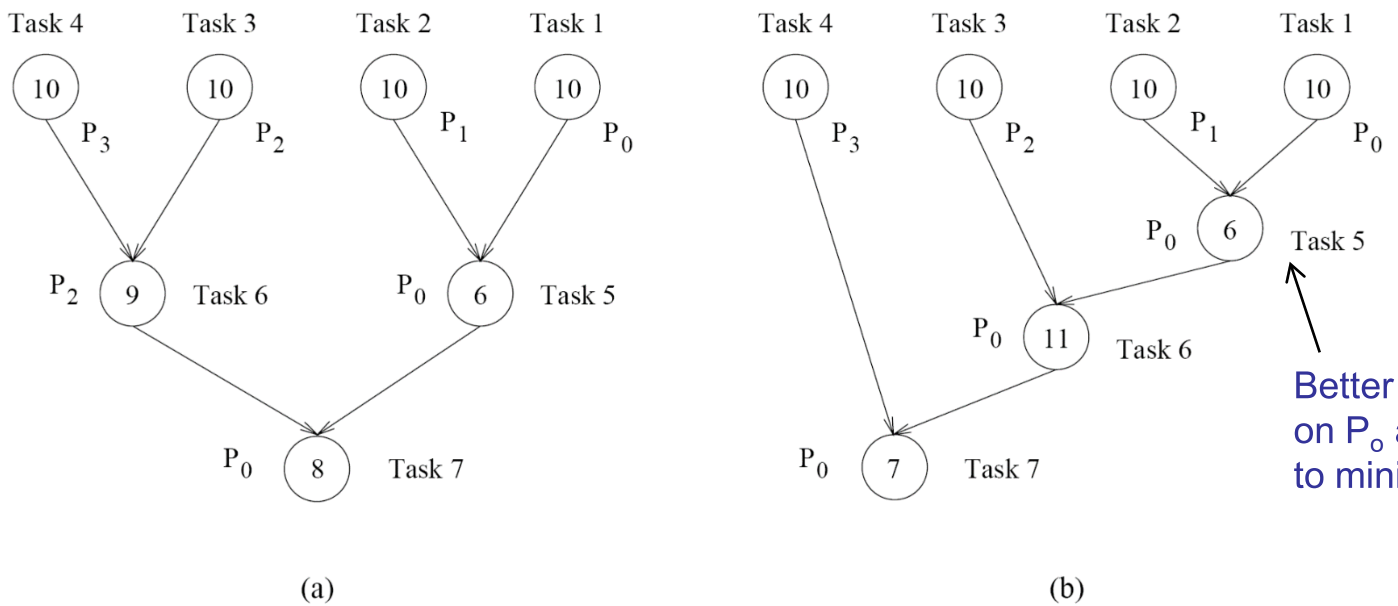
1. Allocation of independent tasks on different processes

2. Assigning the task of critical paths to processors as soon as they become available

3. Minimize interaction between processes by mapping processes with dense interactions on the same process

Note: *These criteria are, unfortunately, often in conflict with each other*. For example, as an extreme, the decomposition of a task in **no decomposition** minimizes interactions but does not result in any increase in speed-up!

# Processors and Mapping: Example




Better to map Task 5 on $P_o$ and not on $P_3$, to minimize interaction!

**Figure 3.7** Mappings of the task graphs of Figure 3.5 onto four processes.

*Mapping of tasks of the previous query to processes obtained by the dependency graph in terms of levels (no node in a level have dependencies)*

Task of the same level are assigned to different processes (degree of concurrency degree = number leaves = 4)

It's useless to increase the number of processors more than 4 as the concurrency degree is 4!