Parallel computing, models and their performances

A high level exploration of the HPC world

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Overview

- Definition of parallel application
- Architectures taxonomy
- Laws managing the parallel domain
- Models in parallel computation
- Examples

Formal definition

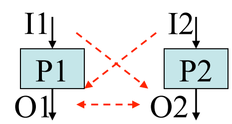
Bernstein

{ I1 ∩ O2 = ∅ and I2 ∩ O1 = ∅ and O1 ∩ O2 = ∅ }

General case: P1… Pn are parallel if and only if
each for each pair Pi, Pj we have Pi || Pj.

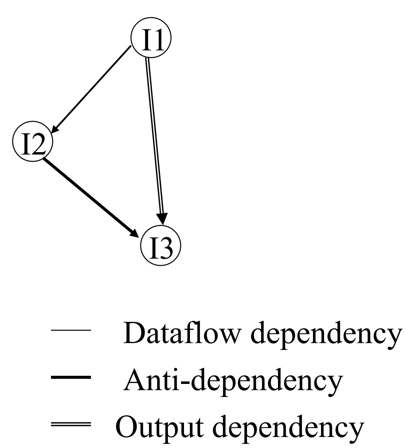
3 limit to the parallel applications:

1. Data dependencies
2. Flow dependencies
3. Resources dependencies



Data dependencies

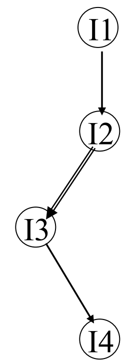
I1: A = B + C
I2: E = D + A
I3: A = F + G



How to avoid them?
Which can be avoided ?

Flow dependencies

I1: A = B + C
I2: if(A) {
I3: D = E + F }
I4: G = D + H



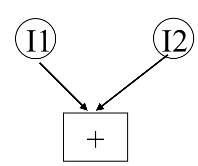
— Dataflow dependency

═ Flow dependency

How to avoid ?

Resources dependencies

I1: A = B + C
I2: G = D + H



How to avoid ?

Flynn Taxonomy

•Computers classified by instruction delivery mechanism and data stream
•4 characters code: 2 for instruction stream and 2 for data stream

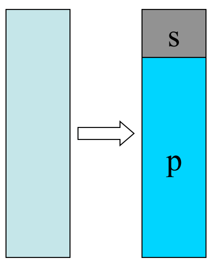
	1 Instruction flow	> 1 Instruction flow
1 data stream	SISD Von Neumann	MISD pipeline
> 1 data stream	SIMD	MIMD

Flynn Taxonomy: Analogy

- SISD: lost people in the desert
- SIMD: rowing
- MISD: pipeline in the car construction chain
- MIMD: airport facility, several desks working at their own pace, synchronizing via a central database.

Amdahl Law

- First law of parallel applications (1967)
- Limit the speedup for all parallel applications



N = number of processors

$$speedup = \frac{s + p}{s + p/N}$$

$$speedup = \frac{1}{a + (1 - a)/N}$$

Amdahl Law

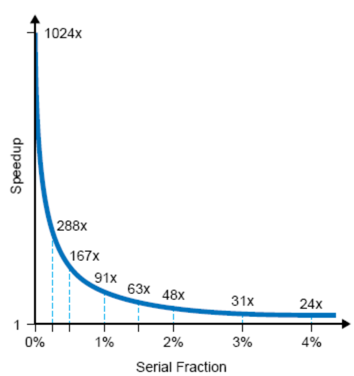


FIGURE 1. Speedup under Amdahl's Law

Speedup is bound by 1/a.

Amdahl Law

- Bad news for parallel applications
- 2 interesting facts:
  - We should limit the sequential part
  - A parallel computer should be a fast sequential computer to be able to resolve the sequential part quickly
- What about increasing the size of the initial problem ?

Gustafson Law

- Less constraints than the Amdahl law.
- In a parallel program the quantity of data to be processed increase, so the sequential part decrease.

$$\left.\begin{array}{l} t = s + P/n \\ P = a * n \end{array}\right\} speedup = \frac{s + a * n}{s + a}$$

$$a \to \infty \Rightarrow speedup \to n$$

Gustafson Law

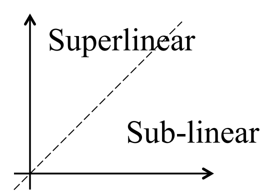
- The limit of Amdahl Law can be transgressed if the quantity of data to be processed increase.

$$speedup \leq n + (1 - n)s$$

Rule stating that if the size of most problems is scaled up sufficiently, then any required efficiency can be achieved on any number of processors.

Speedup

- Superlinear speedup ?



Sometimes superlinear speedups can be observed!
- •Memory/cache effects
- •More processors typically also provide more memory/cache.
- •Total computation time decreases due to more page/cache hits.

•Search anomalies
- •Parallel search algorithms.
- •Decomposition of search range and/or multiple search strategies.
- •One task may be "lucky" to find result early.

Parallel execution models

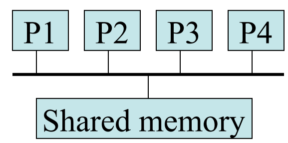
- Amdahl and Gustafson laws define the limits without taking in account the properties of the computer architecture.
- They cannot be used to predict the real performance of any parallel application.
- We should integrate in the same model the architecture of the computer and the architecture of the application.

What are models good for ?

- Abstracting the computer properties
  - Making programming simple
  - Making programs portable ?
- Reflecting essential properties
  - Functionality
  - Costs
- What is the von-Neumann model for parallel architectures ?

Parallel Random Access Machine

- One of the most studied
- World described as a collection of synchronous processors which communicate with a global shared memory unit.



How to represent the architecture

- 2 resources have a major impact on the performances:
  - The couple (processor, memory)
  - The communication network.
- The application should be described using those 2 resources.

$$T_{app} = T_{comp} + T_{comm}$$

Models

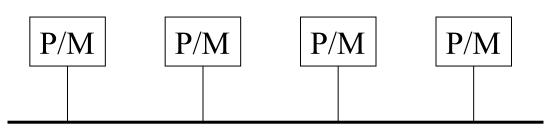
- 2 models are often used.
- They represent the whole system as composed by n identical processors, each of them having his own memory.
- They are interconnected with a predictable network.
- They can realize synchronizations.

Bulk Synchronous Parallel – BSP

- Distributed-memory parallel computer

Valiant 1990

- Global vision as a number of processor/memory pairs interconnected by a communication network

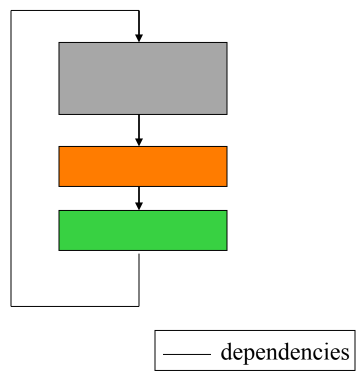


- Each processor can access his own memory without overhead and have a uniform slow access to remote memory

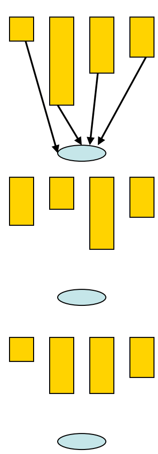
BSP

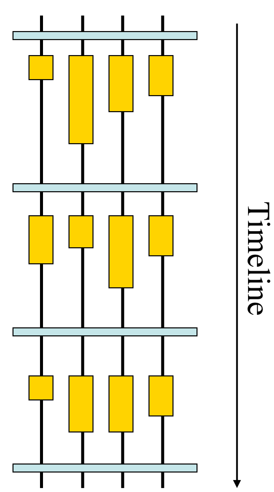
- Applications composed by Supersteps separated by global synchronizations.
- One superstep include:
  - – A computation step
  - – A communication step
  - – A synchronization step

Synchronization used to insure that all processors complete the computation + communication steps in the same amount of time.



BSP





BSP

$$T_{\text{superstep}} = w + g * h + l$$

Where:

w = max of computation time

g = 1/(network bandwidth)

h = max of number of messages

l = time for the synchronization

Sketch the communications

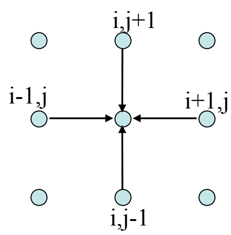
BSP

- An algorithm can be described using only w, h and the *problem size*.
- Collections of algorithms are available depending on the computer characteristics.
  - Small L
  - Small g
- The best algorithm can be selected depending on the computer properties.

BSP - example

- Numerical solution to Laplace's equation

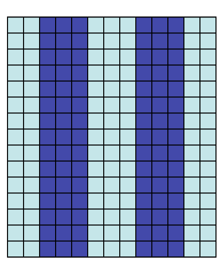
$$U_{i,j}^{n+1} = \frac{1}{4}\left(U_{i-1,j}^{n} + U_{i+1}^{n} + U_{i,j-1}^{n} + U_{i,j+1}^{n}\right)$$




```
for j = 1 to jmax
  for i = 1 to imax
    Unew(i,j) = 0.25 * ( U(i-1,j) + U(i+1,j)
                       +   U(i,j-1) + U(i,j+1))
  end for
end for
```

BSP - example

- The approach to make it parallel is by partitioning the data



BSP - example

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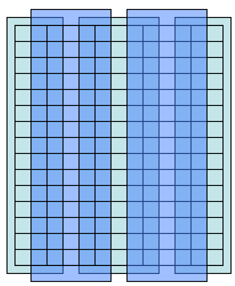
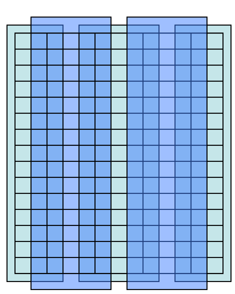


Overlapping the data boundaries allow computation without communication for each superstep

On the communication step each processor update the corresponding columns on the remote processors.

BSP - example



```
for j = 1 to jmax
  for i = 1 to imax
    unew(i,j) = 0.25 * ( U(i-1,j) + U(i+1,j)
                     +  U(i,j-1) + U(i,j+1))
  end for
end for
if me not 0 then
  bsp_put( to the left )
endif
if me not NPROCS – 1 then
  bsp_put( to the right )
Endif
bsp_sync()
```

BSP - example

$$T_{\text{superstep}} = w + g * h + l$$

h = max number of messages

= I values to the left +

I values to the right

= 2 * I (ignoring the inverse communication!)

w = 4 * I * I / p

$$T_{\text{superstep}} = 4\frac{I^2}{p} + 2 * g * I + l$$

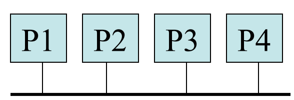
BSP - example

- BSP parameters for a wide variety of architectures has been published.

Machine	s	p	l	g
Origin 2000	101	4 32	1789 39057	10.24 66.7
Cray T3E	46.7	4 16	357 751	1.77 1.66
Pentium 10Mbit	61	4 8	139981 826054	1128.5 2436.3
Pentium II 100Mbit	88	4 8	27583 38788	39.6 38.7

A more sophisticated model LogP

- Tend to be more empirical and network-related.



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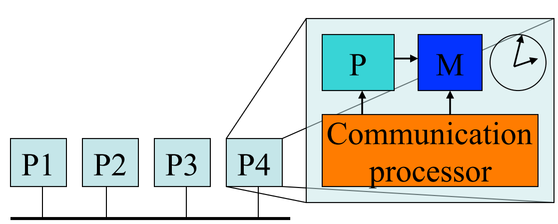
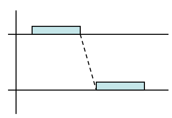
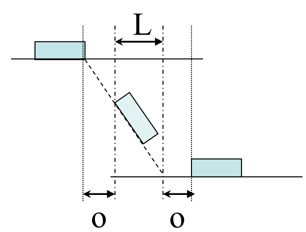


LogP

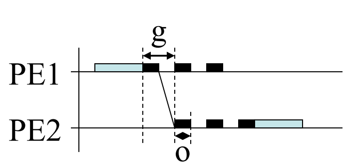
- Decompose the communications in 3 elements:
  - Latency : small message cross the network
  - overhead : lost time in communication

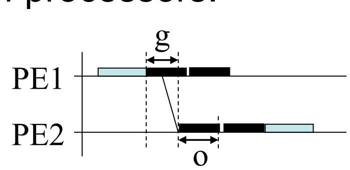




LogP

- Decompose the communications in 3 elements:
  - Latency : small message cross the network
  - overhead : lost time in communication
  - gap : between 2 consecutive messages
- And P the number of processors.





Both g and o matter !

g > o

g < o

LogP

- The total time for a message to go from the processor A to the processor B is:

  L + 2 * o

- There is no model for the application
- We can describe the application using the same approach as for BSP: supersteps

$$T_{\text{superstep}} = w + h * (L + 2o) + l$$

LogP

- The P parameter does not interfere in the superstep computation ?
- When the number of processors is not fixed:
  - The time of the computation change w(p)
  - The number of messages change h(p)
  - The synchronization time change l(p)

LogP

- Allow/encourage the usage of general techniques of designing algorithms for distributed memory machines: exploiting locality, reducing communication complexity and overlapping communication and computation.
- Balanced communication to avoid overloading the processors.

LogP

- Interesting concept : idea of finite capacity of the network. Any attempt to transit more than a certain amount of data will stall the processor.

$\left\lceil \frac{L}{g} \right\rceil$

- This model does not address on the issue of message size, even the worst is the assumption of all messages are of ``small'' size.
- Does not address the global capacity of the network.

Design a LogP program

- Execution time is the time of the slowest process
- Implications for algorithms:
  - – Balance computation
  - – Balance communications

  Are only sub-goals !
- Remember the capacity constraint $\left\lceil \frac{L}{g} \right\rceil$

LogP Machines

Maschine	L	o	g	P
CM-5	6	2.2	4	512
Meiko CS-2	8.6	1.7	$14.2 + 0.03x$	64
Power Xplorer	$21 - 0.82x$	$70 + x$	$115 + 1.43x$	8
Para-Station	$50 - 0.10x$	$3 + 0.112x$	$3 + 0.119x$	4
IBM SP-2	$13 - 0.005x$	$8 + 0.008x$	$10 + 0.01x$	128
IBM SP-2	$17 - 0.005x$	$8 + 0.008x$	$10 + 0.01x$	256

Improving LogP

- First model to break the synchrony of parallel execution
- LogGP : augments the LogP model with a linear model for long messages
- LogGPC model extends the LogGP model to include contention analysis using queuing model on the k-ary n-cubes network
- LogPQ model augments the LogP model on the stalling issue of the network constraint by adding buffer queues in the communication lines.

The CCM model

- Collective Computing Model transform the BSP superstep framework to support high-level programming models as MPI and PVM.
- Remove the requirement of global synchronization between supersteps, but combines the message exchanges and synchronization properties into the execution of a collective communication.
- Prediction quality usually high.