Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Parallel Evolutionary Algorithms

(new trends)

University of Málaga, SPAIN

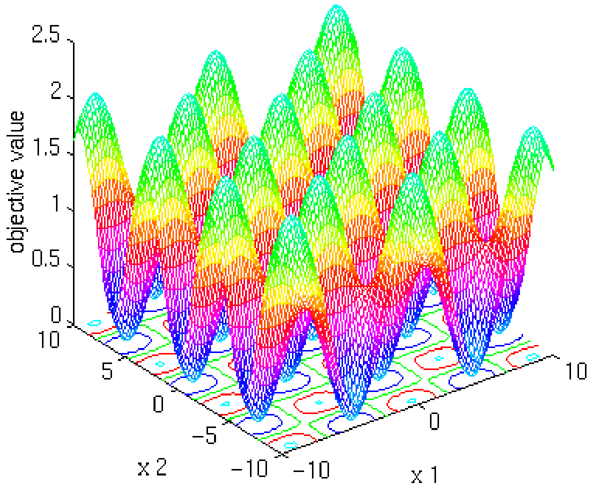
Enrique Alba

Parallel Experiences

Introduction: The Problem

- **Objective of a global optimization problem:**

$$f(\vec{x}) \rightarrow max: \quad find\ a\ vector\ \ \vec{x}^*$$
$$such\ that\ \forall \vec{x} \in M : f(\vec{x}) \leq f(\vec{x}^*) := f^*$$



- **Minimizing is also possible**
- **Vectors can map to other data structures**

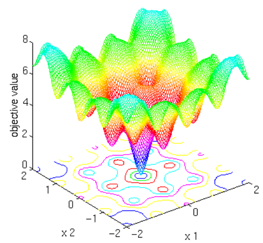
Index

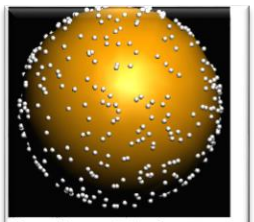
Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

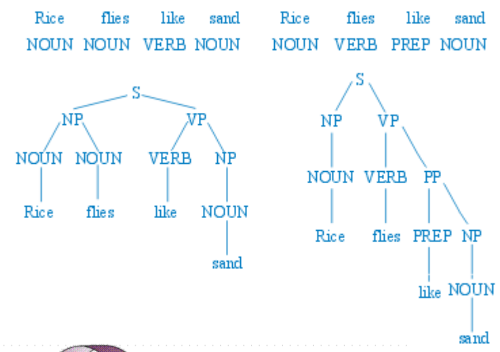
Parallel Experiences

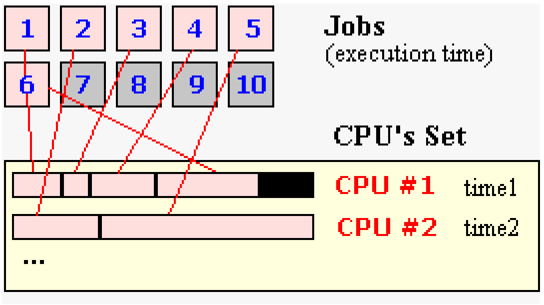
Introduction: Real-World Problems

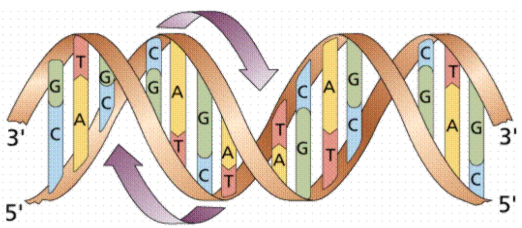
Where can optimization problems be found?

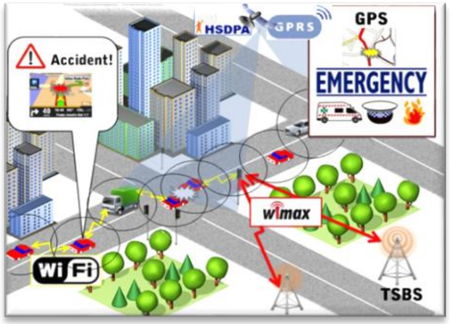



Distribute "n" electrons on a sphere









Index

Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

Parallel Experiences

Index

- **Introduction**
- Facts in PO Research
- Software and PO
- Applications
- Case Studies
- Summary

Introduction: Taxonomy of Optimization Algorithms

Optimization Algorithms

- **Exact**
  - **Calculus**
    - **Direct**
      - Newton
      - Greedy
    - **Indirect**
  - **Enumerative**
    - DP
    - B&B
- **Ad-hoc Heuristic**
- **Metaheuristic**
  - **Trajectory**
    - SA
    - VNS
    - TS
  - **Population**
    - EA
    - ACO
    - PSO

• nature inspired in red

Parallel Experiences

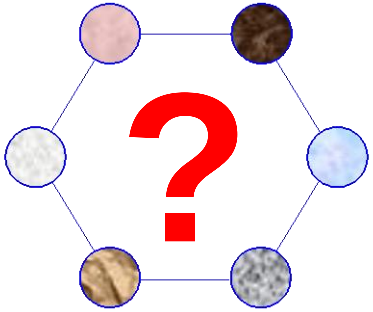
Index

- Introduction
- Facts in PO Research
- Software and PO
- Applications
- Case Studies
- Summary

Introduction: Parallel Algorithms for Optimization

- **Basic components of parallel algorithms are:**
  - **Nodes performing separate search**
  - **Communication pattern among the nodes**
  - **Policy of the search (start, end, solution…)**

Ex1: Parallel ACO
- ACO nodes
- All to all
- Exchange pheromone matrix



Ex3: Parallel EA
- Subpops. of partial solutions
- Static ring
- Exchange random selected sols.

Ex2: Parallel SA
- SA nodes
- Random target
- Exchange actual best solution

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

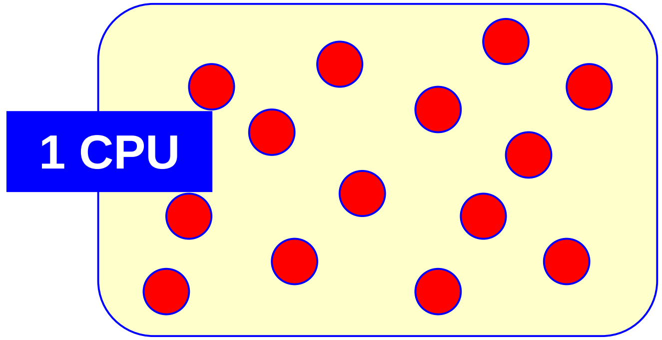
Applications

Case Studies

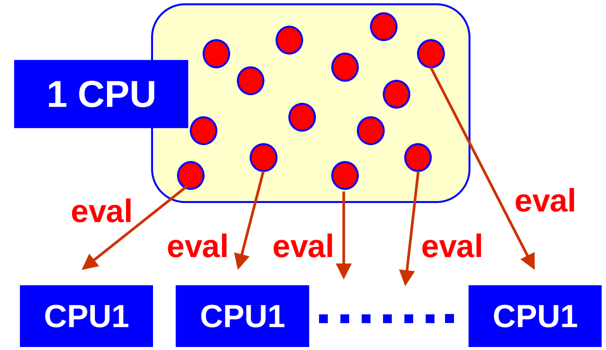
Summary

Introduction: Parallel Algorithms for Optimization

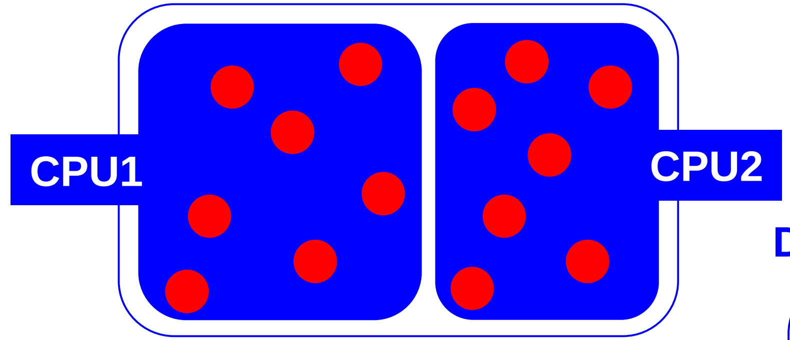
Centralized PSO in sequential



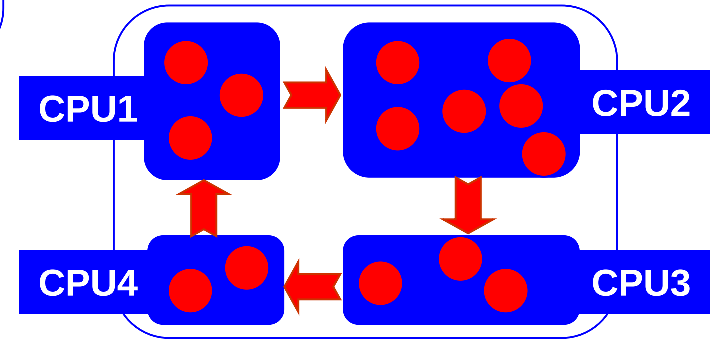
Centralized PSO in parallel M/S



Centralized PSO in parallel distribution



Decentralized PSO in parallel



Parallel models: example with PSO

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

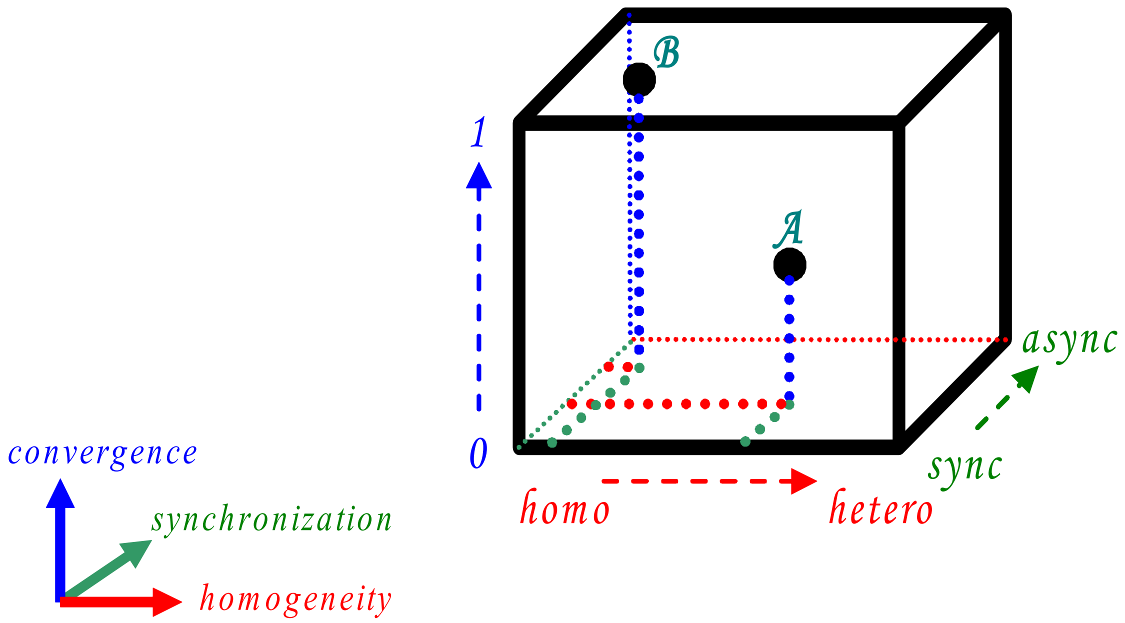
Applications

Case Studies

Summary

Introduction: Taxonomy

- **Three features:**



- **Other important issues are:**
  - **Node granularity**
  - **Central memory**
  - **Static/Dynamic features**
  - **…**

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Research with Parallel Algorithms

Working with parallel algorithms is far from trivial:

1. **Must know on concurrency and parallel theory**
2. **Must know on parallel software languages and tools**
3. **Must know on hardware realizations for communication**
4. **Must know on communication protocols and networks**
5. **Programming is more error prone than in sequential**
6. **A parallel algorithm is hard to analyze**
7. **After all the work, maybe you are not gaining in time**
8. **Many people just don’t want to know on parallel issues**
9. **...**

Parallel Experiences

Research with Parallel Algorithms

Index

- Introduction
- Facts in PO Research
- Software and PO
- Applications
- Case Studies
- Summary

...but it is worthwile!

Problems not solved before become now solvable by using parallel algorithms

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Facts in Research with Parallel Algorithms

Facts in parallel optimization:

❶ **Model and implementation are different**

❷ **Metrics need a revision**

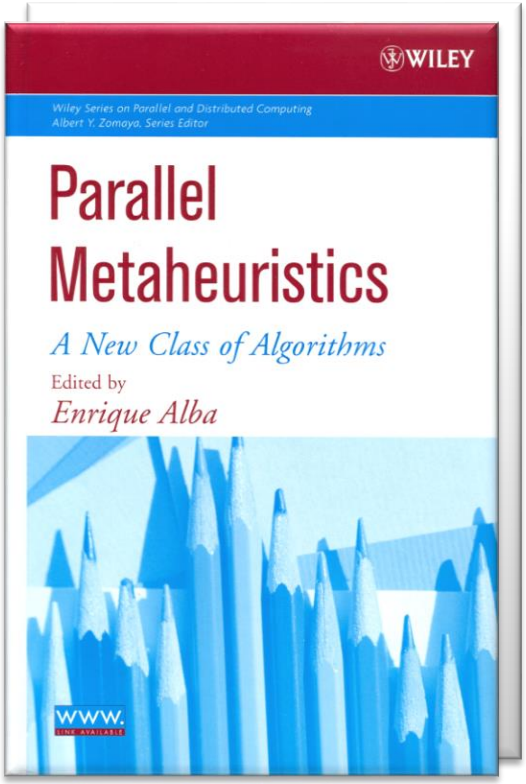
❸ **Superlinear speedup is a fact**

❹ **Heterogeneity is a must nowadays**

❺ **The experimental setup is important**

❻ **Algorithms are Software**

❼ **Other facts**



E. Alba,
Parallel Metaheuristics: A New Class of Algorithms
Wiley, ISBN 0-471-67806-6, July 2005

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

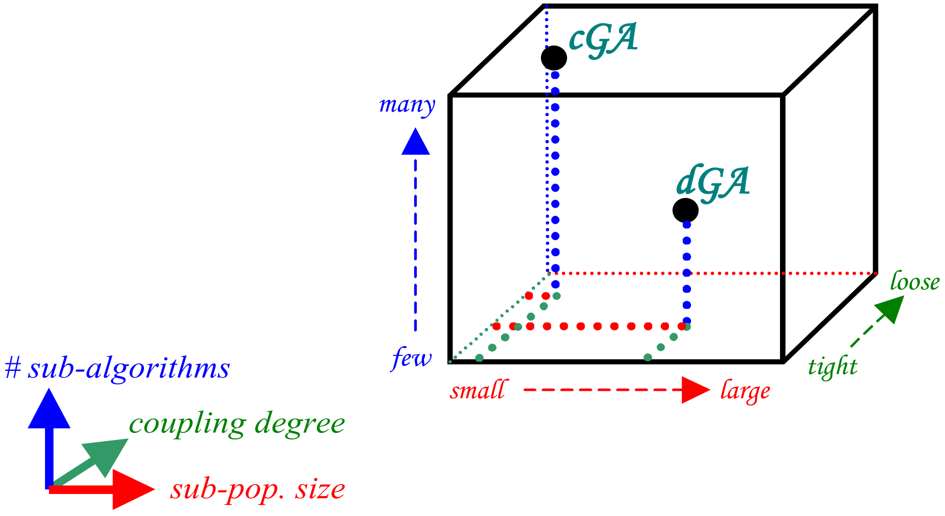
Case Studies

Summary

Fact 1: Model and Implementation are Different

Node in a decentralized EA

① Generate initial population
② Evaluate present evaluation
③ While not stop criterion do:
    ③① Select partners
    ③② Apply variation operators
    ③③ Communication with neighbors
    ③④ Replace old solutions by the new ones
    ③⑤ Compute statistics and performances



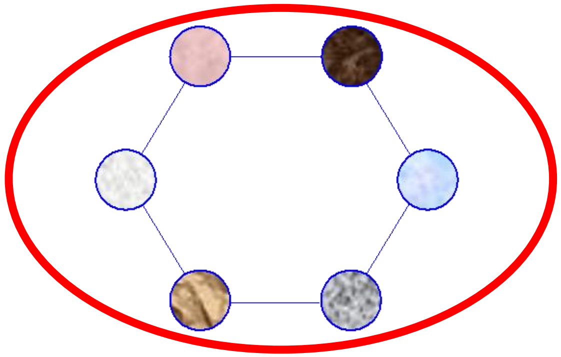
Parallel Experiences

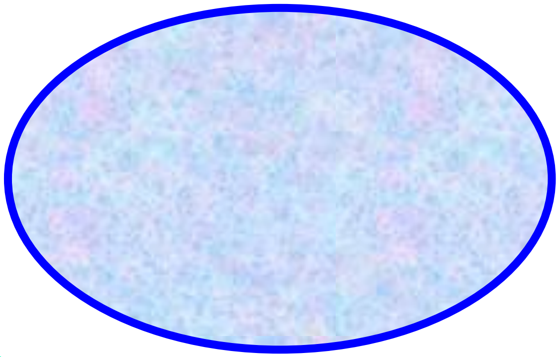
Index

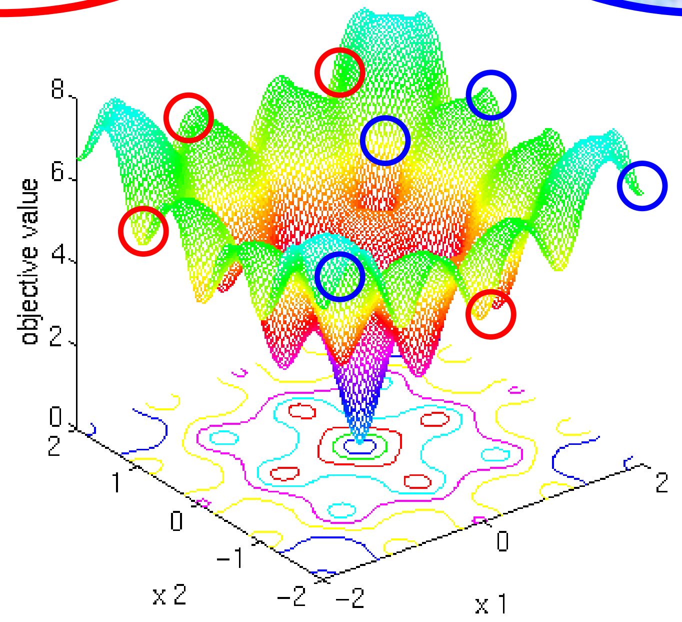
Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

Fact 1: Model and Implementation are Different

Decentralized Model **Centralized Model**







Parallel Experiences

Index

Introduction

Facts in PO Research

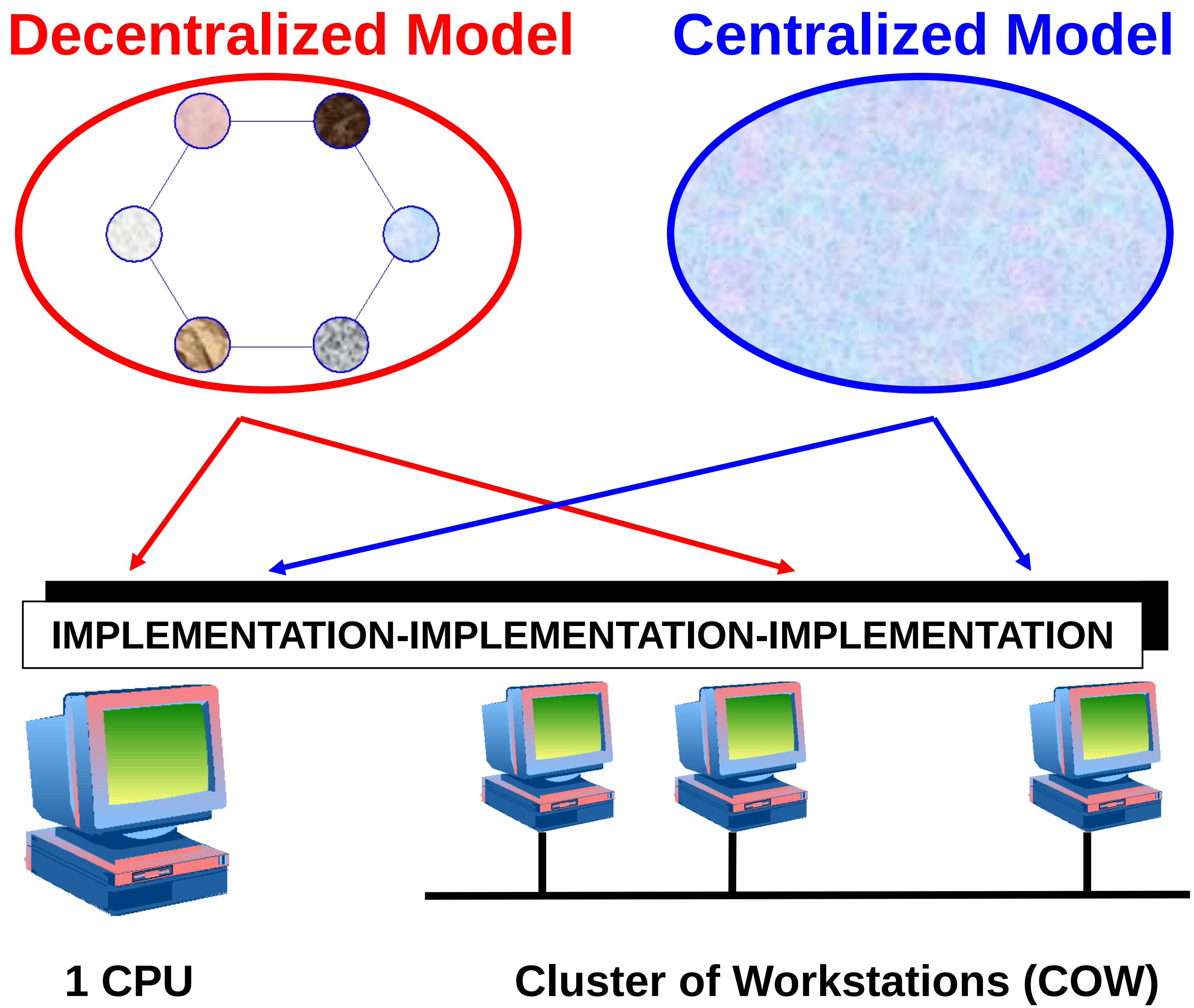
Software and PO

Applications

Case Studies

Summary

Fact 1: Model and Implementation are Different



Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Fact 2: Metrics Need a Revision

- Exact and approximate algorithms could be different algorithms when run in parallel
- Specially, parallel heuristic algorithms can stop at solutions of different quality
- Comparing times against the sequential version could be meaningless if the two algorithms are not exactly the same or the final computed value is different in them
- A clear example is the speedup (efficiency)

A taxonomy is needed

Alba E. (2002) "Parallel EAs Can Achieve SuperLinear Performance". *Information Processing Letters*, Elsevier, 82(1):7-13

I. Strong Speedup

II. Weak Speedup

A. Speedup with solution-stop

1. Versus Panmixia

2. Orthodox ←

B. Speedup with predefined effort

$$s_m = \frac{\overline{T}_1}{\overline{T}_m}$$

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

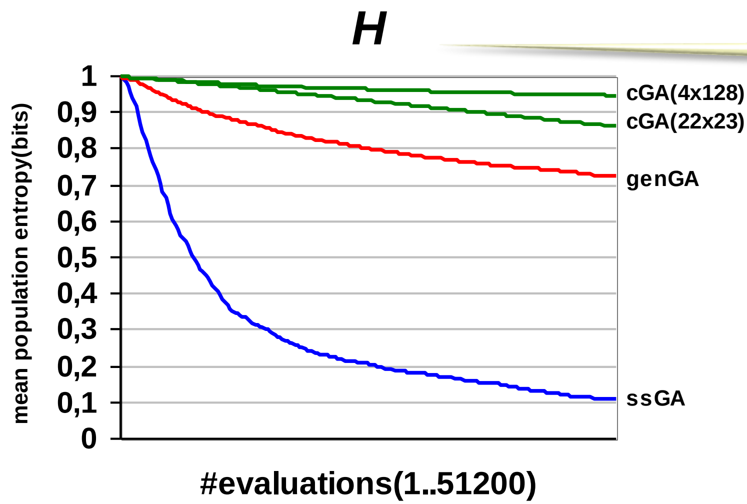
Case Studies

Summary

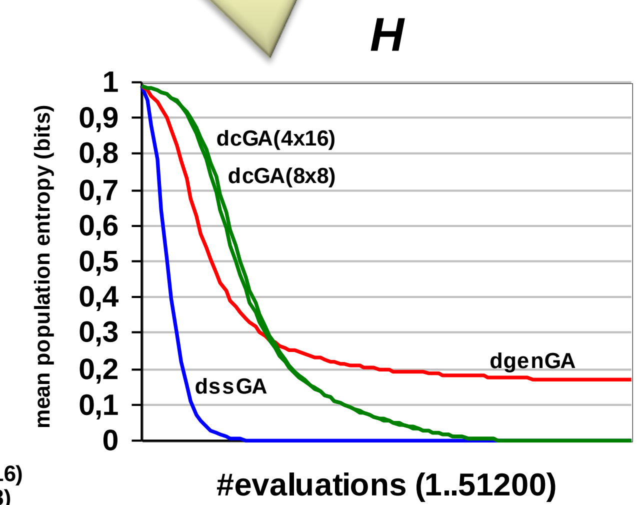
SPH16-32
8×64 individuals
DPX1(p_c=1.0)
MUT(p_m=1/l)

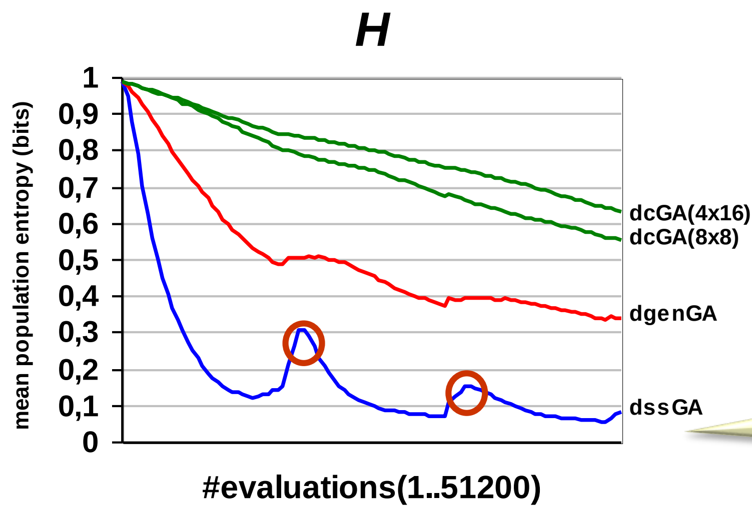
Fact 2: Advanced Metrics (Entropy)

Non Distributed



Distributed Sync (ζ=1)





Distributed Sync (ζ=32)

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

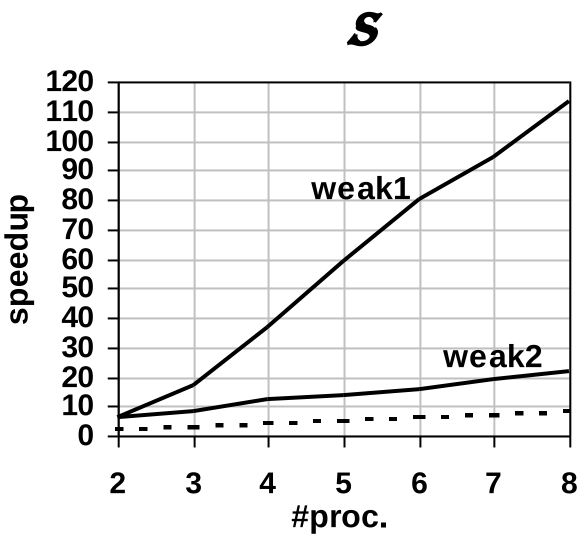
Summary

Fact 3: Superlinear Speedup is a Fact

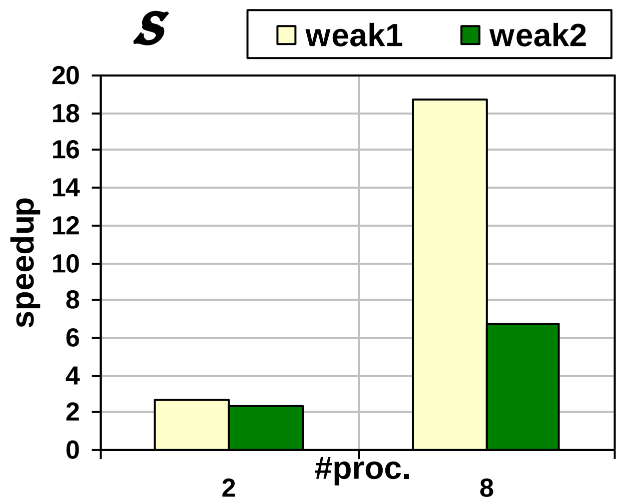
$$s(n_{proc}) = \frac{\bar{T}_1}{\bar{T}_{n_{proc}}}$$

weak1: against panmixia (1 proc)

weak2: only changing n_{proc}



SPH16-32



SSS128

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

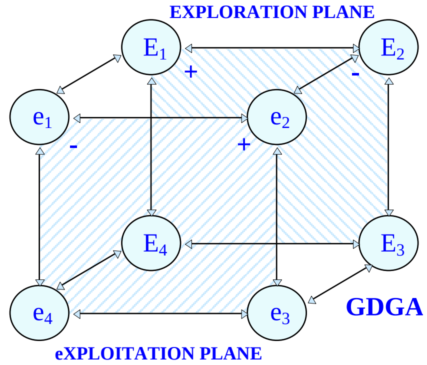
Applications

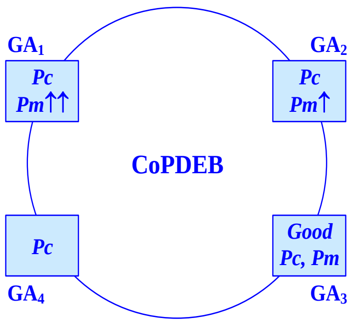
Case Studies

Summary

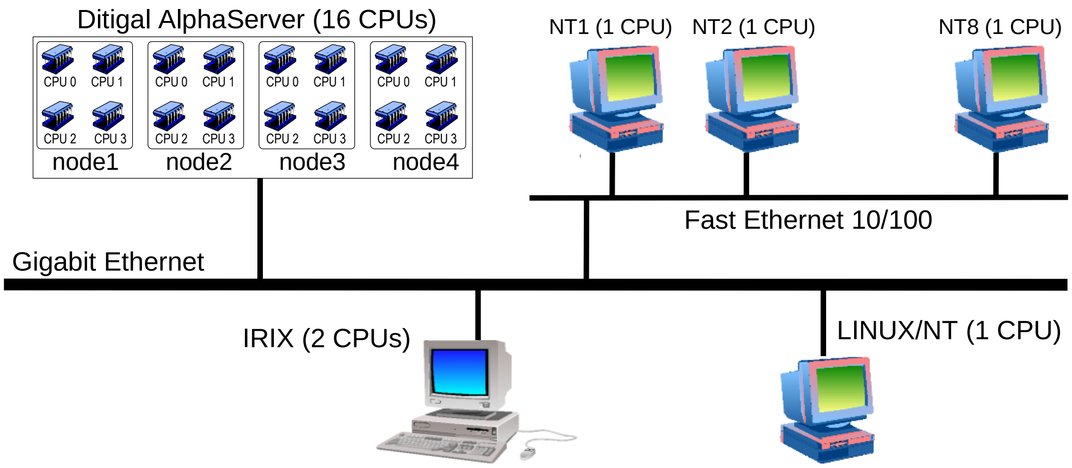
Fact 4: Heterogeneity is a Must Nowadays

Algorithmic components could be heterogeneous

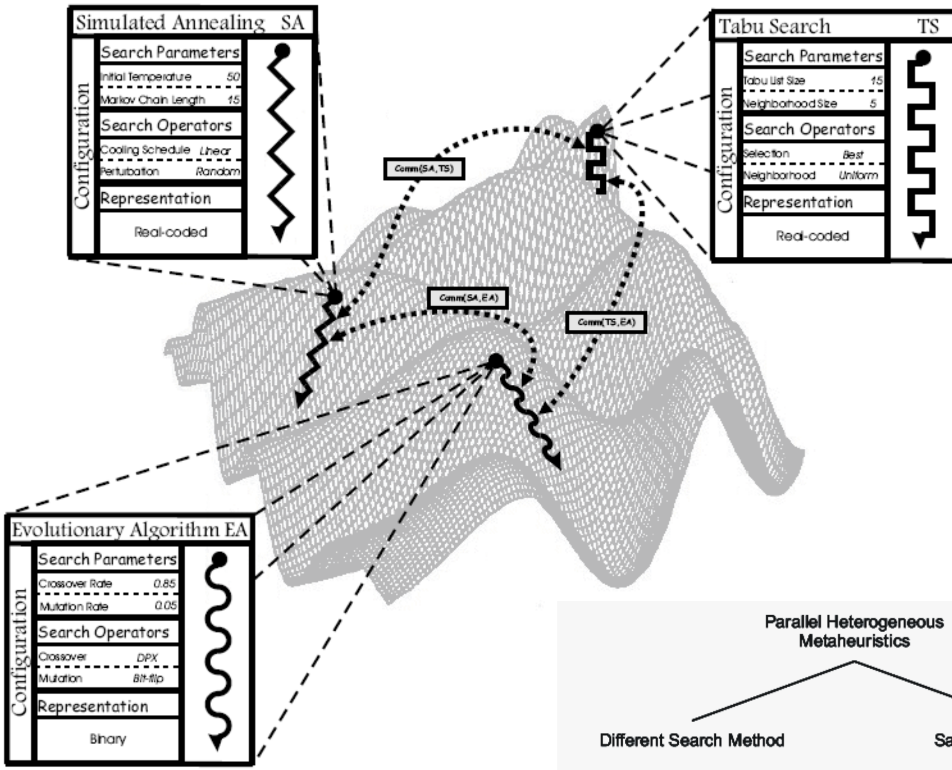


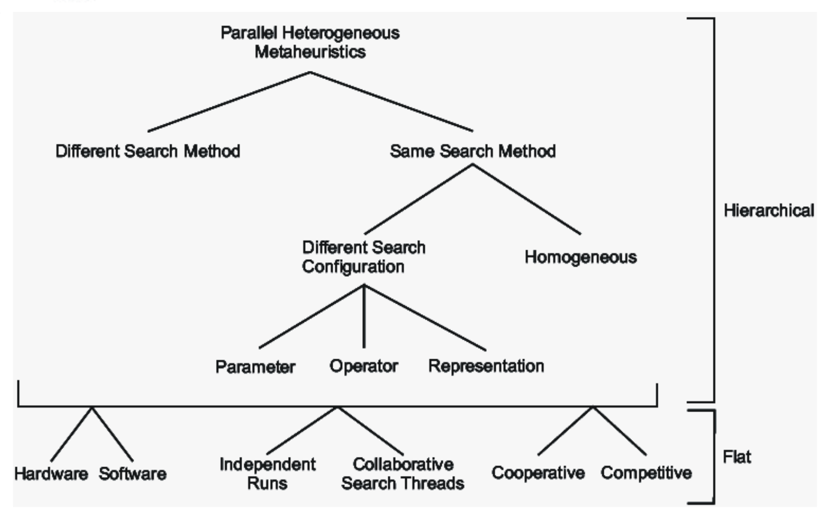


Parallel hardware could be heterogeneous



Fact 4: Heterogeneity is a Must Nowadays





Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Fact 5: The Experimental Setup is Important

Parallel heuristic/exact methods have often nondeterministic behaviors, so:

1. **Multiple independent runs are necessary**
2. **Statistical hypothesis tests must be used: Student t-test, ANOVA, Wilcoxon, …**
3. **Average, max and min values need to be reported, but: is that all?**
4. **Advises: more than 30 ind. runs, give all the parameters in one table, always report on times, give hardware and software used, …**

Parallel Experiences

Index

Introduction

Facts in PO Research

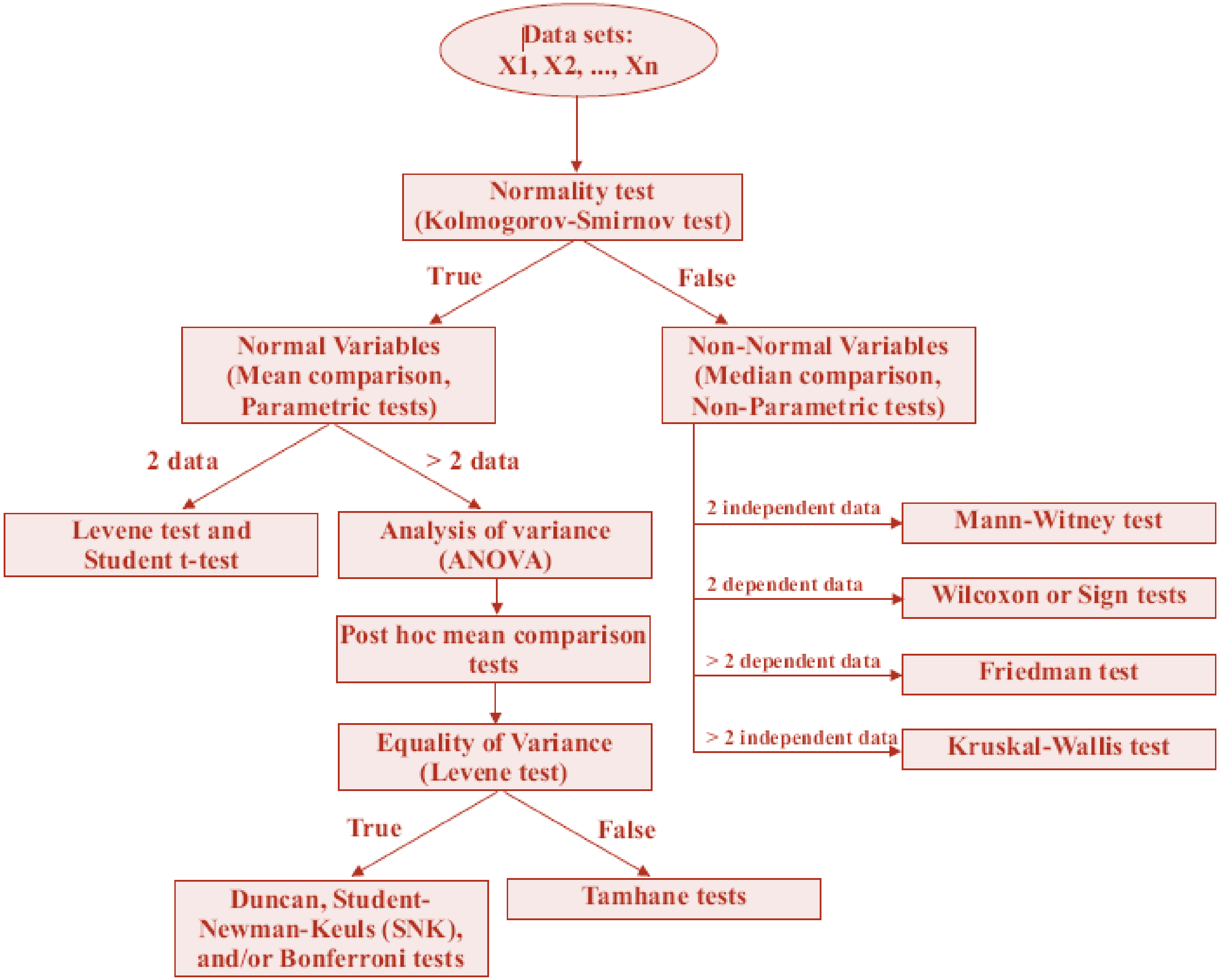
Software and PO

Applications

Case Studies

Summary

Fact 5: The Experimental Setup is Important: Guidelines



Fact 6: Algorithms Are Software

We should worry about the design of algorithms

- **At the end, they are software pieces (!)**
- **Take care of the design and take care of the documentation**
- **Efficiency is usually the more important issue**

Traditional tools

- **Fortran, C, Java, Lisp, ...**
- **Generalization is in conflict with efficiency**
- **Apply well-accepted recomms. on GOTO, global vars, ...**

Object Orientation

- **Present best issue (long term development and design)**
- **Efficiency can be modulated**
- **Parallel software tools are developed nowadays**
- **Java versus C++**

Alba E., Troya J.M., Gaining New Fields of Application for OOP: the Parallel Evolutionary Algorithm Case, *The Journal of Object-Oriented Programming*, December 2001

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

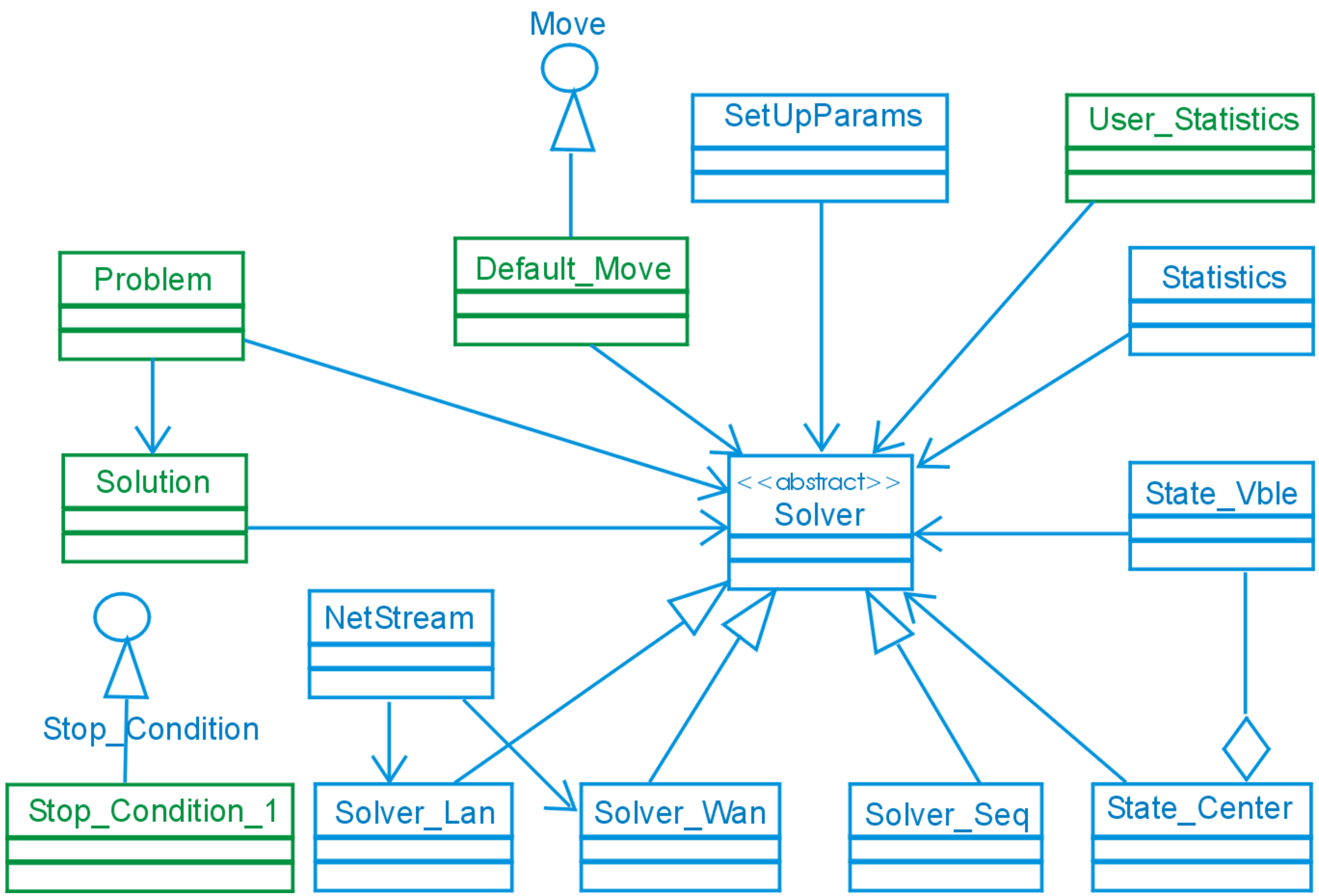
Summary

Parallel Experiences

Index

Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

Fact 6: Algorithms Are Software



MALLBA
http://neo.lcc.uma.es

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

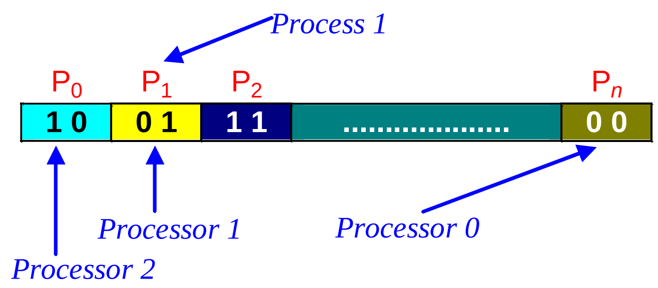
Applications

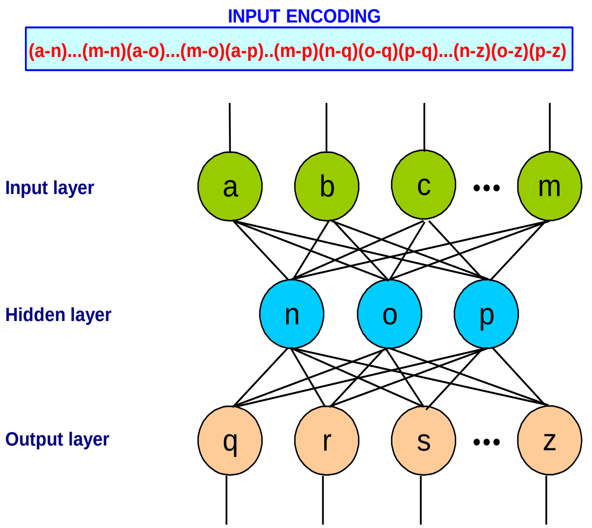
Case Studies

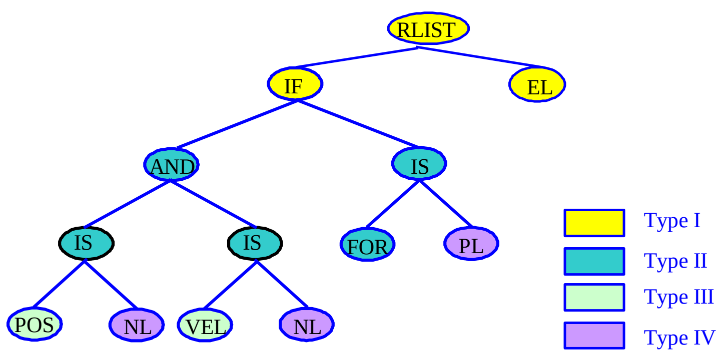
Summary

Fact 6: Algorithms Are Software

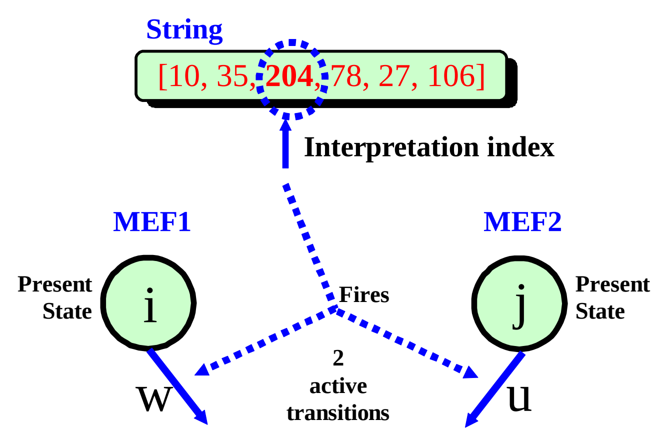
Complex Data Structures for Complex Problems







IF *pos* IS NL AND *vel* IS NL THEN *for* IS PL



Parallel Experiences

Other Facts

- **Theory is hard but important:** **convergence, time complexity, landscape theory, …**
- **Knowledge exchange between fields helps:** **developing common frameworks for grid algorithms, exact and heuristic issues, …**
- **Parallel algorithms are not always better:** **communication overhead, numerical search could progress slowly, …**
- **Be always ready for new facts!**

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Software for Parallelism

There exist multiple software tools to develop parallel applications:

- **Low level tools: Sockets, …**
- **High Level Comm Libraries: PVM, MPI, …**
- **Language Embedded: Java RMI, …**
- **Middleware: CORBA, MANIFOLD, MR, …**
- **Metacomputing Systems: Globus, Condor, BOINC, …**
- **Related to Internet: .NET, SOAP, XML, …**
- **Platform specific: CUDA, OpenCL, Handle C, …**
- **Others: OpenMP, HPF, …**

Parallel Experiences

Our Software

http://neo.lcc.uma.es/software/index/

Index

Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

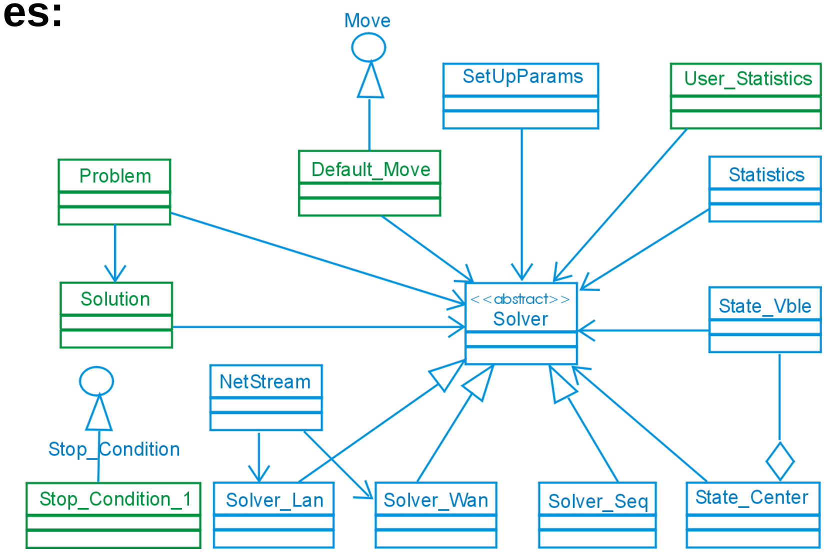
Case Studies

Summary

MALLBA

- **Library for complex optimization problems**
  - **3 types of techniques:**
    - **Exact**
    - **Heuristic**
    - **Hybrid**
  - **3 implementations:**
    - **Sequential**
    - **LAN**
    - **WAN**

UML design of SA in MALLBA



- **Goals:**
  - **Wide genericiy but low effort of instantiation**
  - **Simplified utilization (no parallel skills needed)**
  - **Geographically distributed computing systems**

E. Alba, et al., MALLBA: A Library of Skeletons for Combinatorial Optimisation, *Proceedings of the Euro-Par*, Paderborn (GE), LNCS 2400, pp. 927-932, 2002

Parallel Experiences

Index

Introduction

Facts in PO Research

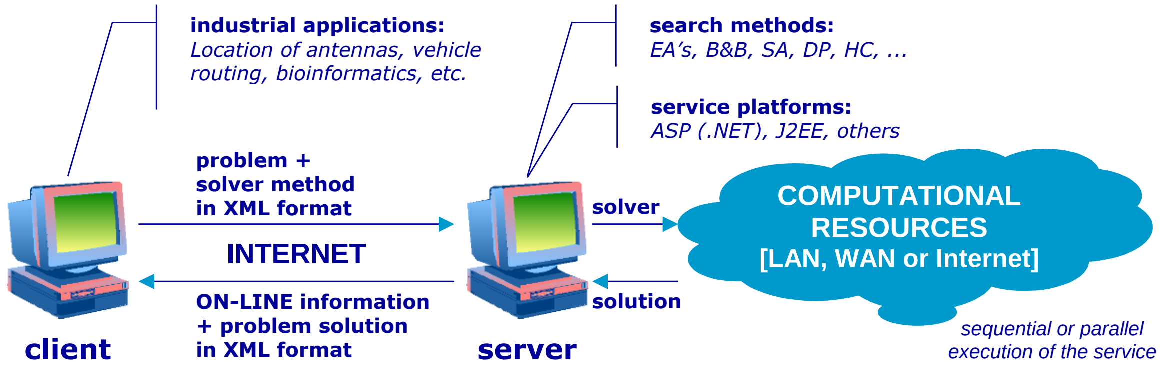
Software and PO

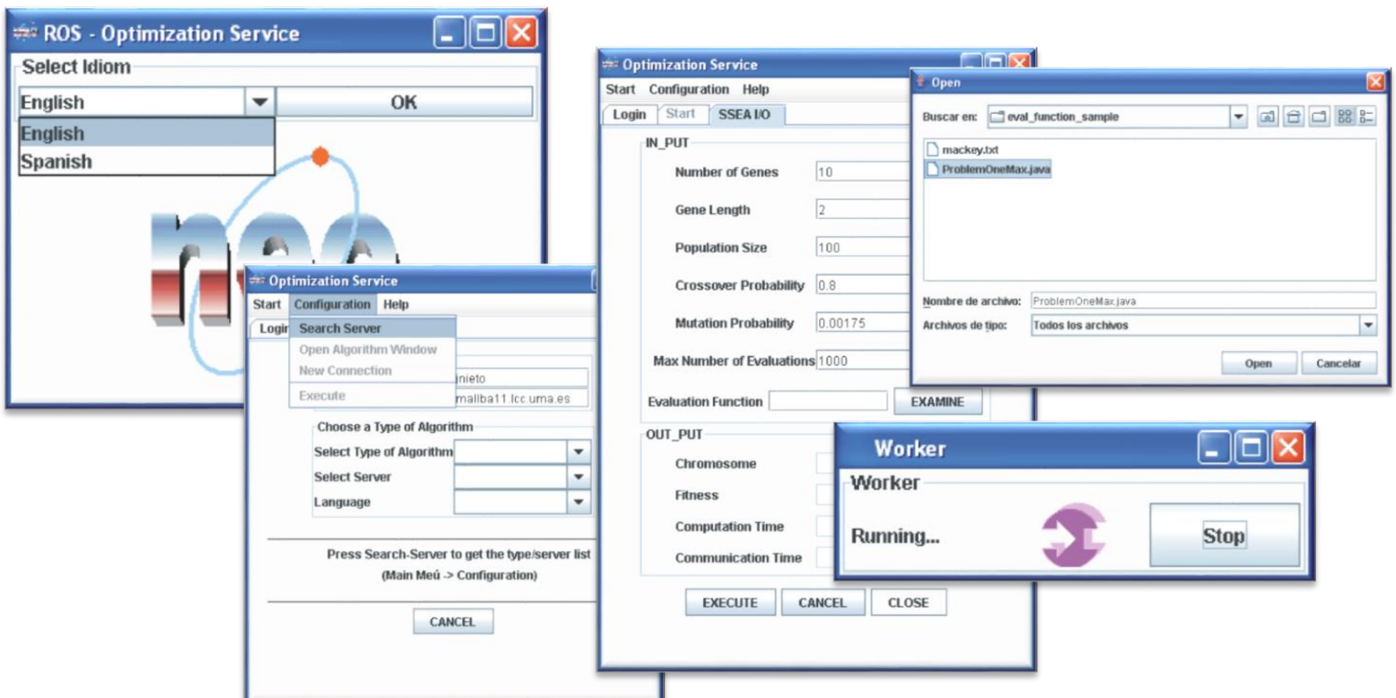
Applications

Case Studies

Summary

R.O.S.





Parallel Experiences

Function Optimization

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Generalized Sphere Function

$$f_{SPH}\left(x_i\big|_{i=1..n}\right)=\sum_{i=1}^{n} x_i^2 \qquad x_i \in [-5.12, 5.12]$$

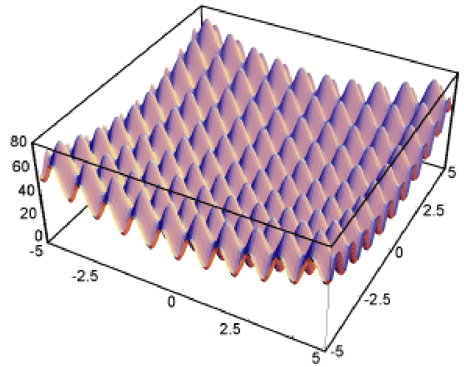
Rosenbrock's Function

$$f_{ROS}(x_i\big|_{i=1..n}) = \sum_{i=1}^{n-1} 100\cdot\left(x_{i+1}-x_i^2\right)^2+\left(x_i-1\right)^2 \qquad x_i \in [-5.12, 5.12]$$

Domain Dependent Benchmarks

Typical benchmarks for every domain: multiobjective, temporal series, data mining, neural network training, etc.

Rastrigin



CEC 05/08/10, GECCO 09…

$$f_{RAS}(x_i\big|_{i=1..n}) = 10\cdot n+\sum_{i=1}^{n} x_i^2 - 10\cdot\cos(2\cdot\pi x_i)$$

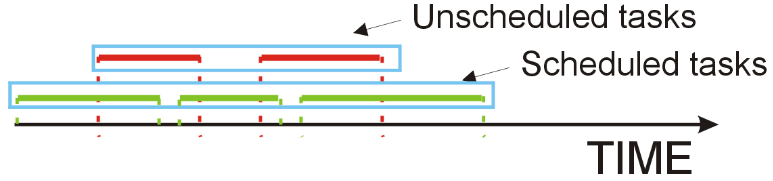
$$x_i \in [-5.12, 5.12]$$

Index

Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

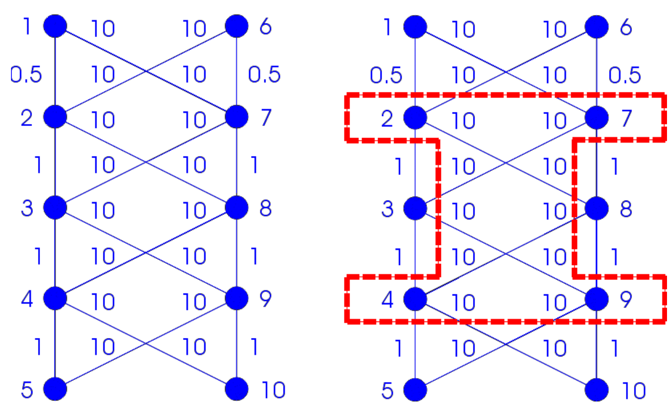
NP-hard Problems (I)

Minimum Tardy Task Problem (MTTP)



Maximum Cut Problem (MaxCut)

- **Partitioning a weighted graph with "*maxicum cut*"**
- **100 vertices (MaxCut100)**



Parallel μCHC

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

NP-hard Problems (II)

Satisfiability Problem (MAXSAT)

Goal: Find a feasible assignment for boolean variables

Fitness Function:

$$fitness = \frac{\sum_{i=1}^{m} true(C_i)}{m}$$

Example:

Can theory guide a PEA?

$$(\neg A \vee B \vee C) \wedge (\neg B \vee C \vee D) \wedge (A \vee \neg D \vee E) \wedge (C \vee \neg D \vee \neg E)$$

Clauses (*m*): 4

Variables per Clause (*k*): 3

	A	B	C	D	E
Variables (*n*): 5					
Unfeasible Assigment:	1	1	0	1	1
Feasible Assigment:	1	1	1	0	1

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

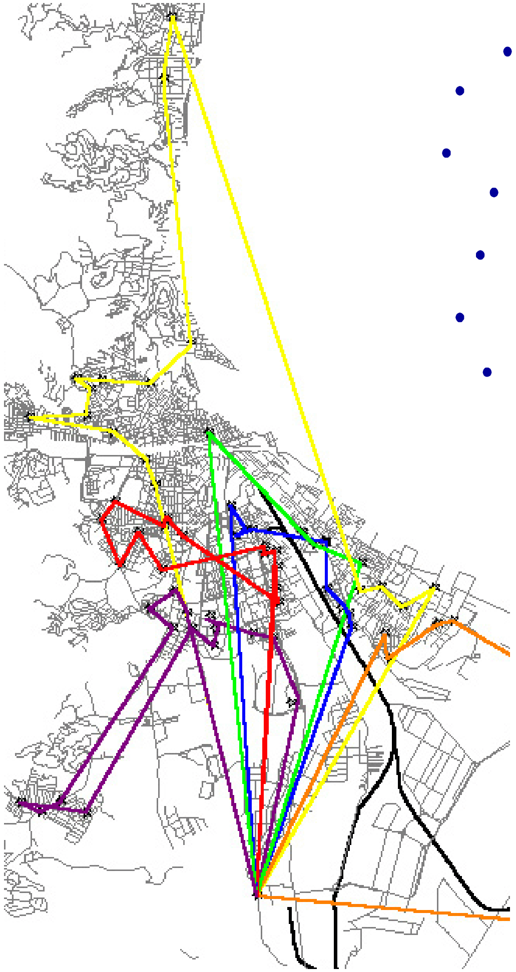
Applications

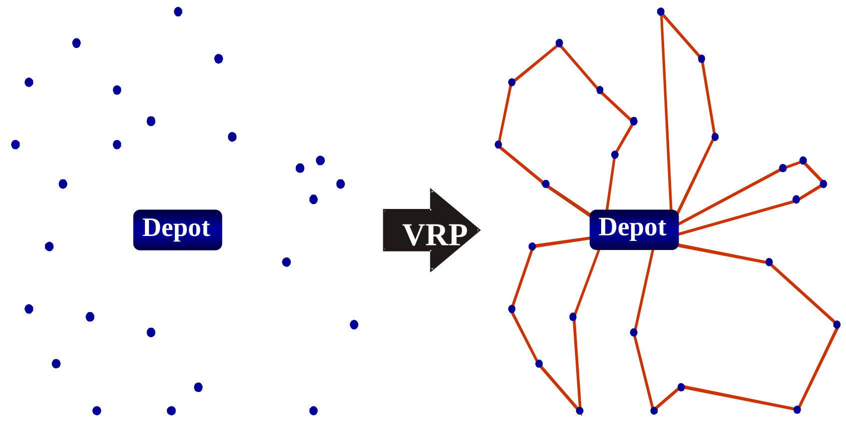
Case Studies

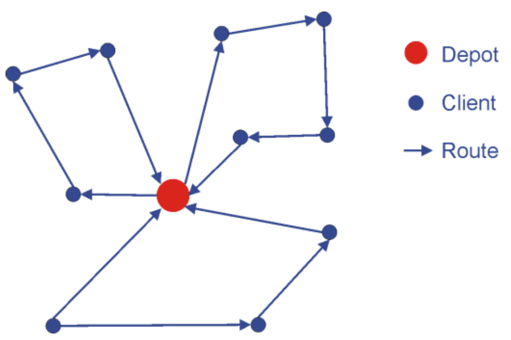
Summary

NP-hard Problems (III)

Vehicle Routing Problem (VRP)







GPUs can boost COP !!!

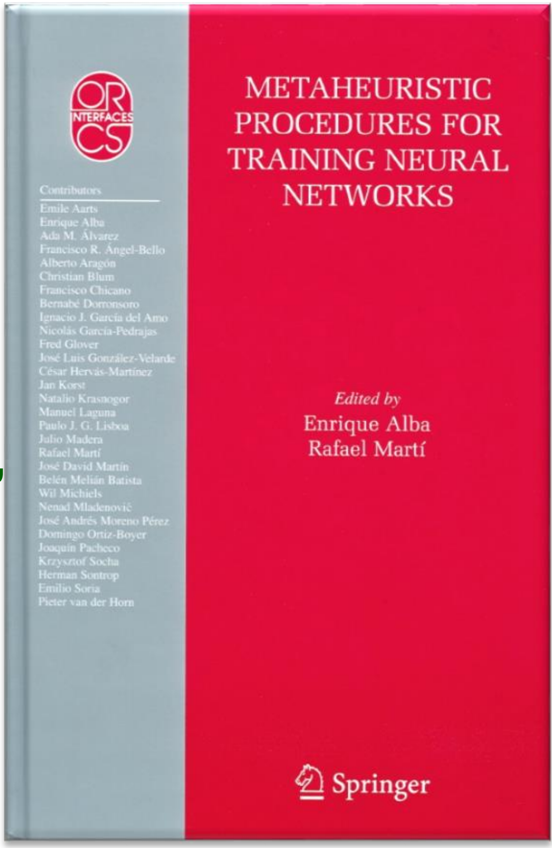
Index

Introduction
Facts in PO Research
Software and PO
Applications
Case Studies
Summary

Training Neural Networks

Training

Minimizing the error between expected and actual values. Both, classification and prediction are possible applications



Structure Optimization

OPTIMUM LINKAGE

Minimizing the number of links

OPTIMUM LAYER DESIGN

Optimizing the number of layers, neurons per layer and transfer functions in neurons

Pattern Filtering

Find the minimum number of patterns

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

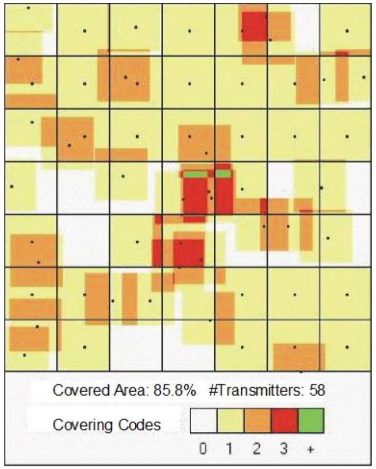
Applications

Case Studies

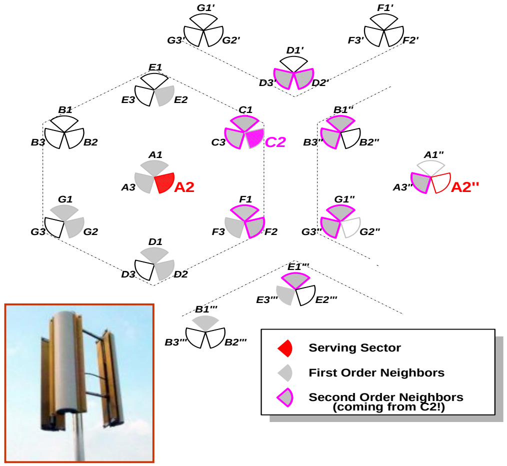
Summary

Telecommunications

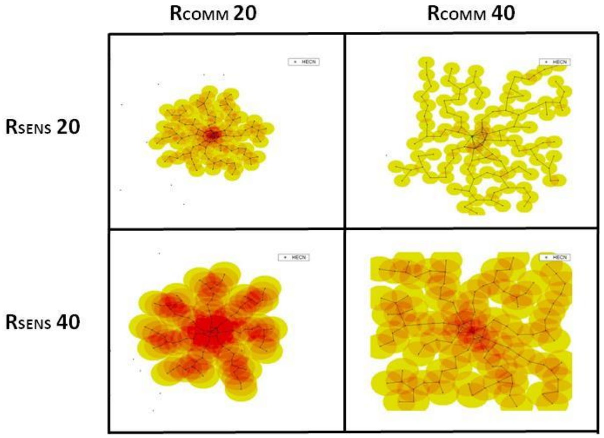
Radio Network Design



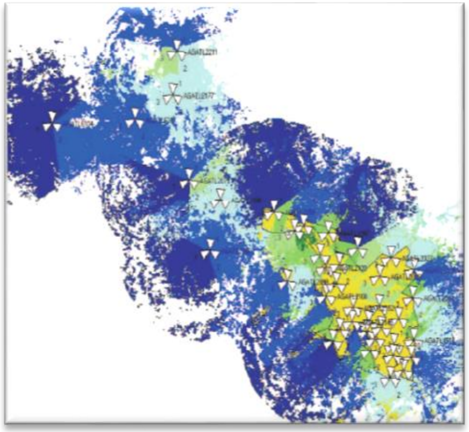
GSM Frequency Assignment



Sensor Network Layout



Location Area in 2G/3G



Parallel Experiences

Index

Introduction

Facts in PO Research

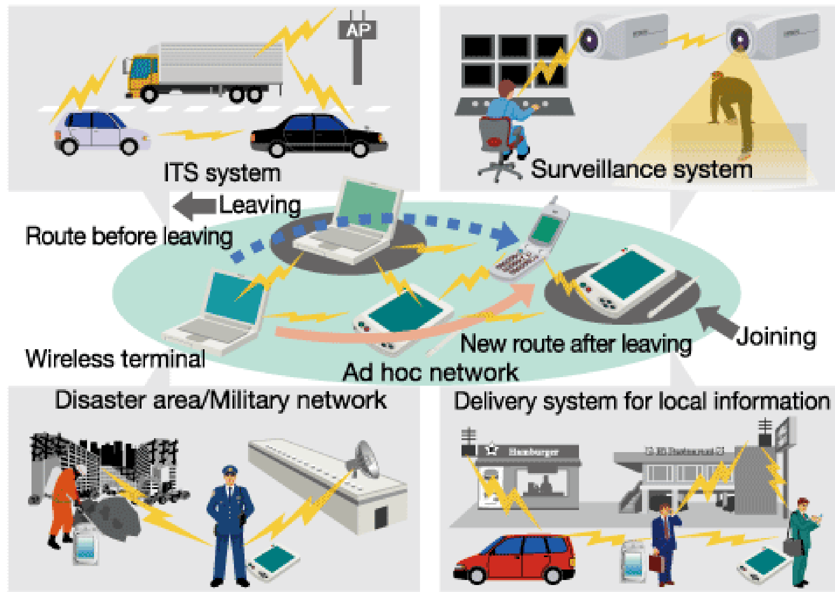
Software and PO

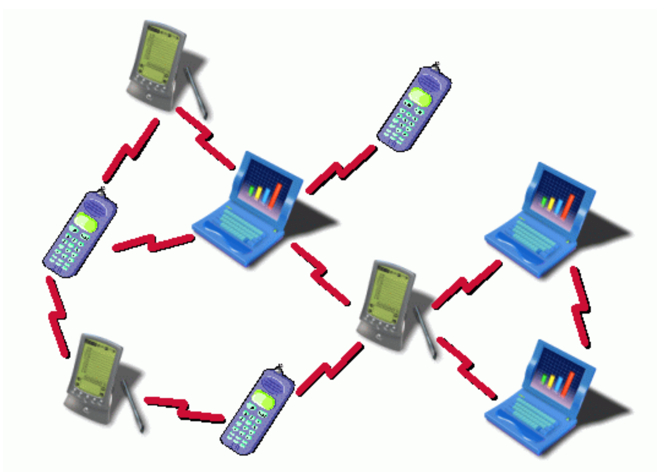
Applications

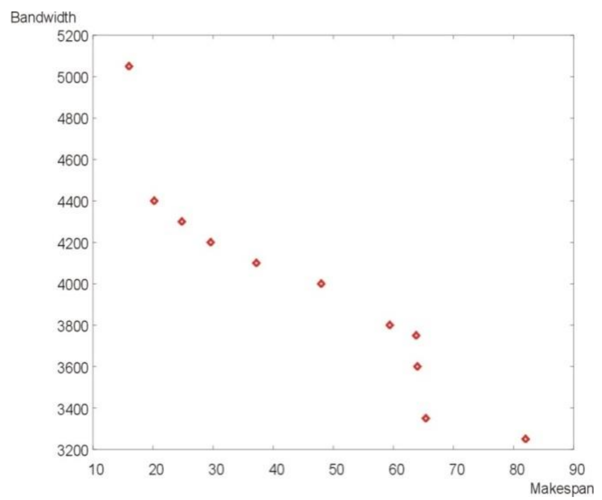
Case Studies

Summary

MANETs







Parallel Experiences

VANETs

http://diricom.lcc.uma.es

Information Dissemination

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

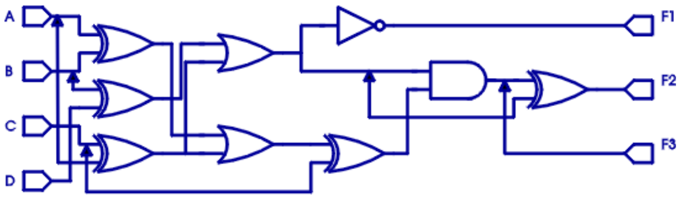
Applications

Case Studies

Summary

Miscellaneous

Designing VLSI Circuits



Data Based (Data Mining, Query Optimization)

Dynamic Optimization Problems (DOP)

Tasks Scheduling in Operating Systems

Genomics (Fragment assembly, protein structure)

Games:
Master Mind,
Unreal Tournament, ...

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Globus and Multiobjective: First Case Study

$$
\begin{array}{lll}
\text{Optimize} & f_m(\vec{x}) & m = 1, 2, \ldots, m \\
\text{Subject to} & g_j(\vec{x}) \geq 0 & j = 1, 2, \ldots, j \\
 & h_k(\vec{x}) = 0 & k = 1, 2, \ldots, k
\end{array}
$$

a	2	3	4	5
b	4	6	5	7

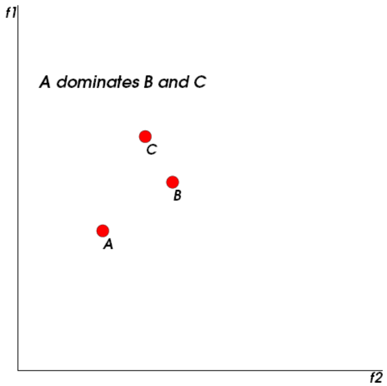
a	3	7	4	8
b	2	1	2	5

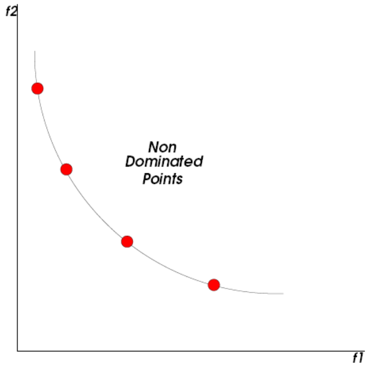
A is better than B

B is better than A

a	1	9	4	5
b	3	6	5	7

None is better





Parallel Experiences

Globus and Multiobjective: First Case Study

Base pseudocode of the enumerative algorithm

```
F[M] = {F1, F2, ..., FM} // Objective functions
R[C] = {R1, R2, ..., RC} // Constraints
x[N] = {x1, x2, ..., xN} // Decision variables
f[M] = {f1, f2, ..., fM} // Function values
P = ∅ // Set of non-dominated solutions

Fix the discretization degree G of the decision variables
For each vector x[i]
  If x[i] satisfies the constraints R[C]
    f[j] = evaluation of x[i] by F[M]
    Compare f[j] with members of P for dominance
    If f[j] is a non-dominated solution
      Add f[j] to P
    Remove the solutions dominated by f[j] from P
```

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Index

Introduction

Facts in PO Research

Software and PO

Applications

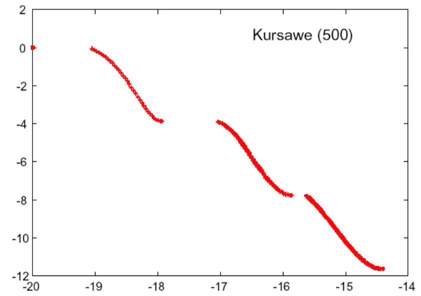
Case Studies

Summary

Globus and Multiobjective: First Case Study

Kursawe

$$\text{Min}\, F = (f_1(\vec{x}), f_2(\vec{x}))$$
$$f_1(\vec{x}) = \sum_{i=1}^{n-1}\left(-10e^{\left(-0.2*\sqrt{x_i^2+x_{i+1}^2}\right)}\right)$$
$$f_2(\vec{x}) = \sum_{i=1}^{n}\left(|x_i|^a + 5\sin(x_i)^b\right)$$



$-5 \leqslant x_i \leqslant 5$

$i = 1, 2, 3$

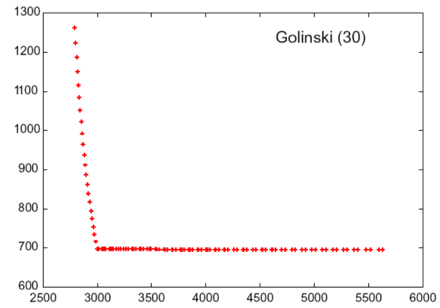
$a = 0.8$

$b = 3$

Golinski

$$\text{Min}\, F = (f_1(\vec{x}), f_2(\vec{x}))$$

$$f_1(\vec{x}) = 0.7854x_1x_2^2(10x_3^2/3 + 14.933x_3 - 43.0934)$$
$$-1.508x_1(x_6^2 + x_7^2) + 7.477(x_6^3 + x_7^3) + 0.7854(x_4x_6^2 + x_5x_7^2)$$
$$f_2(\vec{x}) = \frac{\sqrt{(745.0x_4/x_2x_3)^2 + 1.69 * 10^7}}{0.1x_6^3}$$



$$\frac{1.0}{x_1x_2^2x_3} - \frac{1.0}{27.0} \leqslant 0;\ \frac{1.0}{x_1x_2^2x_3} - \frac{1.0}{27.0} \leqslant 0$$
$$\frac{x_4^3}{x_2x_3^2x_6^4} - \frac{1.0}{1.93} \leqslant 0;\ \frac{x_5^3}{x_2x_3x_7^4} - \frac{1.0}{1.93} \leqslant 0$$

$$x_2x_3 - 40 \leqslant 0;\ x_1/x_2 - 12 \leqslant 0$$
$$5 - x_1/x_2 \leqslant 0;\ 1.9 - x_4 + 1.5x_6 \leqslant 0$$
$$1.9 - x_5 + 1.1x_7 \leqslant 0;\ f_2(x) \leqslant 1300$$
$$\frac{\sqrt{(745.0x_5/x_2x_3)^2 + 1.575 * 10^8}}{0.1x_7^3} \leqslant 1100$$
$$2.6 \leqslant x_1 \leqslant 3.6;\ 0.7 \leqslant x_2 \leqslant 0.8$$
$$17.0 \leqslant x_3 \leqslant 28.0;\ 7.3 \leqslant x_4 \leqslant 8.3$$
$$7.3 \leqslant x_5 \leqslant 8.3;\ 2.9 \leqslant x_6 \leqslant 3.9$$
$$5.0 \leqslant x_7 \leqslant 5.5$$

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

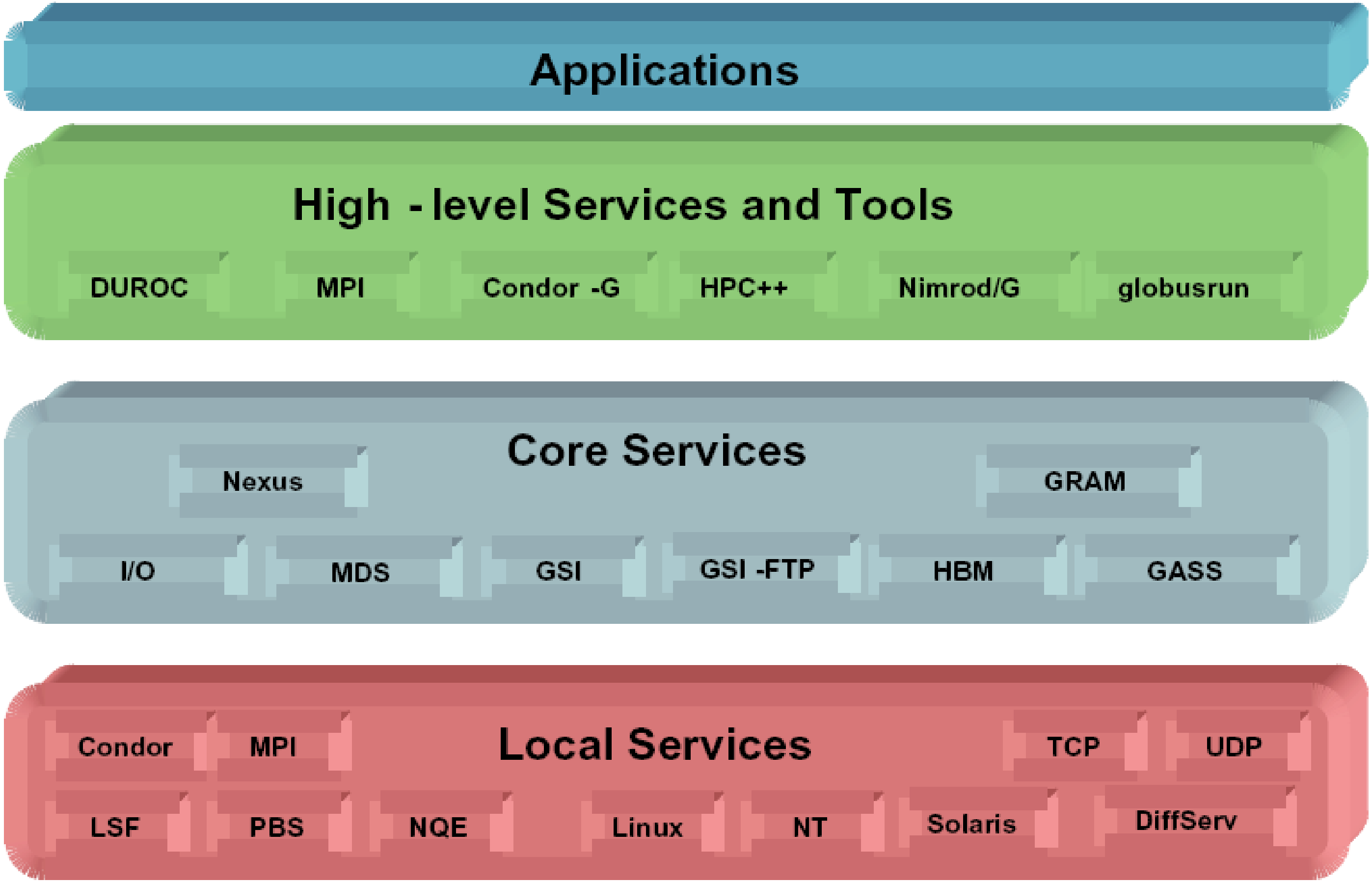
Applications

Case Studies

Summary

Globus and Multiobjective: First Case Study

GLOBUS LAYERED ARCHITECTURE



Parallel Experiences

Index

Introduction

Facts in PO Research

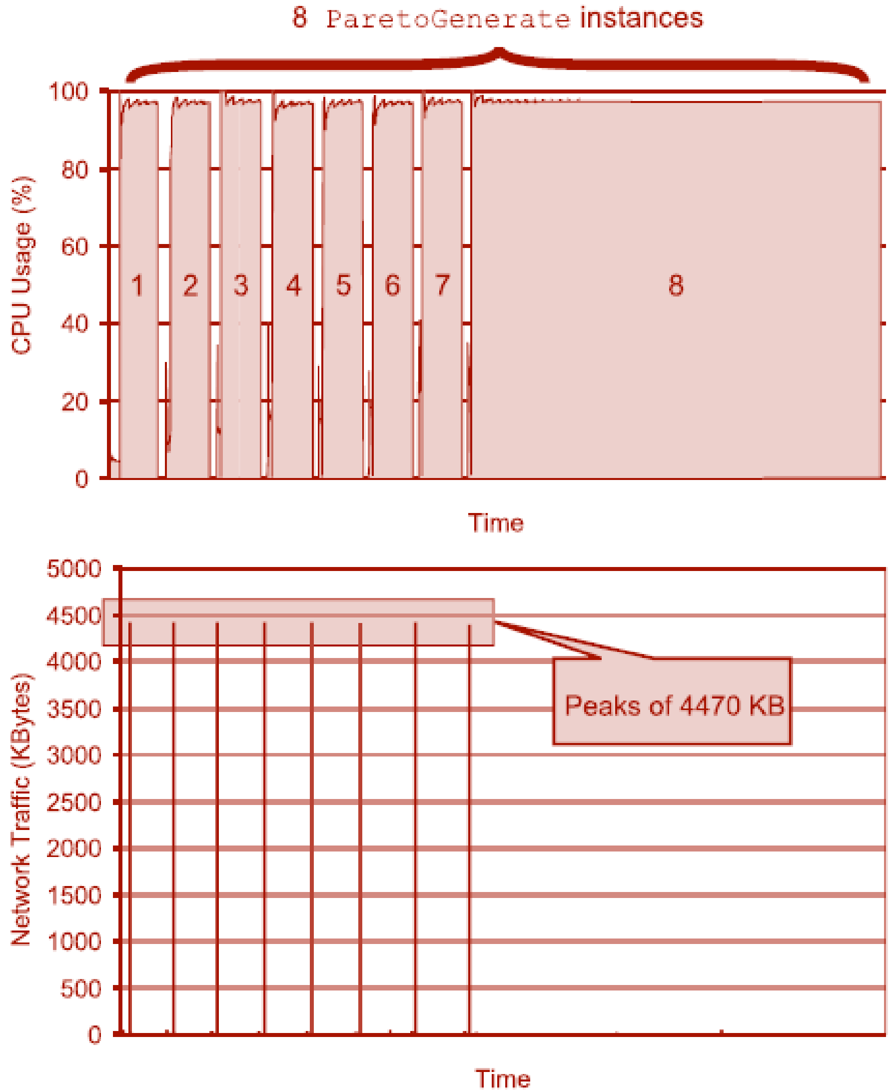
Software and PO

Applications

Case Studies

Summary

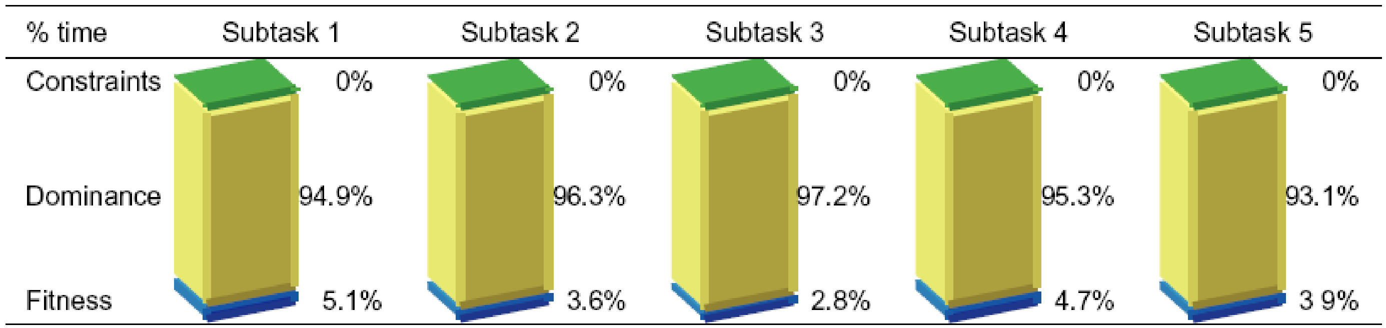
Globus and Multiobjective: First Case Study



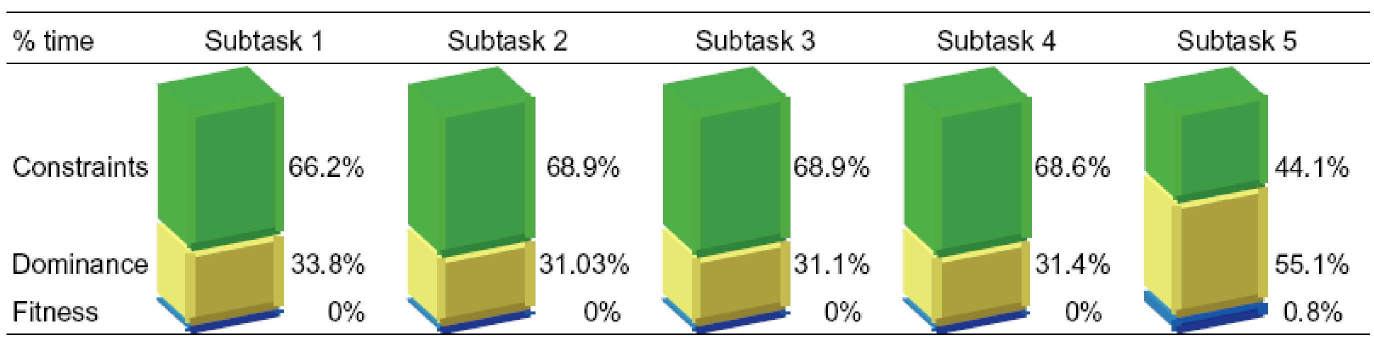
Parallel Experiences

Globus and Multiobjective: First Case Study

KURSAWE



GOLINSKI



Index

Introduction

Facts in PO Research

Software and PO

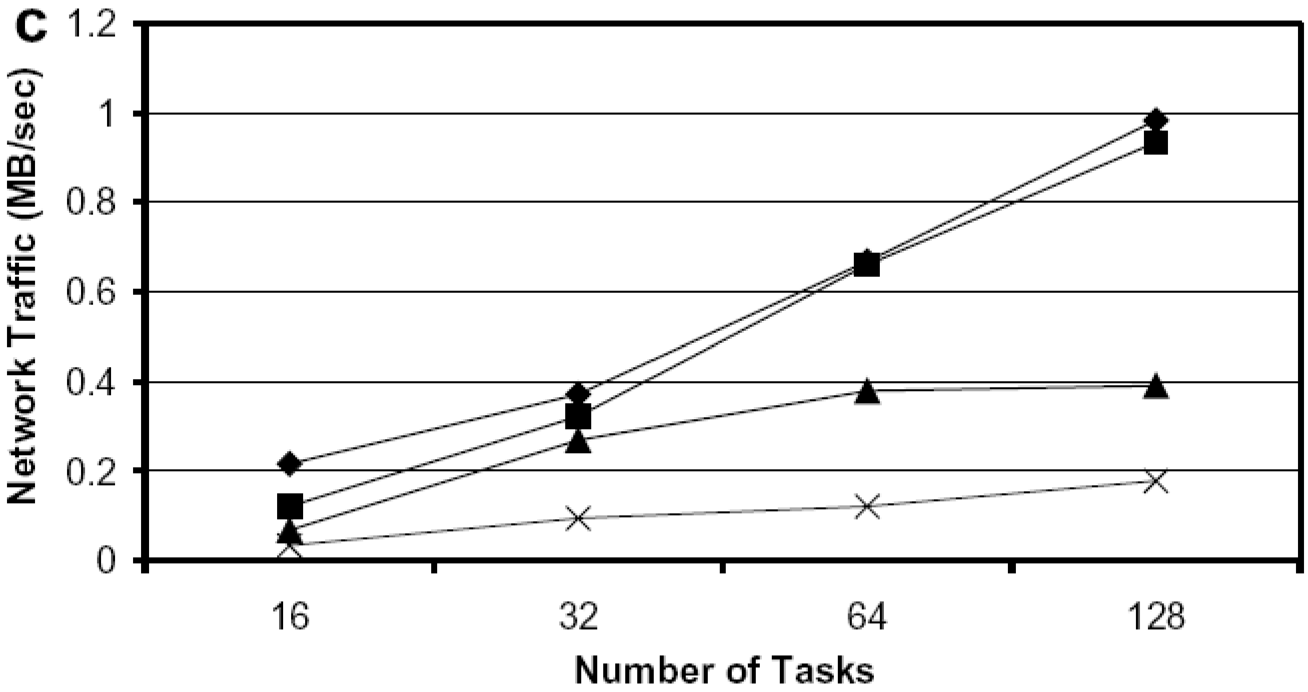
Applications

Case Studies

Summary

Parallel Experiences

Globus and Multiobjective: First Case Study



Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

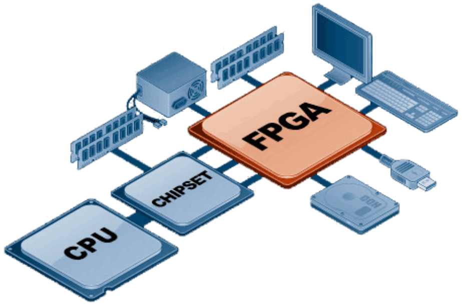
New Hardware: 2nd. Case Study

GPUs and Multicore systems are revitalizing the research in parallel algorithms

Grid and cloud computing

GPU

FPGA



multicore

Index

Introduction

Facts in PO Research

Software and PO

Applications

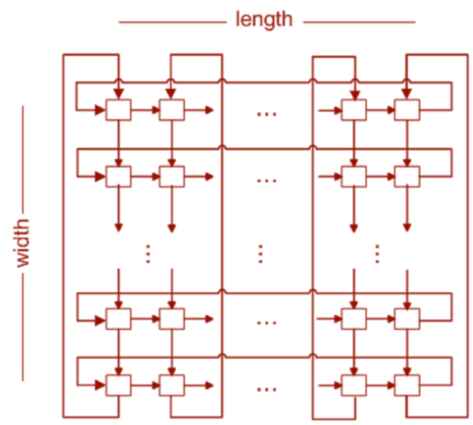
Case Studies

Summary

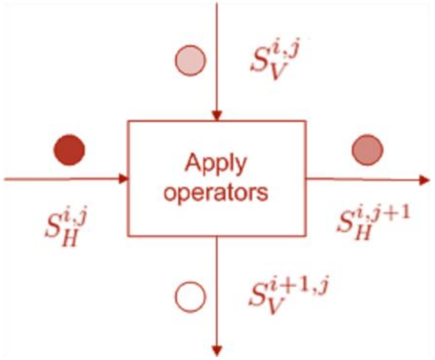
New Hardware: 2nd. Case Study

Genetic Algorithm + Systolic Computing = Systolic Genetic Search

- Systolic Genetic Search (SGS)
  - Solutions sync. pumped in a grid
  - When two solutions meet in a cell, adapted evolutionary operators
  - New solutions continue moving along the grid



- Each cell
  - Applies crossover and mutation on different pre-computed positions
  - Use elitism (there is no selection)



Parallel Experiences

Index

Introduction

Facts in PO Research

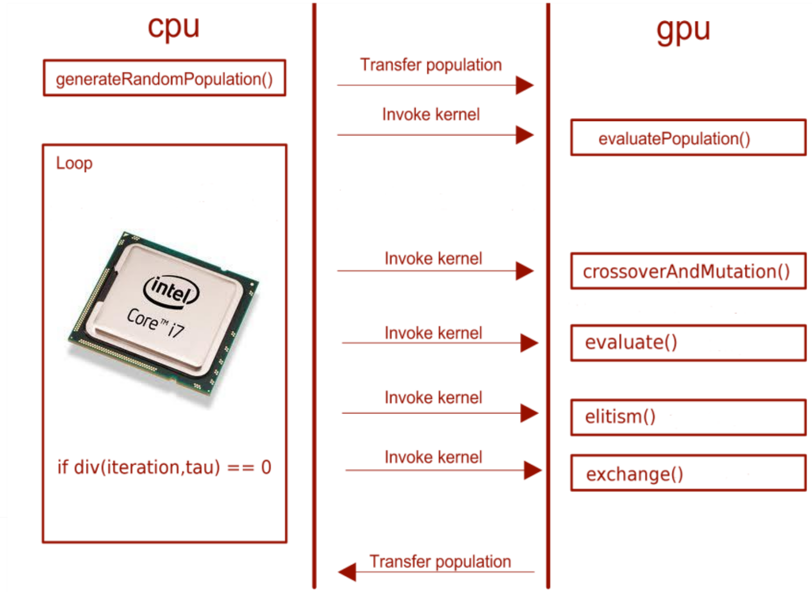
Software and PO

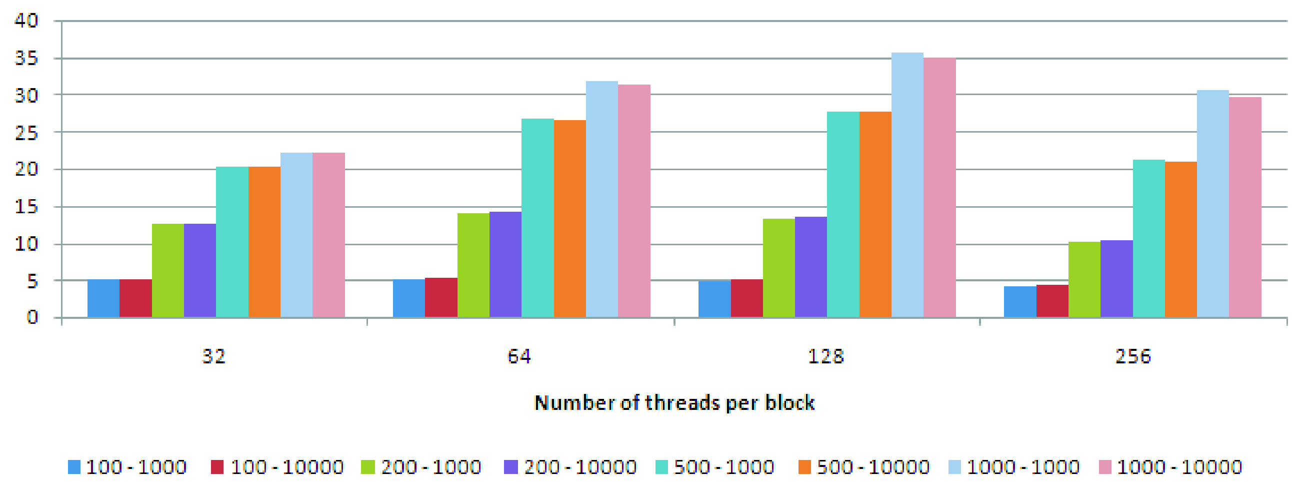
Applications

Case Studies

Summary

New Hardware: 2nd. Case Study





Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

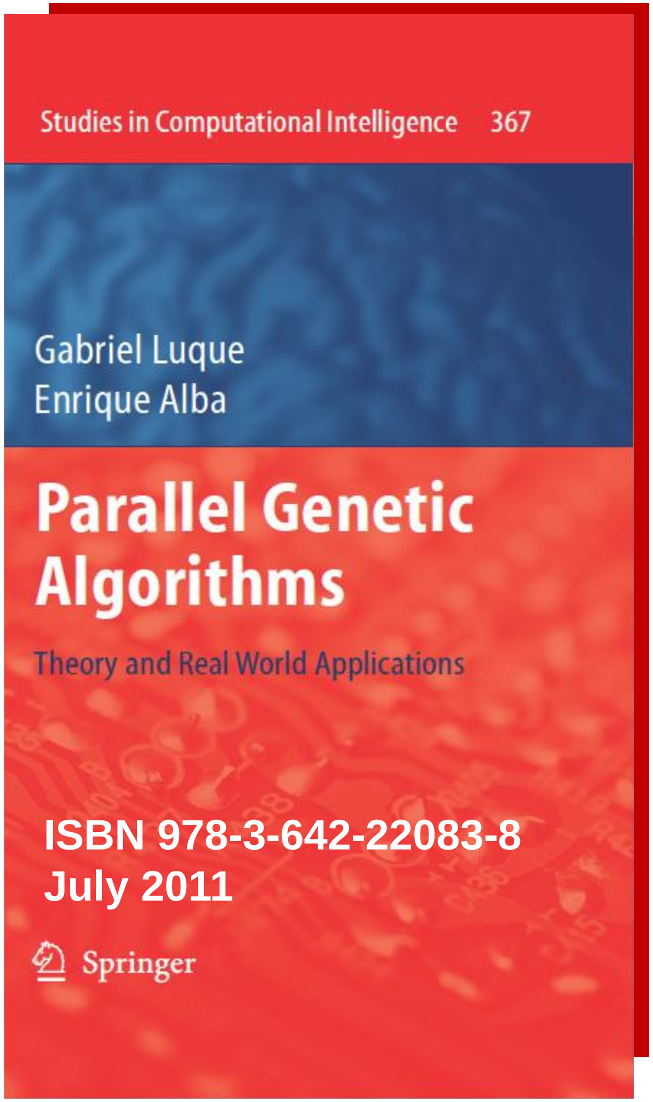
Summary

Summary of Challenges

1. **Parallel algorithms are not fast versions of sequential algorithms: they are new algorithms**
2. **Create standard benchmarking for parallel optimization**
3. **Develop a uniform experimental setup methodology (metrics and stats)**
4. **Connect the algorithm field to the application and software fields**
5. **Tackle new issues in grid/cloud/ambient computing**
6. **New research fields: GPGPU, Multicores, programming**
7. **Create a body of knowledge in parallel algorithmics**

Parallel Experiences

Luque & Alba 2011



Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

Parallel Experiences

Index

Introduction

Facts in PO Research

Software and PO

Applications

Case Studies

Summary

End of Presentation

Málaga

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