Optimization Meets Smart Networks

Research and Technological Challenges in Systems and Control

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RESEARCH FUNDED BY

European Research Council
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OPT4SMART

From Smart Devices ...

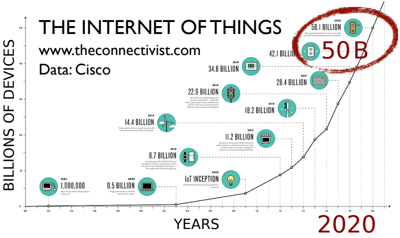
Ubiquitous Smart Devices

Massive

embedded computation

communication

sensing/control



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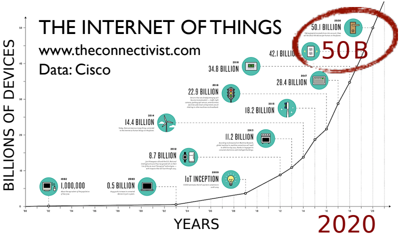

SPATIALLY-DISTRIBUTED and UNSTRUCTURED

Computation Power: a Rough Comparison

OPT4SMART

Sunway TaihuLight
(fastest supercomputer as of 2016)

Processing pwr: 105 PFLOPS
Memory: 1.31 PB
Storage: 20 PB

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Iphone 7
(active since 2016)

Processing pwr: 10 GFLOPS
Memory: 2 GB
Storage: 256 GB

Computation Power: a Rough Comparison

Sunway TaihuLight
(fastest supercomputer as of 2016)

Processing pwr: 105 PFLOPS
Memory: 1.31 PB
Storage: 20 PB

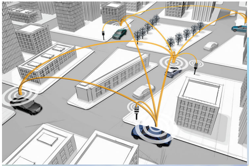
1.4M smartphones
(Milan population)

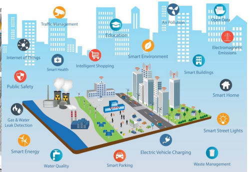
Processing pwr: 14 PFLOPS
Memory: 2.8 PB
Storage: 360 PB

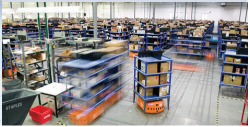
... to Cyber-Physical Networks

Turn smart devices into **Cooperative Intelligent Systems**

- car-2-x systems
- smart cities
- smart grids
- automated factories
- ...







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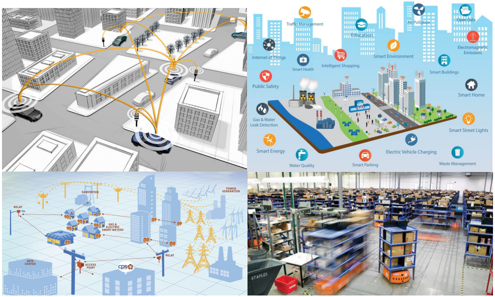

This is "our" (Control Engineers') job!

Why Optimization?

Optimization is a building block for many problems in Engineering

but also Economics, Social Sciences, Biology, ...

- **ESTIMATION and LEARNING**

  traffic estimation, localization, classification, clustering, ...

- **DECISION and CONTROL**

  cooperative robotics, smart grid control, resource/task allocation ...

A Step Back ... Computational Paradigms

Centralized Methods

- Small-size problems
- Sequential computations

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Parallel (and "Classical Distributed") Methods

- Large-scale problems
- Several computations simultaneously

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Parallel (and "Classical Distributed") Methods

- Large-scale problems
- Several computations simultaneously

- Main goal: computation speedup
- Network topology is a design parameter

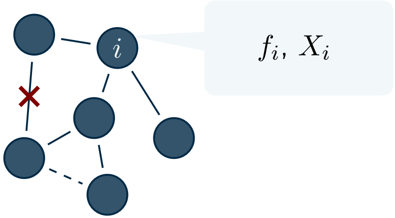
Main Challenges in Distributed Optimization

Structured optimization problem

$$\min_x \sum_{i=1}^{N} f_i(x)$$

$$\text{subj. to } x \in \bigcap_{i=1}^{N} X_i$$

cost
coupled



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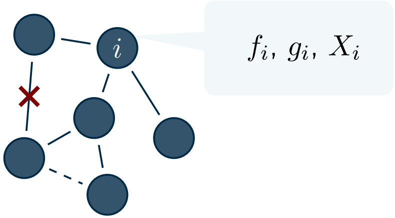
Structured optimization problem

$$\min_{\{x_i \in X_i\}} \sum_{i=1}^{N} f_i(x_i)$$

$$\text{subj. to} \sum_{i=1}^{N} g_i(x_i) \leq 0$$

constraint coupled

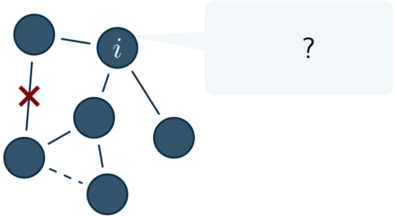


Main Challenges in Distributed Optimization

GOAL

solve (given!) problem via

Distributed Algorithm



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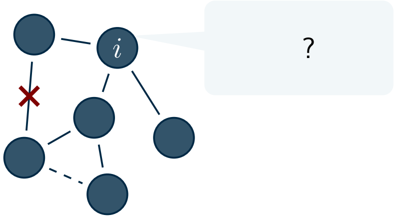

- processors know only a portion of the problem
- ASYNCHRONOUS and unreliable communication
- large-scale and BIG-DATA problems
- possibly NONCONVEX (mixed-integer, combinatorial)
- ... to be solved in REALTIME!

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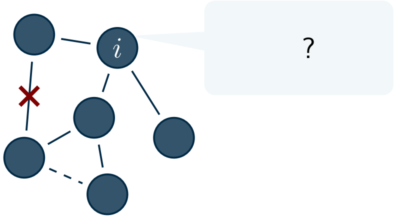

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NO central coordinator!

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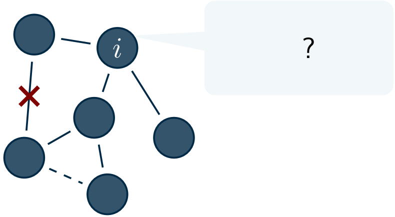

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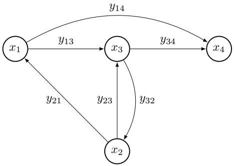
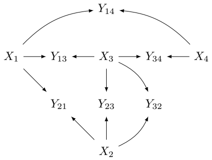
network topology NOT a design parameter!

Profiling in Social Networks





- users mutually evaluate themselves
- local interaction and cooperation
- GOAL: cooperative self-profiling

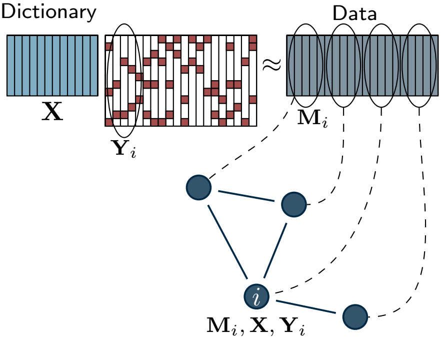
Empirical Bayes (relaxed) Estimator

$$(\hat{\theta}, \hat{\gamma}) = \operatorname*{argmax}_{(\theta,\gamma)\in\mathcal{S}_\Theta\times\mathcal{S}_\Gamma} \sum_{i=1}^{N} g(\theta, \gamma; n_i)$$

$(\theta,\, \gamma)$ unknown "world" parameters

n_i aggregate statistics at node i

Dictionary Learning for Big-Data Analytics

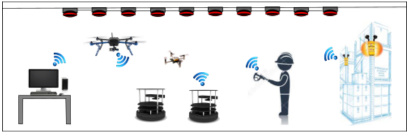


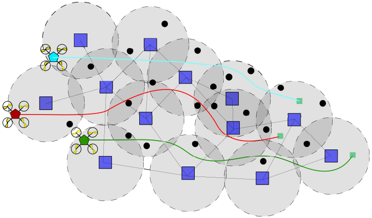
- inpainting
- denoising
- collaborative filtering (recommender systems)

$$\min_{\mathbf{X}, \mathbf{Y_1}, \ldots, \mathbf{Y}_N} \sum_{i=1}^{N} \|\mathbf{M}_i - \mathbf{X}\mathbf{Y}_i\|_F^2 + \lambda \|\mathbf{Y}_i\|_1$$

$$\text{subj. to } \mathbf{X} \in \mathcal{X}$$

Task Allocation in Robotic Networks





- smart environment
  (sensors, processors, mobile robots)
- local processing and communication
- GOAL: assign tasks in realtime
  (e.g., paths that minimize time)

$$\min_{x,y} \; c_x^\top x + y$$

$$\text{subj. to } a_i^\top x \leq y \,, \; \forall i = 1, \ldots, d_Z$$

$$A_T \, x \leq -\mathbf{1}_{N_T} w$$

$$P x = \mathbf{1}_{N_v}$$

$x \in \{0,1\}$ (binary), $y \in \mathbb{R}$

Smart Grid Control

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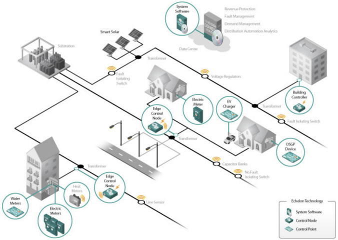
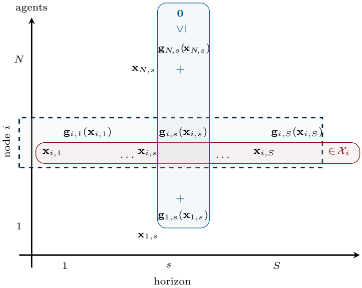




- smart generators/accumulators/loads
- local processing and communication
- GOAL: cooperatively optimize generation/consumption

$$\min_{\{x_{i,s}\}} \sum_{i=1}^{N} \sum_{s=1}^{S} f_{i,s}(x_{i,s})$$

$$\text{subj. to } \sum_{i=1}^{N} g_{i,s}(x_{i,s}) \leq 0, \;\; s \in \{1, \dots, S\}$$

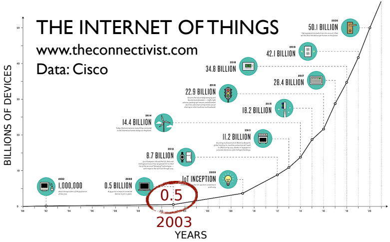
$$x_i \in X_i, \;\; i \in \{1, \dots, N\}$$

Back to Technological Growth ...

Start of

exponential growth

2002/2003



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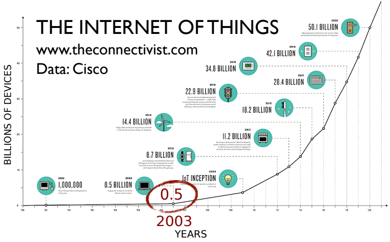

What happened in those years in our Controls Community?

Jadbabaie, Lin, Morse, "Coordination of groups of mobile autonomous agents using nearest neighbor rules", CDC 2002, TAC 2003.

new distributed "control" research started

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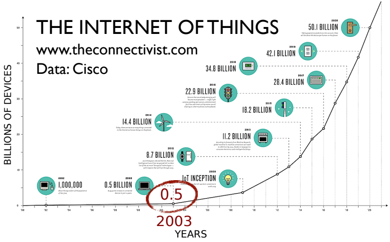

What about Italian community? (Personal experience!)

RECSYS - FP5 (09/2002 - 08/2005)
Real-Time Emb. Control of Mobile Systems w/ Distributed Sensing
Coordinator: G. Picci (UNIPD)
Partners: UNIPI (A. Bicchi), S. Anna, EPFL, KTH, Intecs

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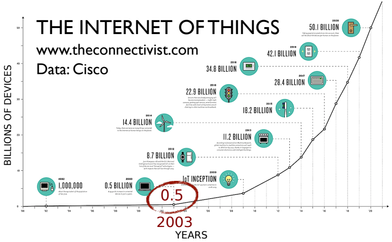

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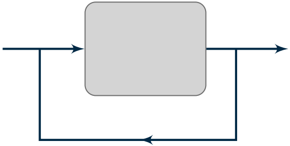
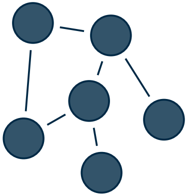
OBJECTIVES
"... new paradigms and methods for control design of embedded systems with distributed sensing, limited communication and computational resources ..."

New “Distributed Era” in Control Community





- new research problems ... not even clear which ones!
- need to look for novel methodological tools
- combine “systems theory” with “graph theory”

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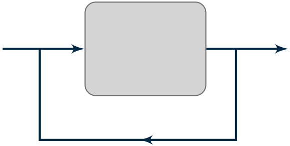

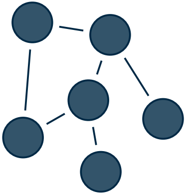

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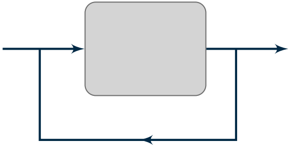

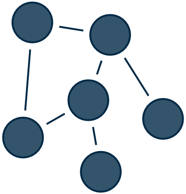

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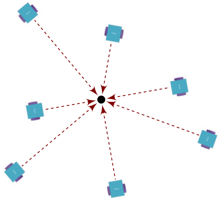
Note: At the beginning “toy” problems ... applications not clear

My Personal Experience

Minimum time rendezvous for first order agents

Centralized solution:
move at maximum speed toward the center of the smallest enclosing ball



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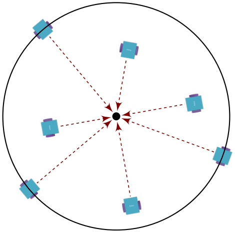

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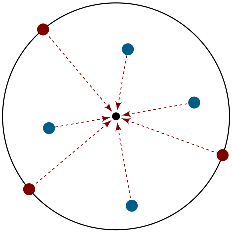

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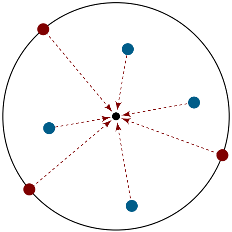

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Distributed Optimization Problem

Today's Disruptive Innovations

What is the role of our Control Community in today's innovation challenges?

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OPT4SMART

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MCKINSEY GLOBAL INSTITUTE

WHAT'S NOW AND NEXT IN ANALYTICS, AI, AND AUTOMATION

BRIEFING NOTE • MAY 2017

"Innovations in digitization, analytics, artificial intelligence, and automation are creating performance and productivity opportunities for business and the economy, even as they reshape employment and the future of work."

(McKinsey Briefing Note 2017)

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Analytics

"Data and analytics are already disrupting business models and bringing performance benefits"

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Automation

"AI and Automation will provide a much-needed boost to global productivity"

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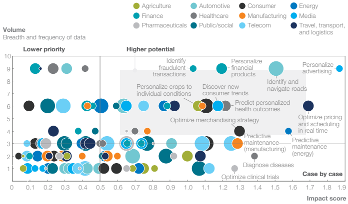

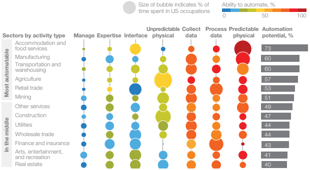

courtesy McKinsey Briefing Note 2017

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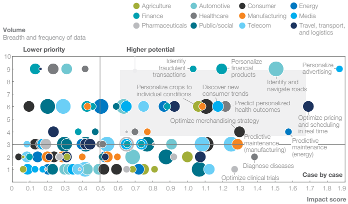

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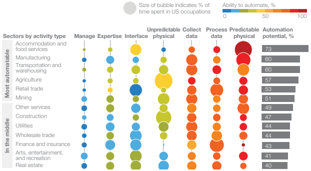

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this is "Controls" moment!

What About Keywords?

Some modern "catchy" keywords

Artificial Intelligence

Machine Learning
(Deep Learning, Reinforcement Learning)

Collective Intelligence

Cognitive Systems

Cyber-Physical Systems

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Another one ... our own brand

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"[...] we're focusing on autonomous systems. And clearly one purpose of autonomous systems is self-driving cars."

Tim Cook (Bloomberg, June 2017)

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"[...] It's probably one of the most difficult AI projects, actually, to work on."

Tim Cook (Bloomberg, June 2017)

Conclusions

Opportunities

- new powerful technology with massive computation and communication capability available
- optimization is a building block in many estimation, learning, decision and control problems

Challenges

- asynchronous, unreliable, directed communication
- complex (optimization) problems in smart networks
- large-scale, dynamic problems to be solved in realtime

RESEARCH FUNDED BY

European Research Council
Established by the European Commission