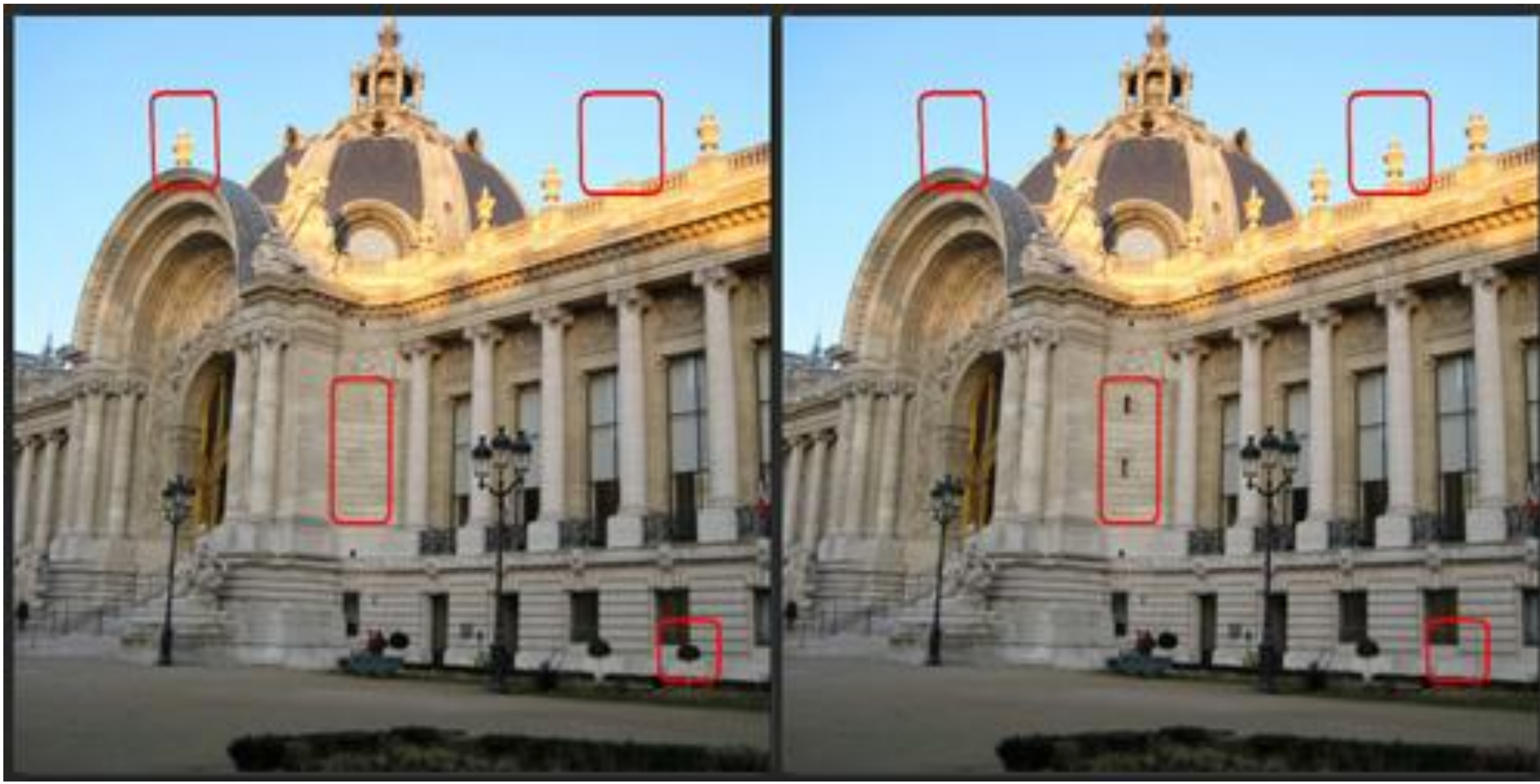
Physical Algorithms

Spot the Differences



Spot the Differences

Too Many!

Spot the Differences

Still Many!

Spot the Differences

Better Screen

Bigger Disk

More RAM

Cooler Design

…

Better Screen

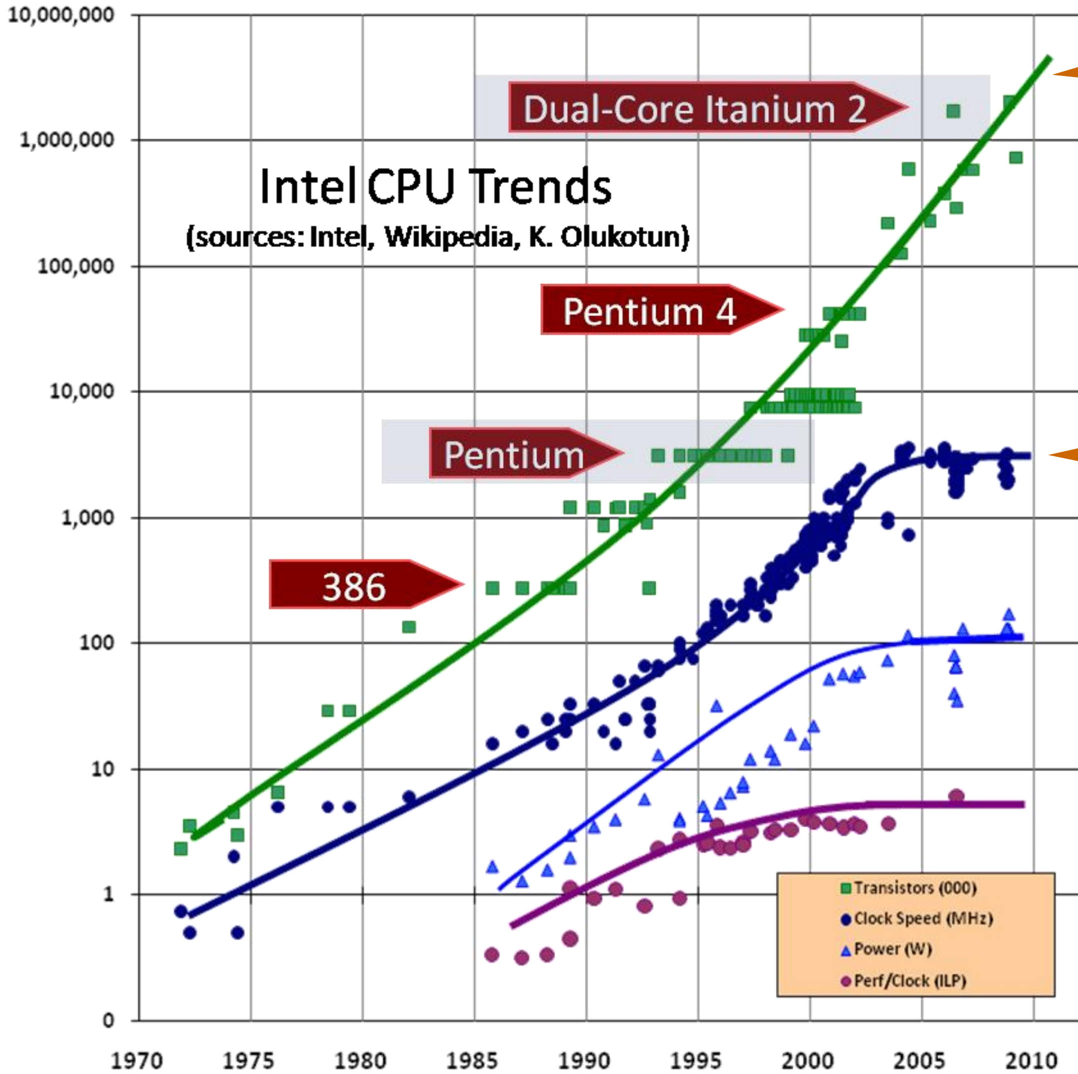
Bigger Disk

More RAM

Cooler Design

...

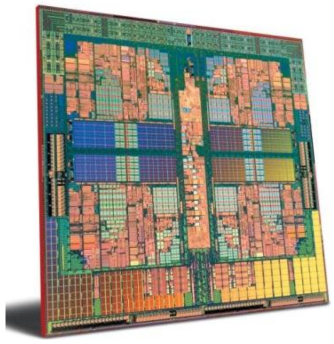
Same CPU Clock Speed



Transistor count still rising

Clock speed flattening sharply

Advent of multi-core processors!

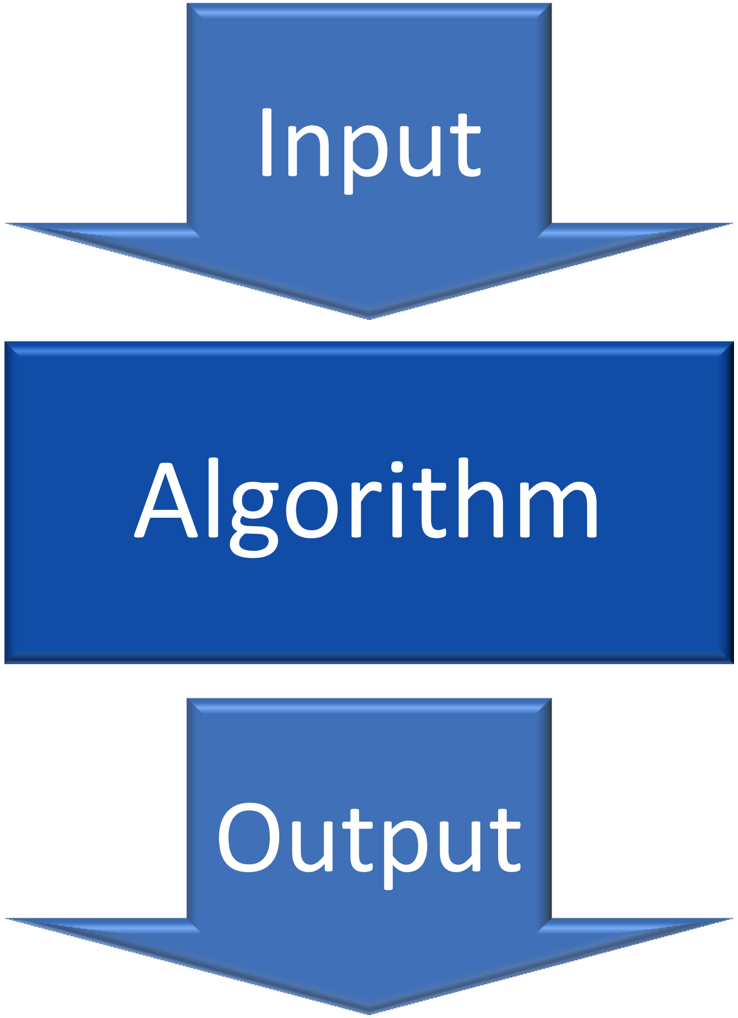


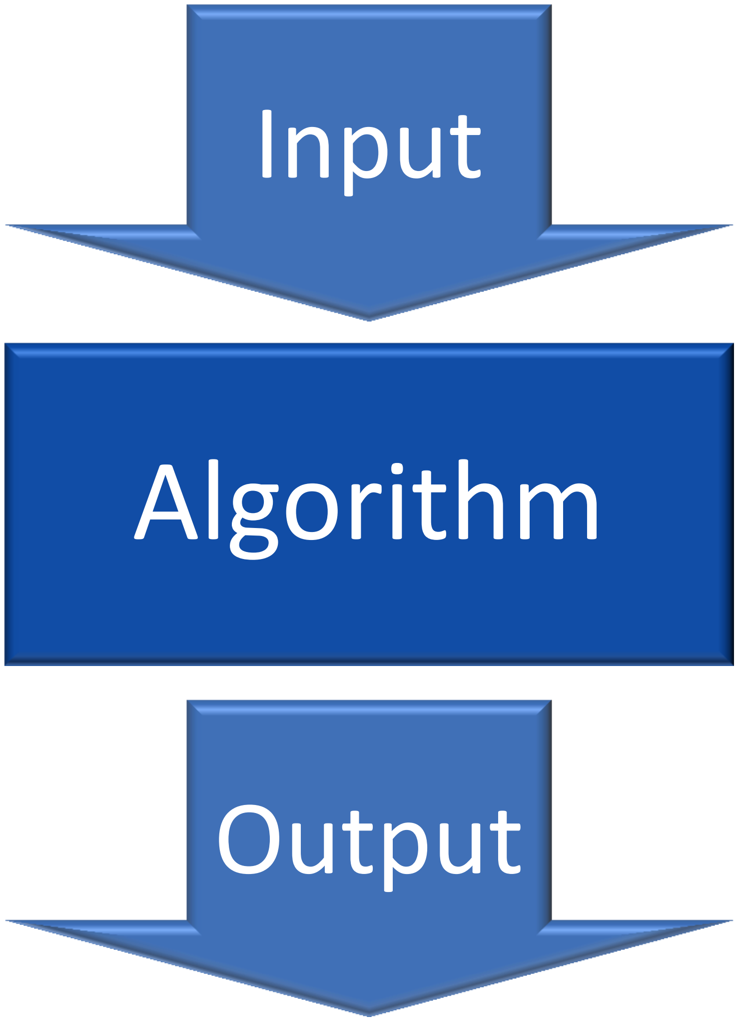
Why Should I Care?

Computer Science → Washing Machine Science

[Roger Boyle, Maurice Herlihy]

Algorithms

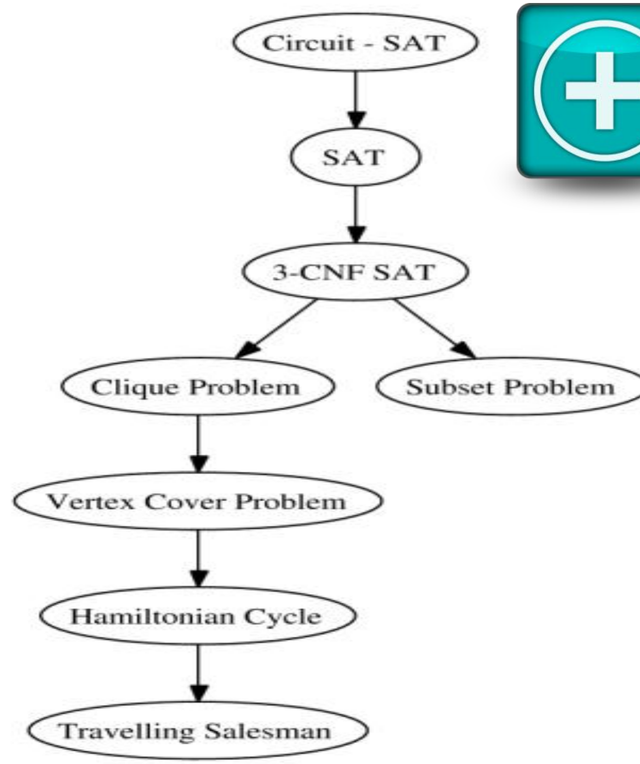

Input
Algorithm
Output



simple and robust model

comparable results

complexity theory

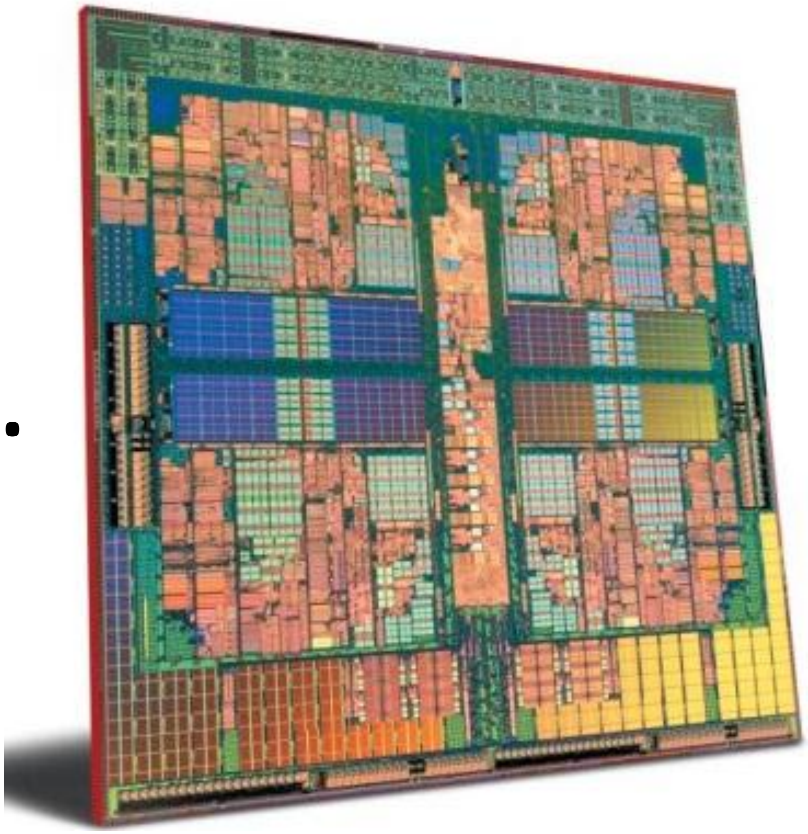


Input

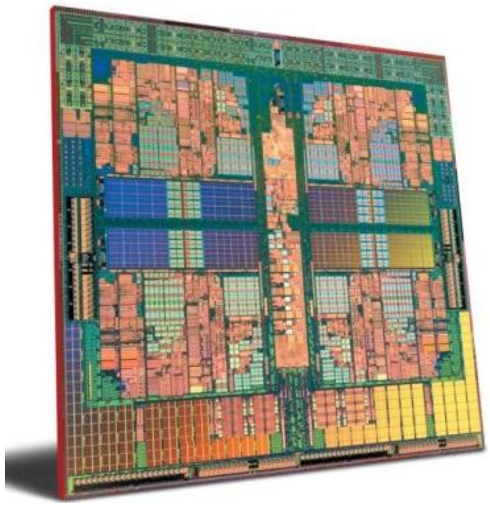
Algorithm

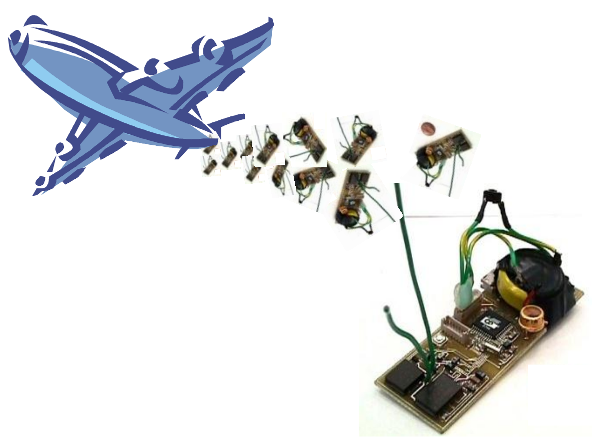
Output

vs.



The Future of Computing?





Talk Overview

Introduction & Motivation

Examples for Physical Algorithms
in the Context of Sensor Networks

What are Physical Algorithms?

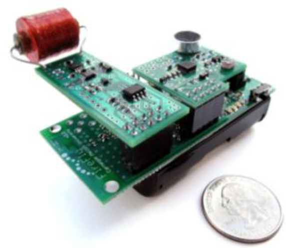
Clock Synchronization

Clock Synchronization in Networks

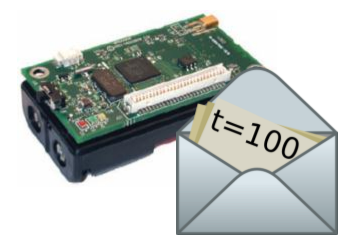
Global Positioning System (GPS)

Radio Clock Signal

AC-power line radiation



Synchronization messages



Clock Synchronization in Networks

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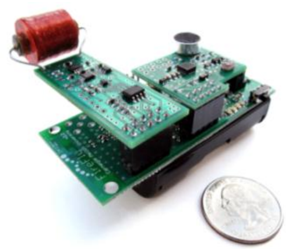
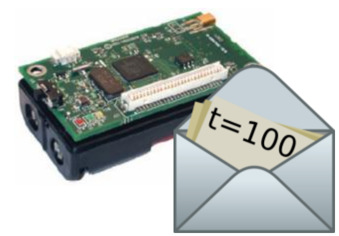
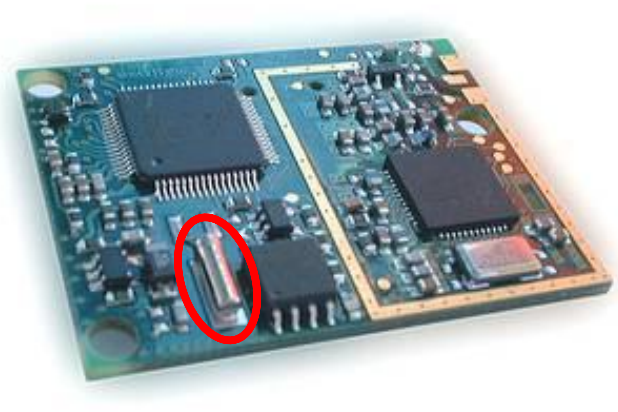


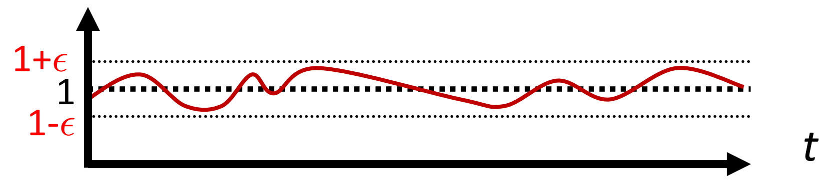
Synchronization messages

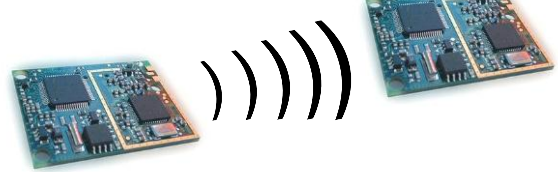


Problem: Physical Reality

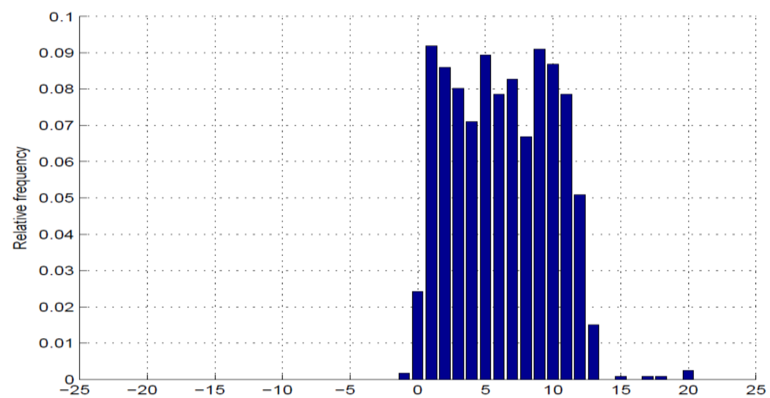


clock rate





message delay

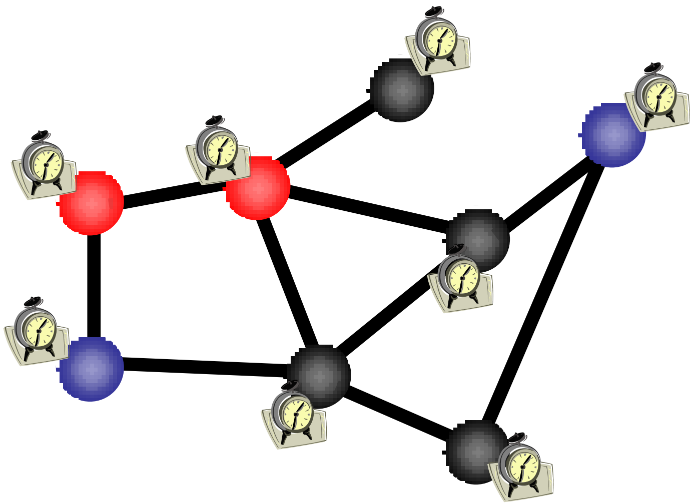


Clock Synchronization in Theory?

Given a communication network

1. Each node equipped with hardware clock with drift
2. Message delays with jitter

worst-case (but constant)



Goal: Synchronize Clocks ("Logical Clocks")

- Both global and local synchronization!

Time Must Behave!

- Time (logical clocks) should not be allowed to stand still or jump

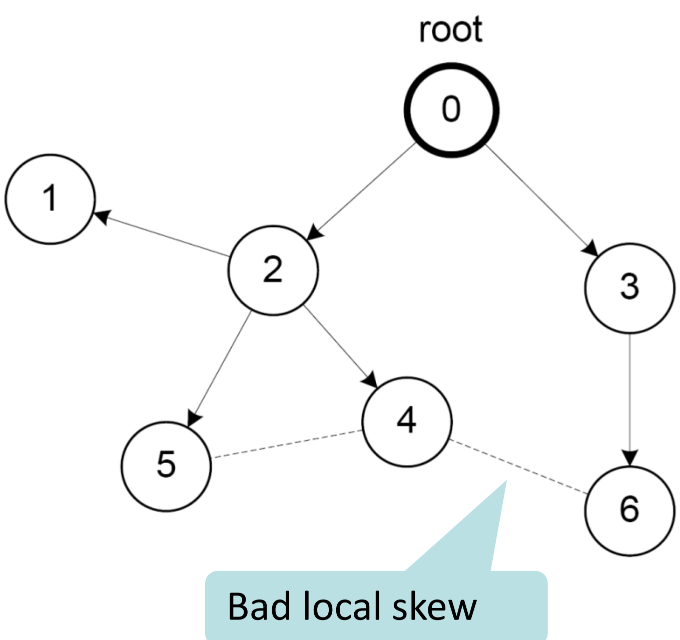
Time Must Behave!

- Time (logical clocks) should not be allowed to stand still or jump

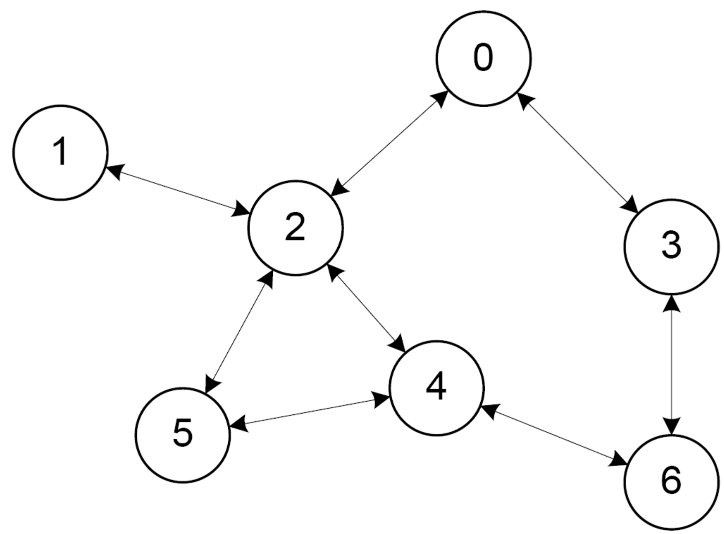
- Let’s be more careful (and ambitious):
- Logical clocks should always move forward
  - Sometimes faster, sometimes slower is OK.
  - But there should be a minimum and a maximum speed.
  - As close to correct time as possible!

Local Skew

Tree-based Algorithms
e.g. FTSP



Neighborhood Algorithms
e.g. GTSP

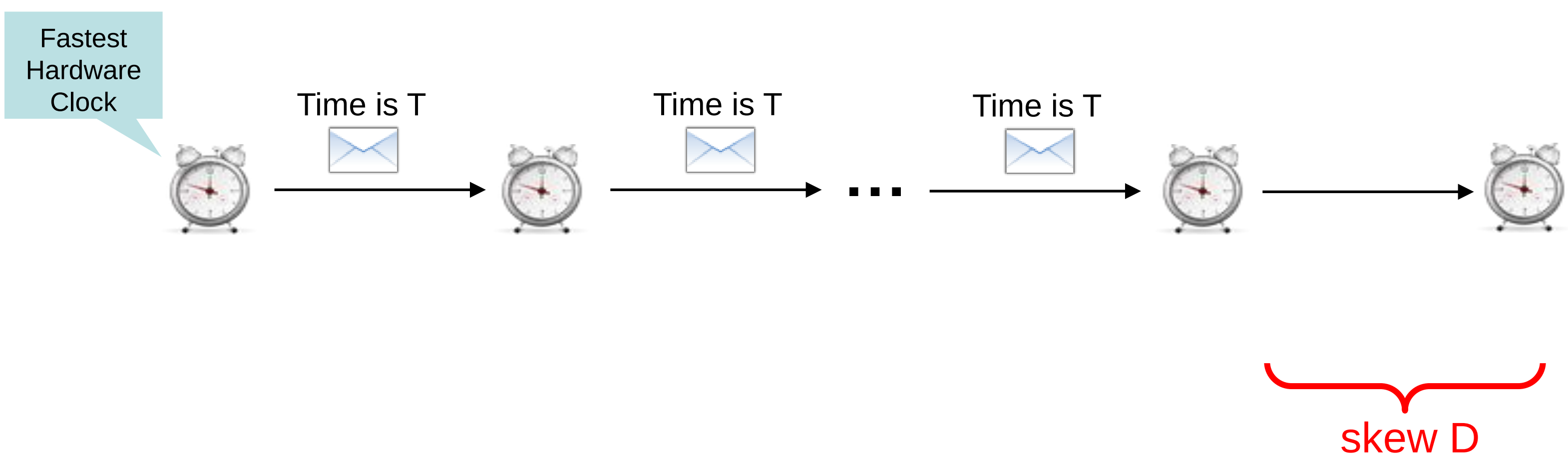


Synchronization Algorithms: An Example ("A^{max}")

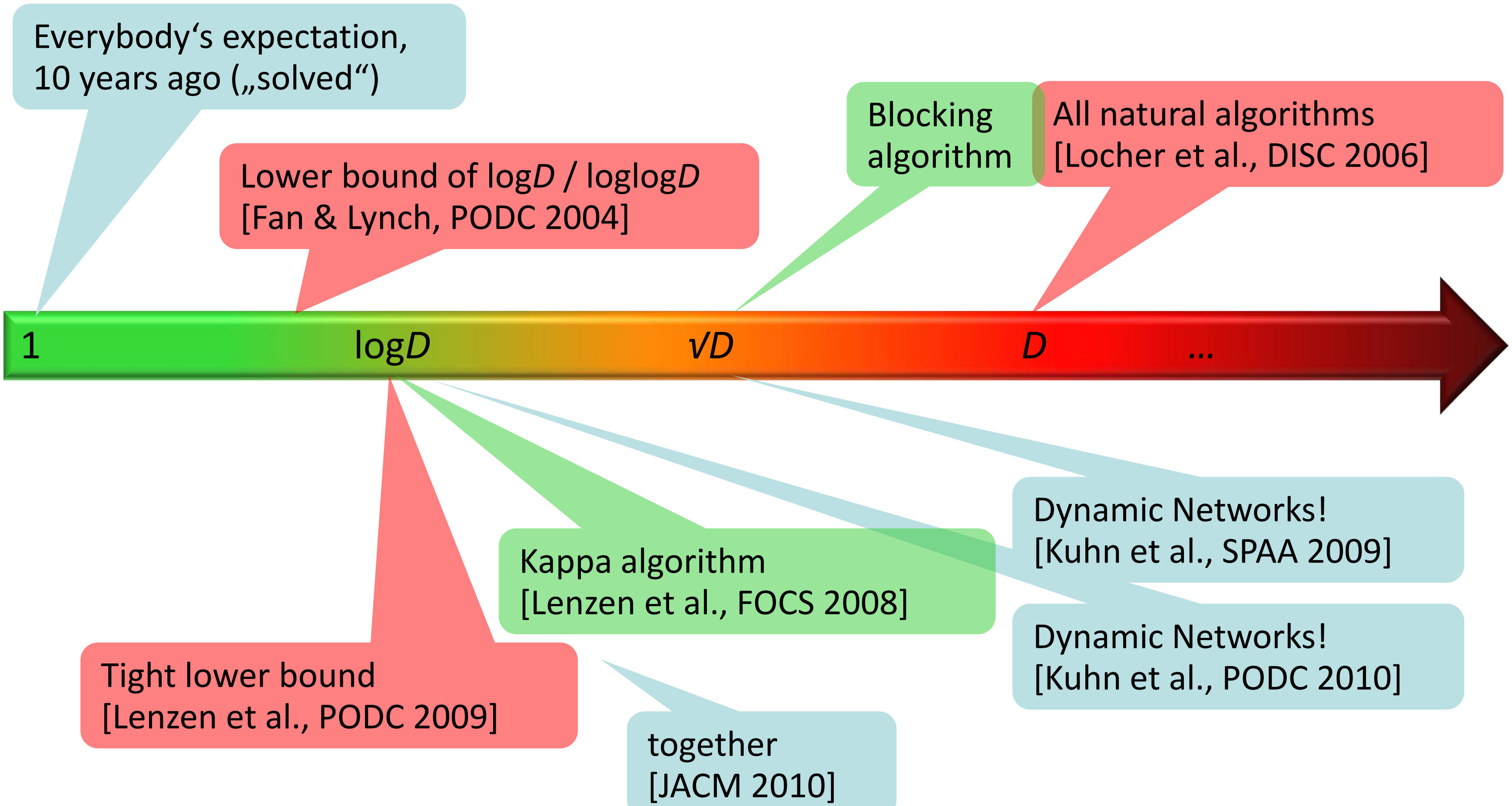
- Question: How to update the logical clock based on the messages from the neighbors?

- Idea: Minimizing the skew to the fastest neighbor
  - Set clock to maximum clock value you know, forward new values immediately

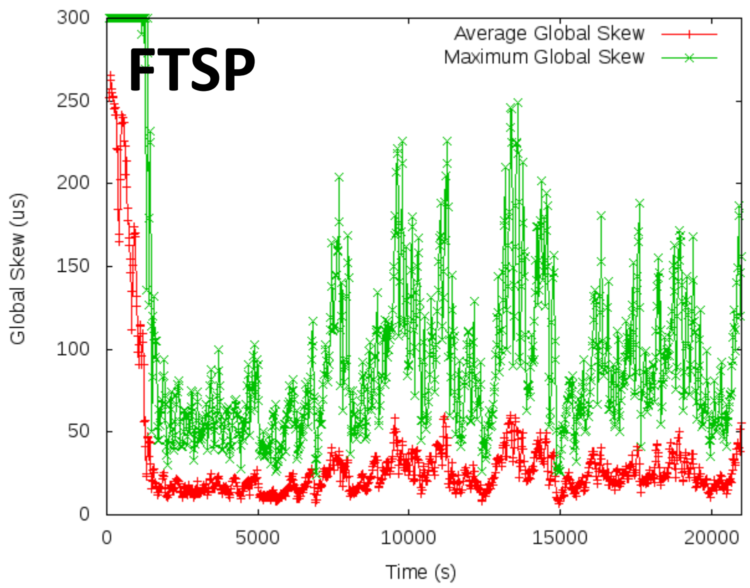
- First all messages are slow (1), then suddenly all messages are fast (0)!

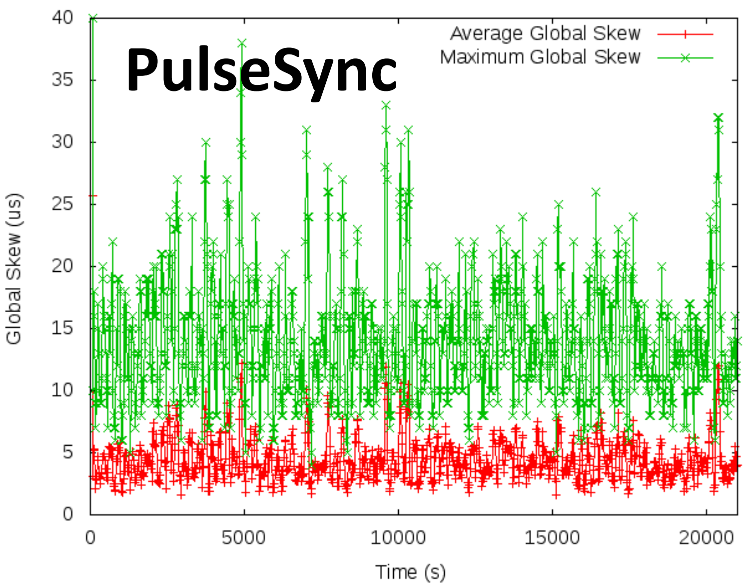


Local Skew: Overview of Results



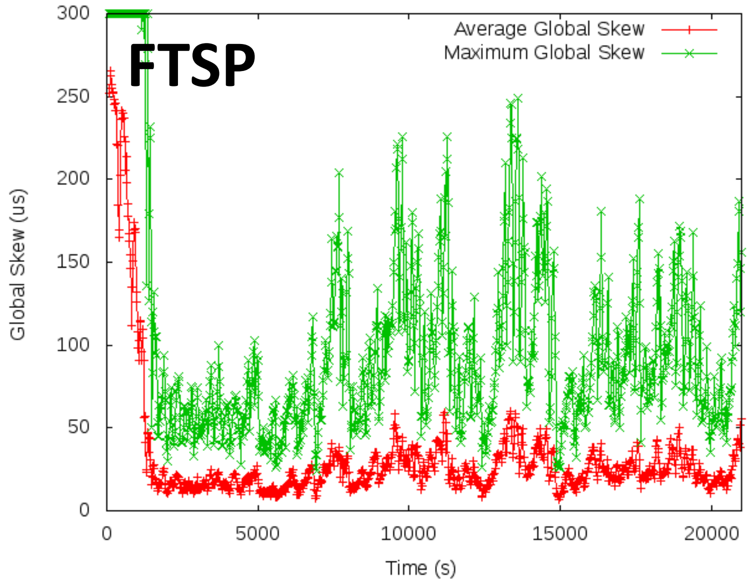
Experimental Results for Global Skew

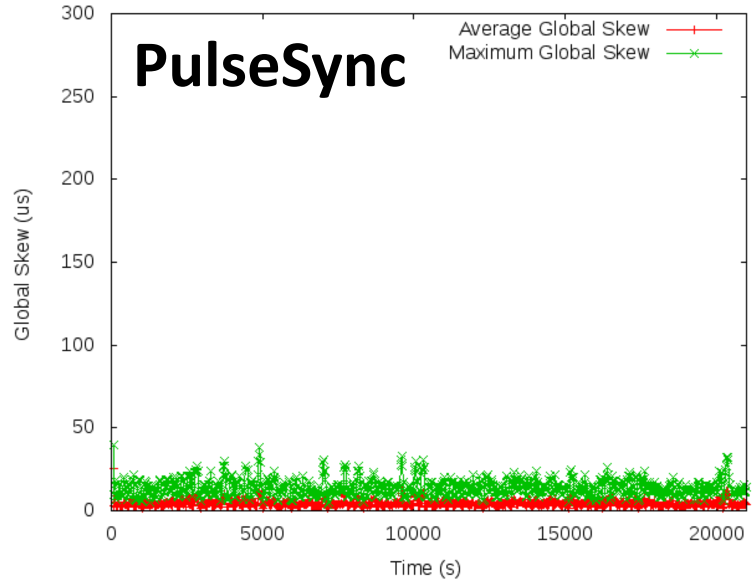




[Lenzen, Sommer, W, SenSys 2009]

Experimental Results for Global Skew





[Lenzen, Sommer, W, SenSys 2009]

Clock Synchronization vs. Car Coordination

- In the future cars may travel at high speed despite a tiny safety distance, thanks to advanced sensors and communication

Clock Synchronization vs. Car Coordination

- In the future cars may travel at high speed despite a tiny safety distance, thanks to advanced sensors and communication

- How fast & close can you drive?

- Answer possibly related to clock synchronization
  - clock drift ↔ cars cannot control speed perfectly
  - message jitter ↔ sensors or communication between cars not perfect

Wireless Communication

Wireless Communication

EE, Physics

Maxwell Equations

Simulation, Testing

‘Scaling Laws’

Network Algorithms

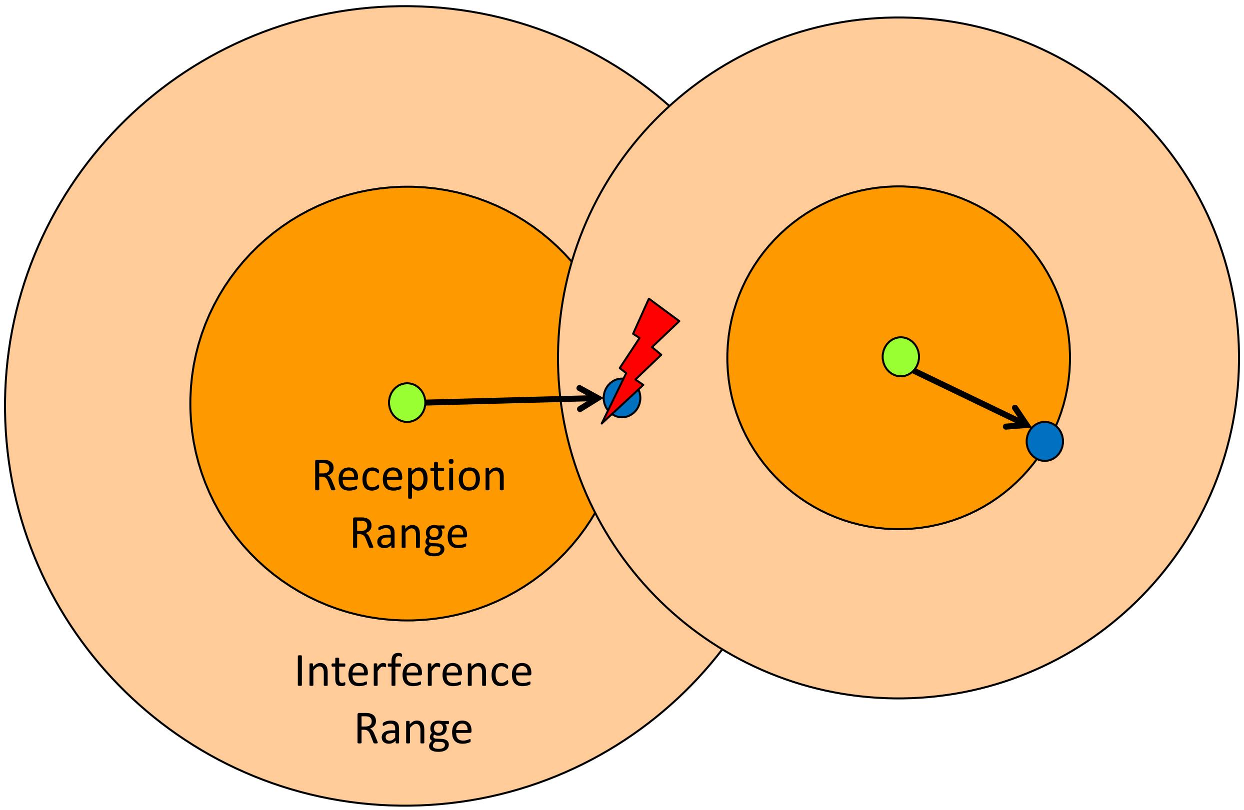
CS, Applied Math

[Geometric] Graphs

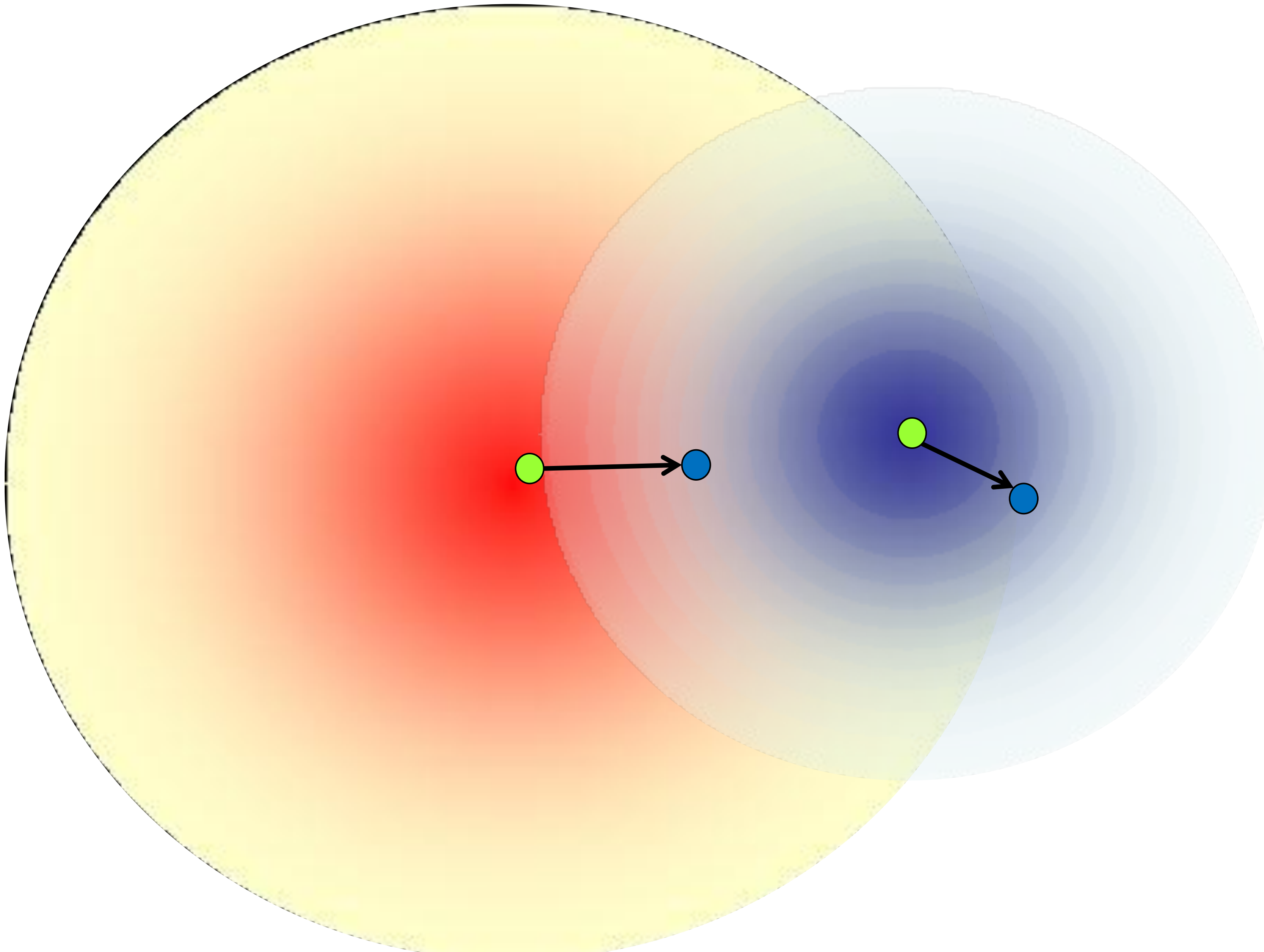
Worst-Case Analysis

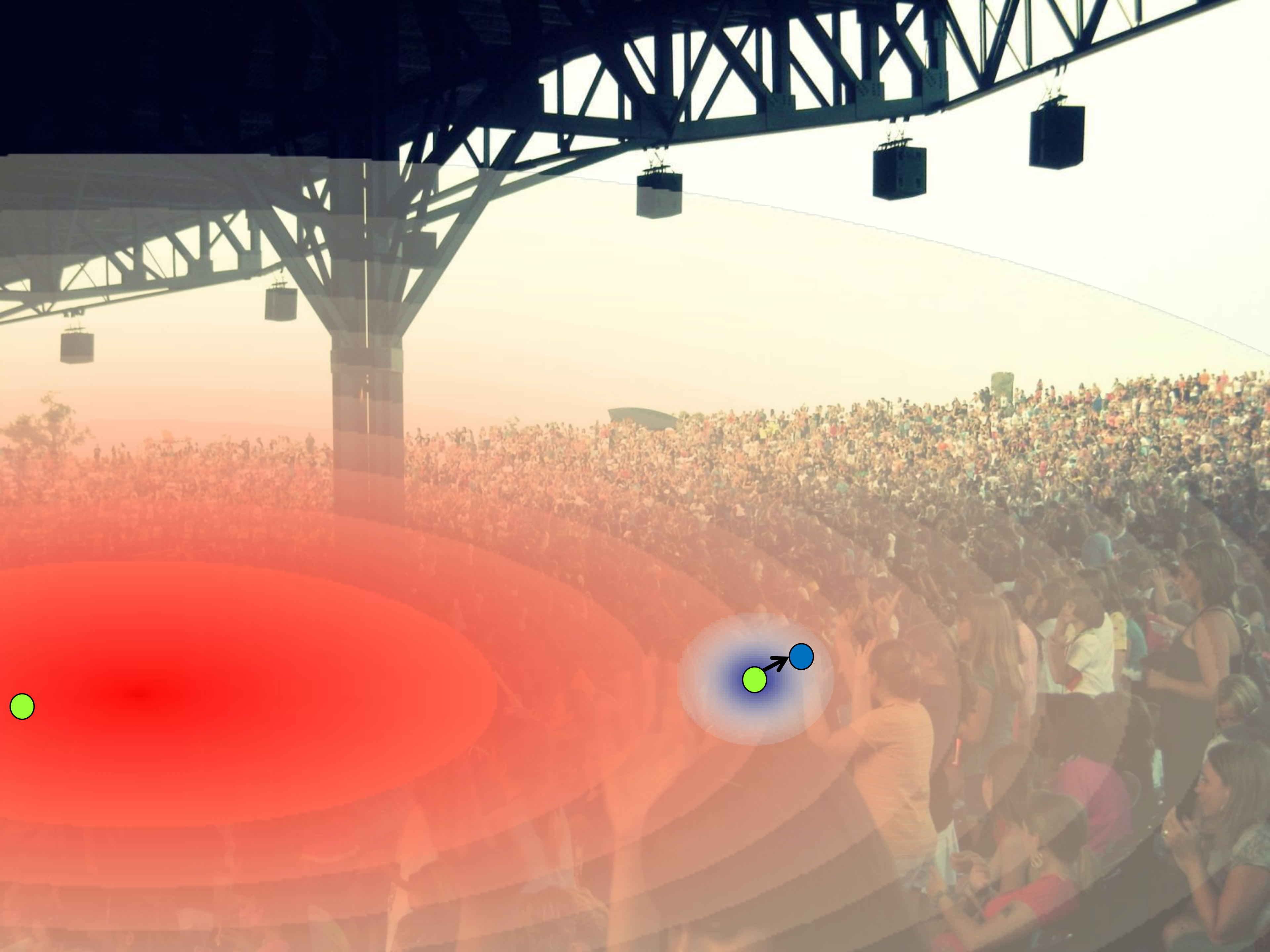
Any-Case Analysis

CS Models: e.g. Disk Model (Protocol Model)



EE Models: e.g. SINR Model (Physical Model)





Signal-To-Interference-Plus-Noise Ratio (SINR) Formula

$$\frac{\frac{P_u}{d(u,v)^{\alpha}}}{N + \sum_{w \in V \setminus \{u\}} \frac{P_w}{d(w,v)^{\alpha}}} \geq \beta$$

Received signal power from sender

Power level of sender *u*

Path-loss exponent

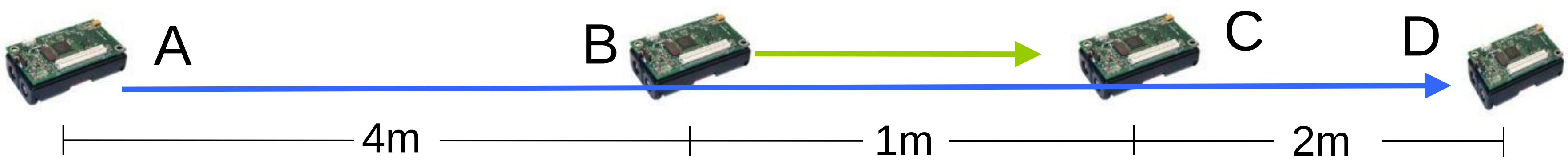
Noise

Minimum signal-to-interference ratio

Received signal power from all other nodes (=interference)

Distance between two nodes

Example: Protocol vs. Physical Model



Assume a single frequency (and no fancy decoding techniques!)

Is spatial reuse possible?

- NO — Protocol Model
- YES — With power control

Let α=3, β=3, and N=10nW

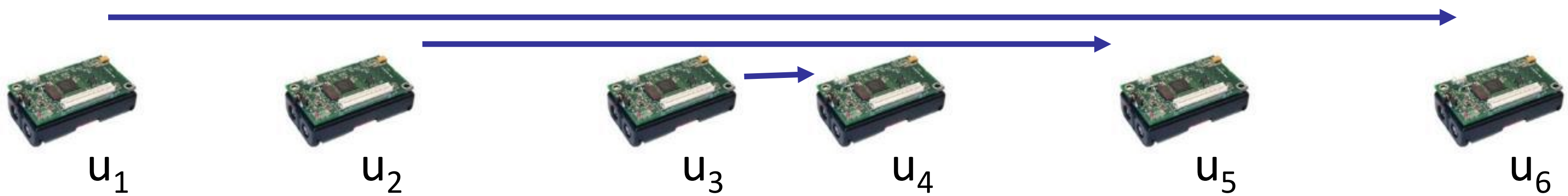
Transmission powers: P_B= -15 dBm and P_A= 1 dBm

SINR of A at D: $$\frac{1.26mW/(7m)^3}{0.01\mu W + 31.6\mu W/(3m)^3} \approx 3.11 \geq \beta$$

SINR of B at C: $$\frac{31.6\mu W/(1m)^3}{0.01\mu W + 1.26mW/(5m)^3} \approx 3.13 \geq \beta$$

This works in practice!

… even with very simple hardware (sensor nodes)



Time for transmitting 20‘000 packets:

	Time required	
	standard MAC	“SINR-MAC”
Node u_1	$721s$	$267s$
Node u_2	$778s$	$268s$
Node u_3	$780s$	$270s$

	Messages received	
	standard MAC	“SINR-MAC”
Node u_4	19999	19773
Node u_5	18784	18488
Node u_6	16519	19498

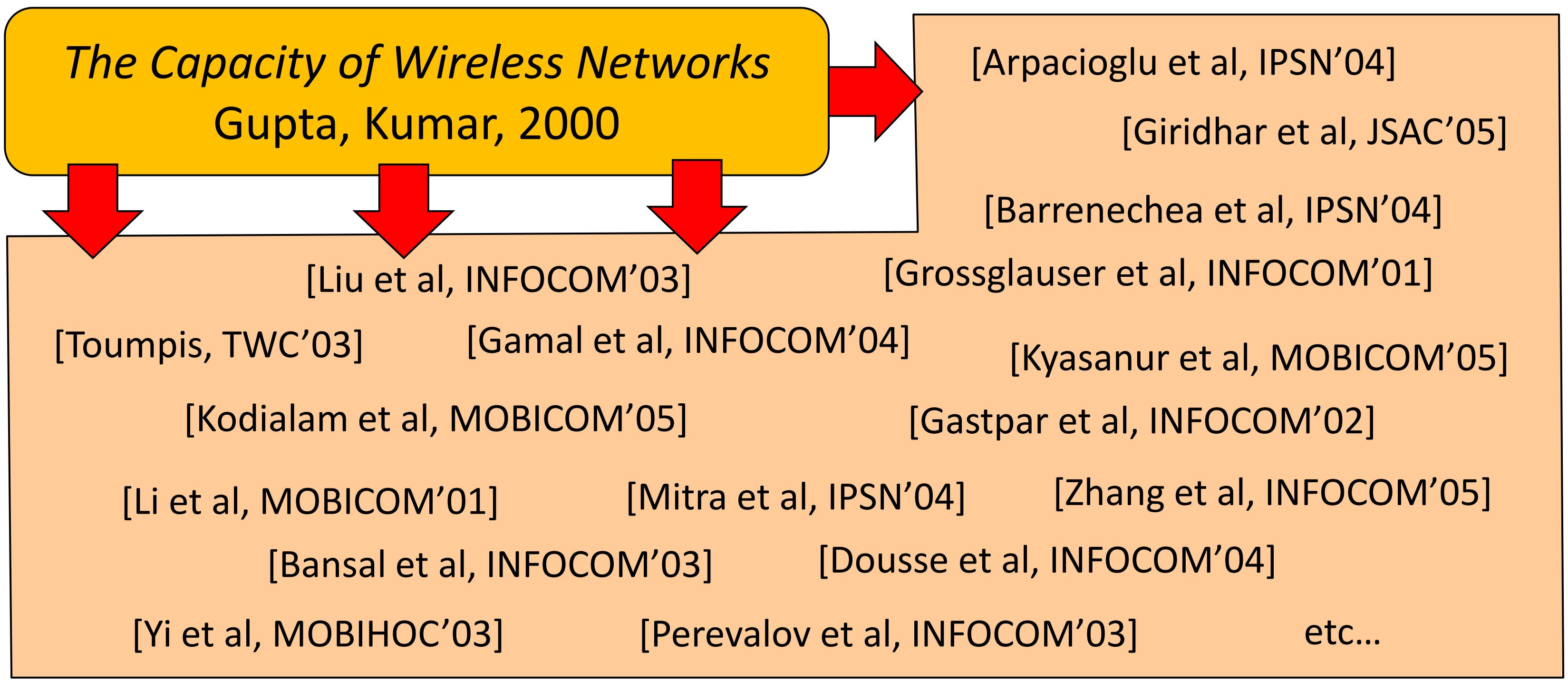
Speed-up is almost a factor 3

[Moscibroda, W, Weber, Hotnets 2006]

The Capacity of a Network

(How many concurrent wireless transmissions can you have)

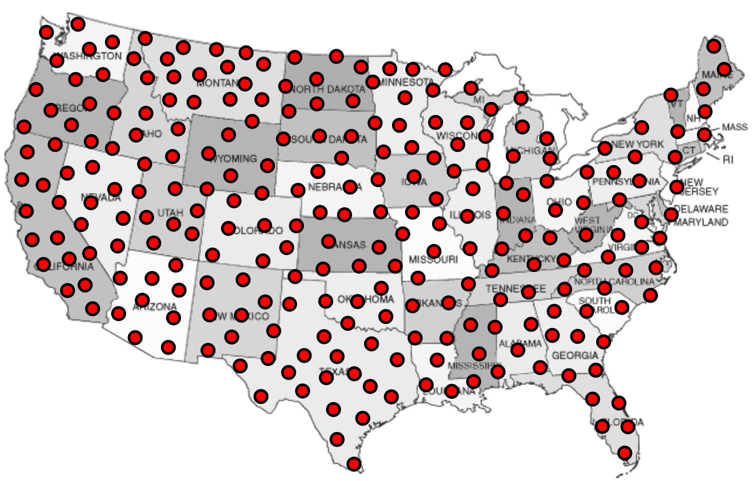
… is a well-studied problem in Wireless Communication

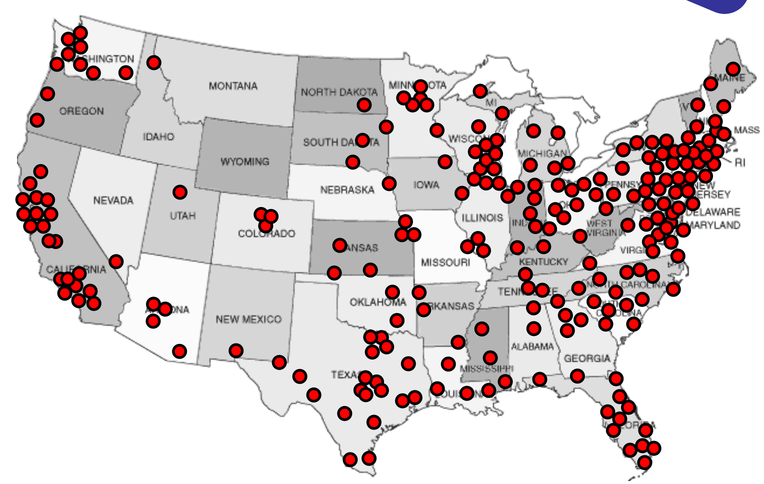


Network Topology?

- All these capacity studies make very strong assumptions on node deployment, topologies
  - randomly, uniformly distributed nodes
  - nodes placed on a grid
  - etc.

What if a network looks differently…?





"Convergecast Capacity" in Wireless Sensor Networks

[Moscibroda, W, 2006]
[Halldorsson, Mitra, 2012]

Worst-Case Capacity

[Giridhar, Kumar, 2005]

Best-Case Capacity

Networks / Model/Power	Max. rate in arbitrary, worst-case deployment	Max. rate in random, uniform deployment
Protocol Model	$\Theta(1/n)$	$\Theta(1/\log n)$
Physical Model (power control)	$\Omega(1/\log n)$	$\Omega(1/\log n)$

Exponential gap between protocol and physical model!

<u>The Price of Worst-Case Node Placement</u>

- Exponential in protocol model
- Polylogarithmic in physical model (almost no worst-case penalty!)

Physical Algorithms

Real Capacity

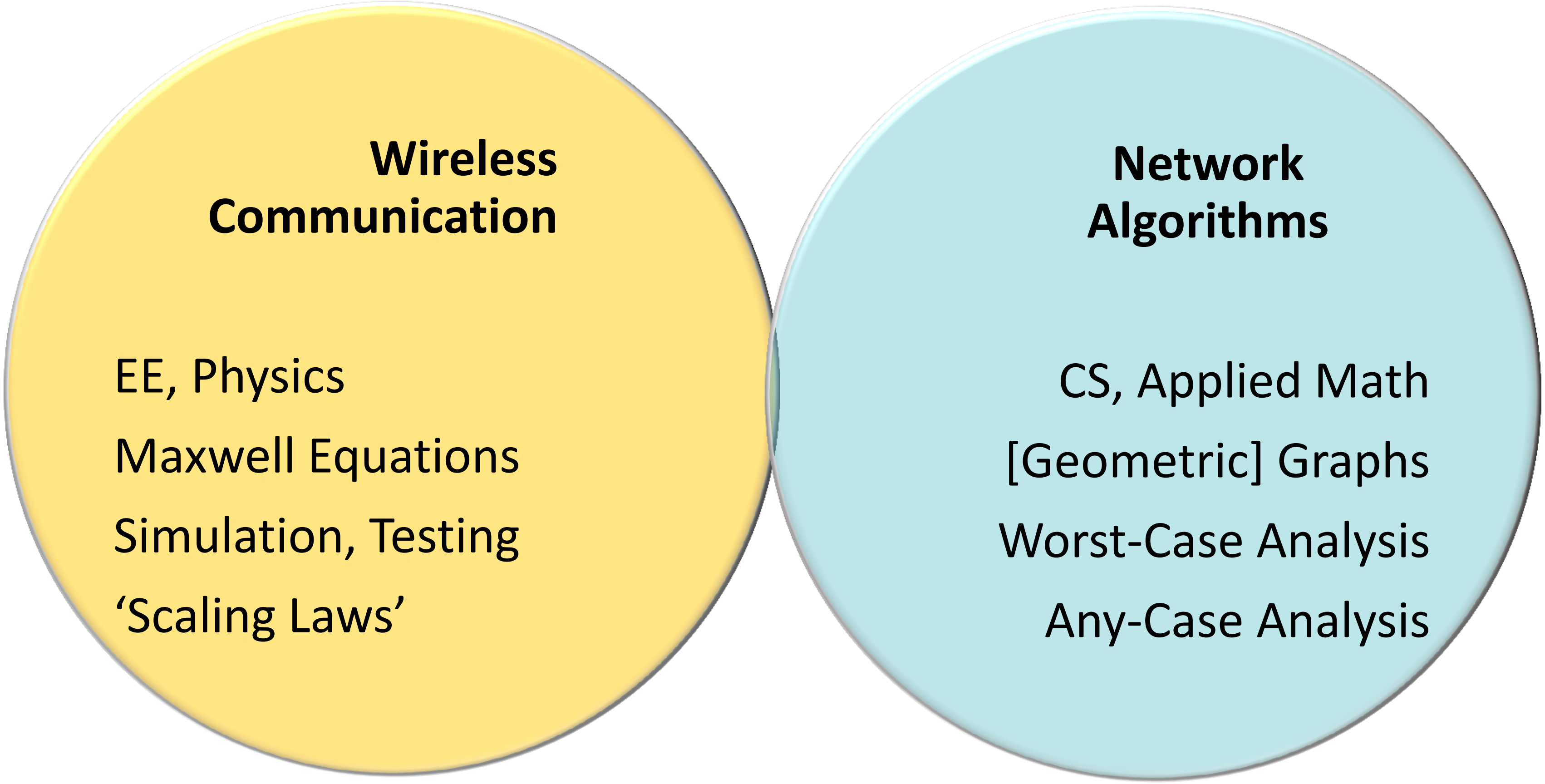
How much information can be transmitted in any network?

“Classic” Capacity

How much information can be transmitted in nice networks?

Worst-Case Capacity

How much information can be transmitted in nasty networks?


Wireless Communication
EE, Physics
Maxwell Equations
Simulation, Testing
'Scaling Laws'
Network Algorithms
CS, Applied Math
[Geometric] Graphs
Worst-Case Analysis
Any-Case Analysis

… is really taking off right now!

The Complexity of Connectivity …
Moscibroda et al., Infocom 2006

[Halldorsson et al, ICALP'11]

[Dams et al, ICALP'11]

[Hoefer et al, SPAA'10]

[Fanghaenel et al, PODC'09]

[Goussevskaia et al, INFOCOM'09]

[Lotker et al., INFOCOM'11]

[Kesselheim, SODA'11]

[Fanghaenel et al, ICALP'09]

[Kesselheim et al, DISC'10]

[Halldorsson et al, SODA'11]

[Avin et al, PODC'11]

[Kantor et al, STOC'11]

[Lebhar et al, IPDPS'09]

[Halldorsson, ESA'09]

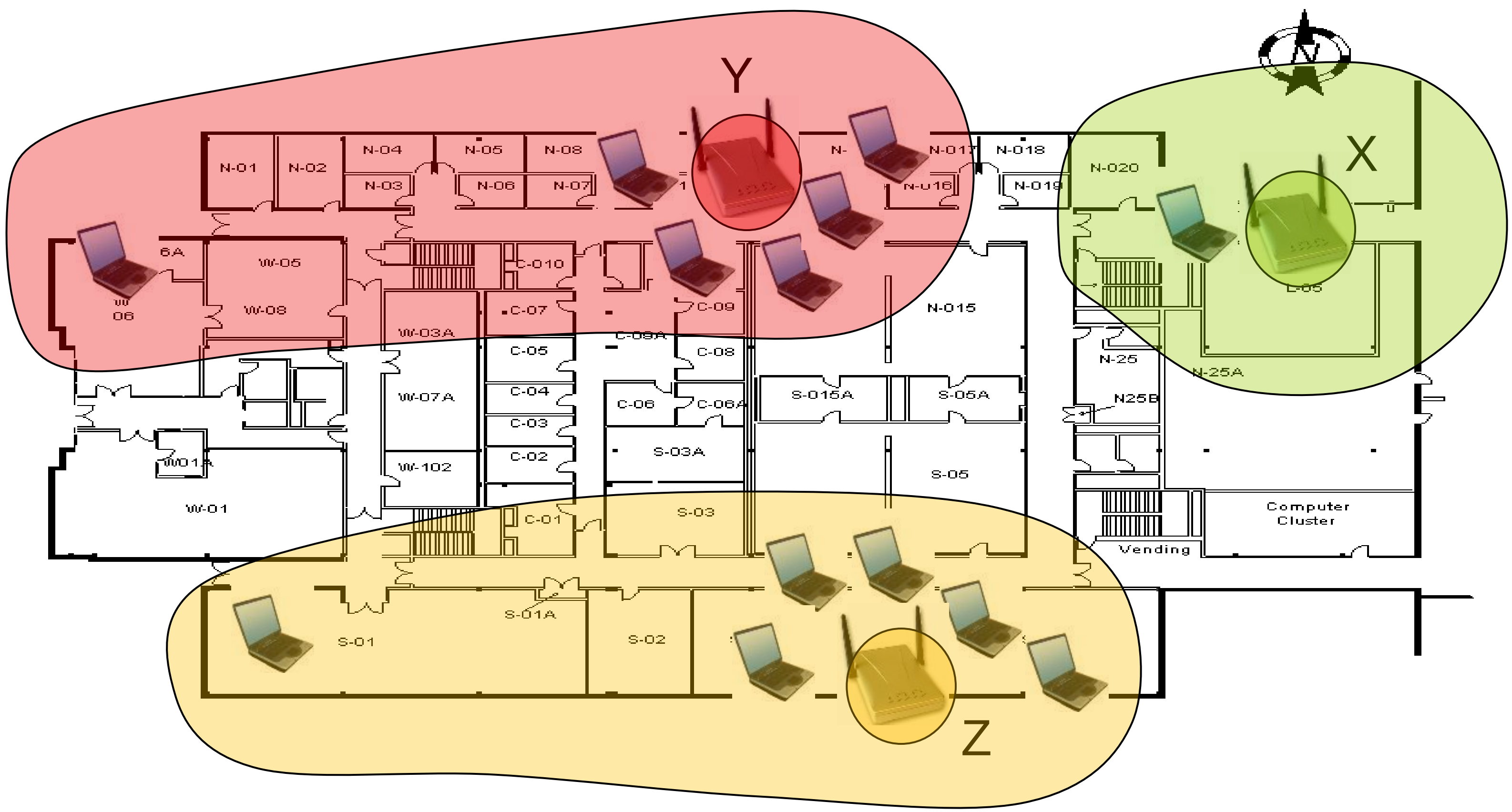
[Hua et al, TCS'09]

[Yu et al, DCOSS'11]

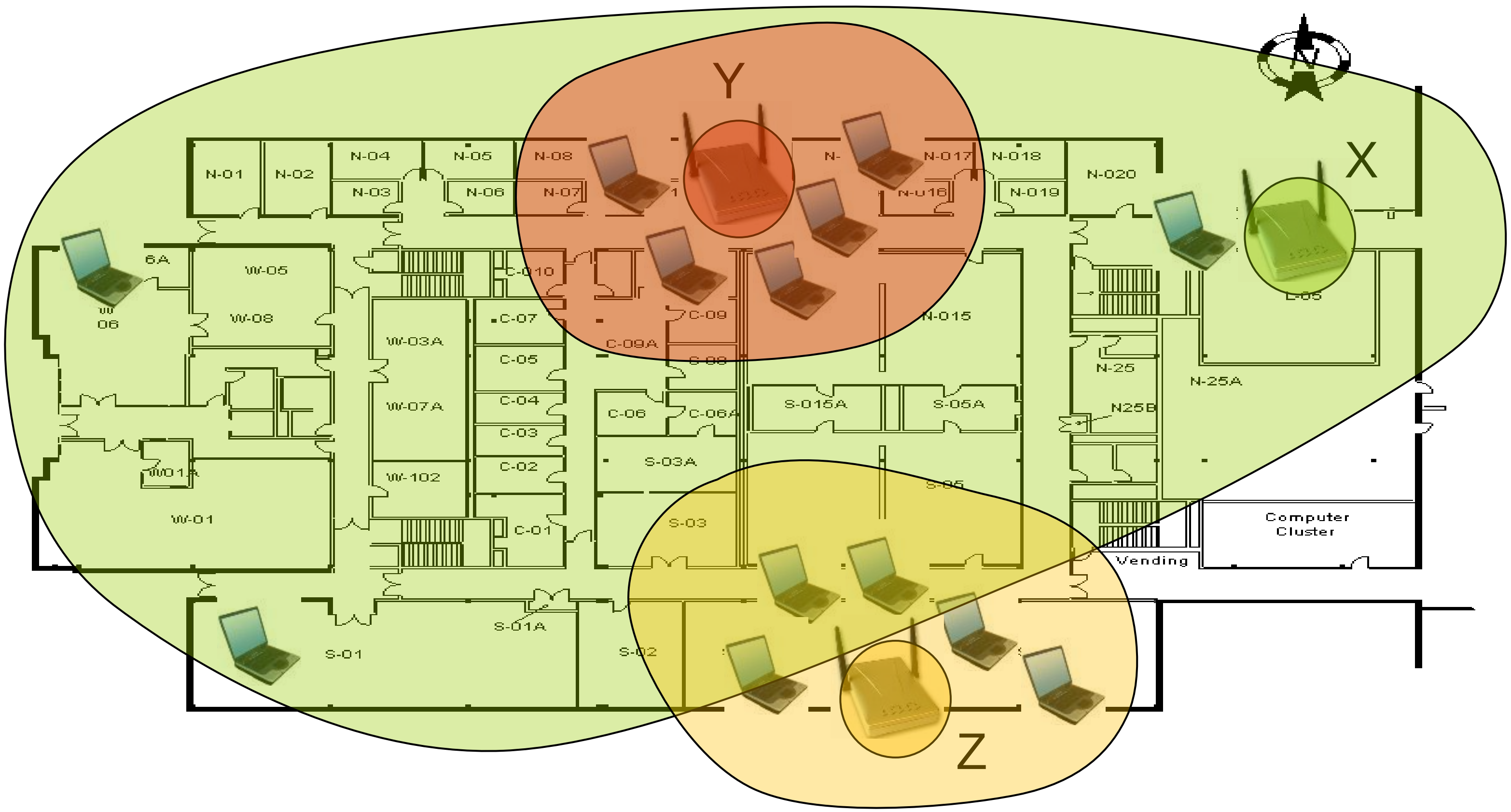
[Goussevskaia et al, MOBIHOC'07]

etc…

Possible Application – Hotspots in WLAN

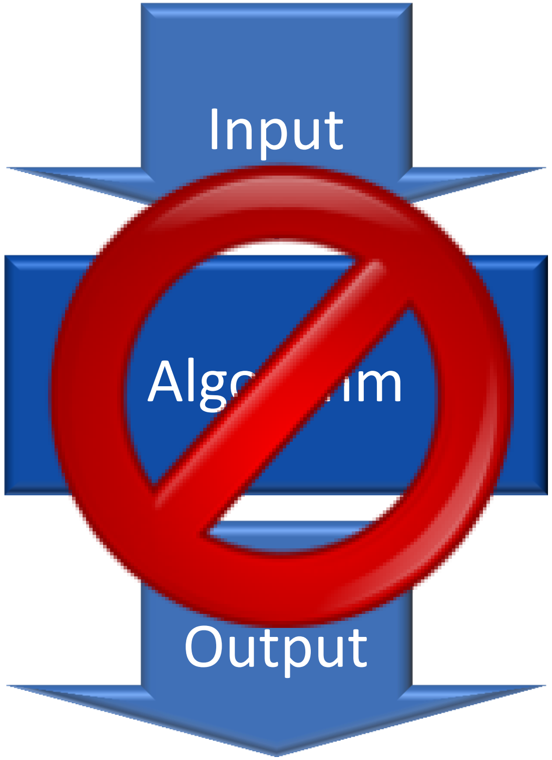


Possible Application – Hotspots in WLAN



Physical Algorithms?

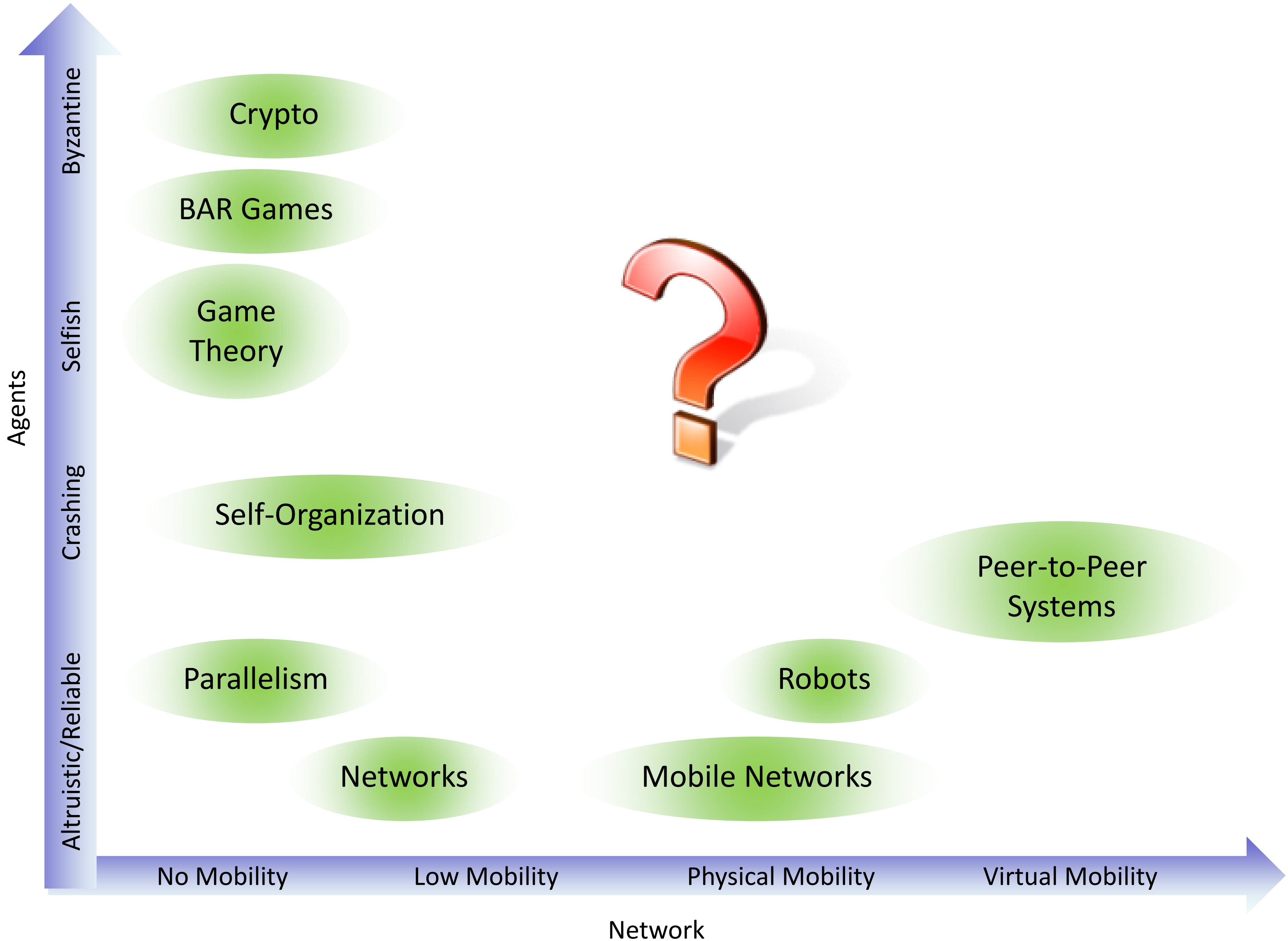
Physical Algorithms



no seq. input/output

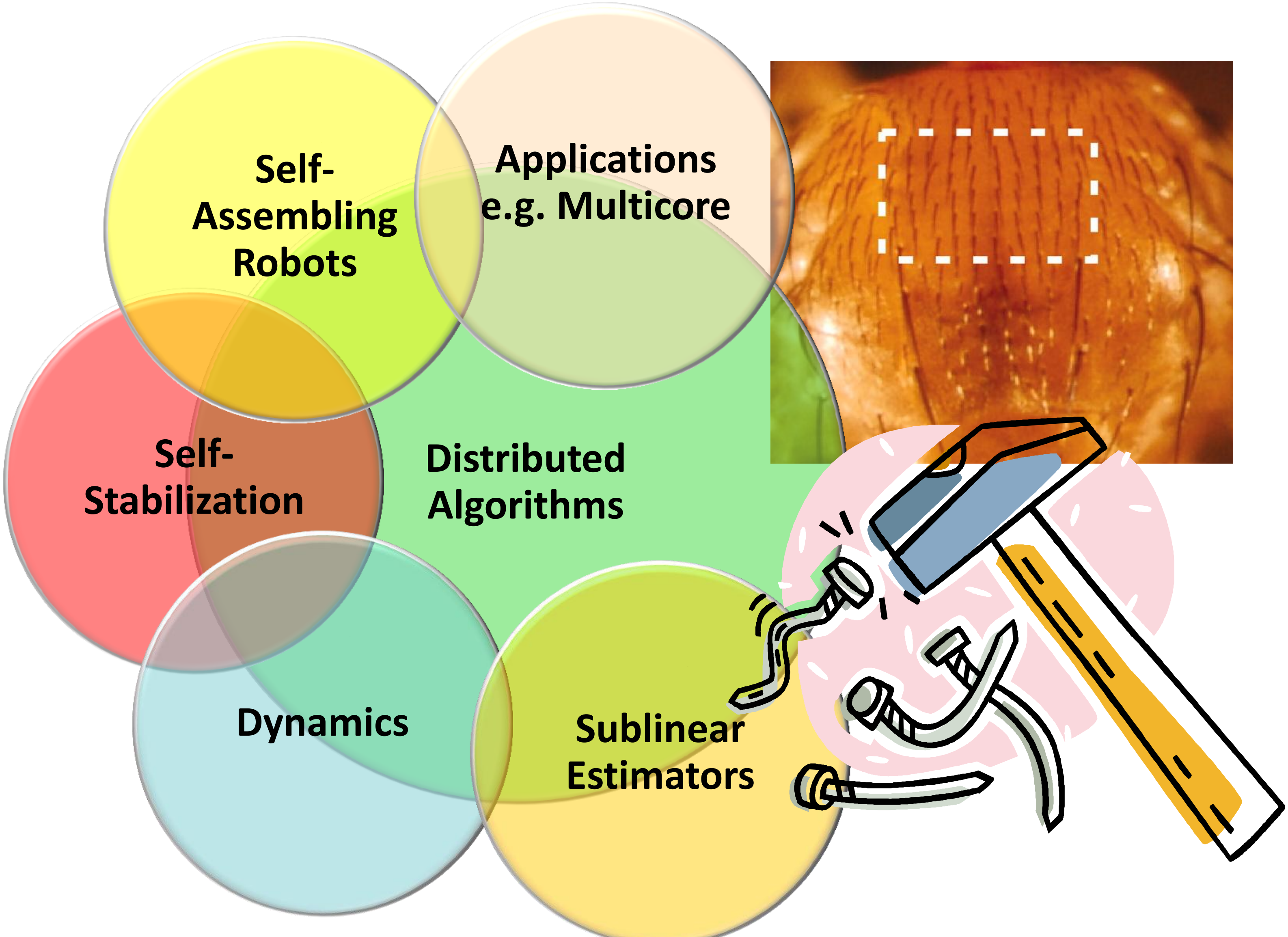
beyond laws of physics


Byzantine
Selfish
Crashing
Altruistic/Reliable
Agents
No Mobility
Low Mobility
Physical Mobility
Virtual Mobility
Network


Agents
Byzantine
Selfish
Crashing
Altruistic/Reliable
Crypto
BAR Games
Game Theory
Self-Organization
Parallelism
Networks
Mobile Networks
Robots
Peer-to-Peer Systems
No Mobility
Low Mobility
Physical Mobility
Virtual Mobility
Network

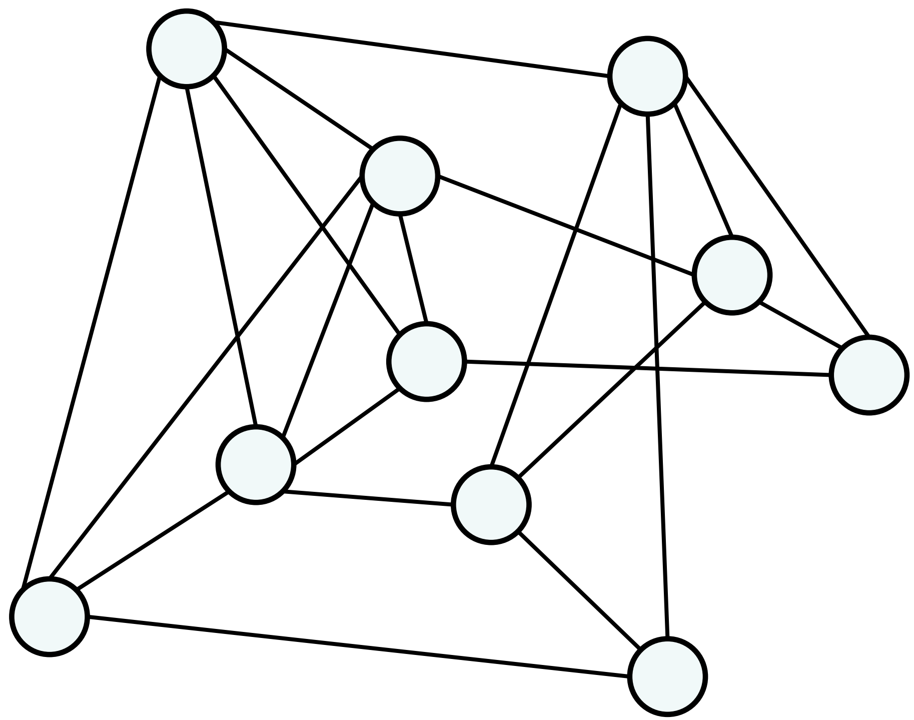
Some Unifying Theory?

Distributed Algorithms is Tool to Understand Physical Algorithms



Distributed Algorithms: A Simple Example

How Many Nodes in Network?



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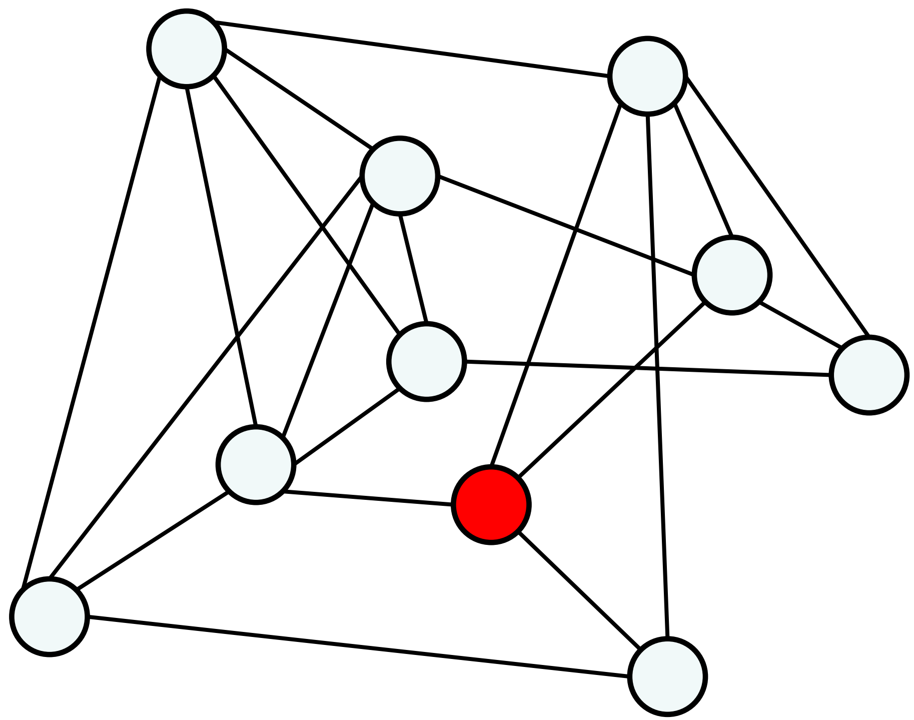

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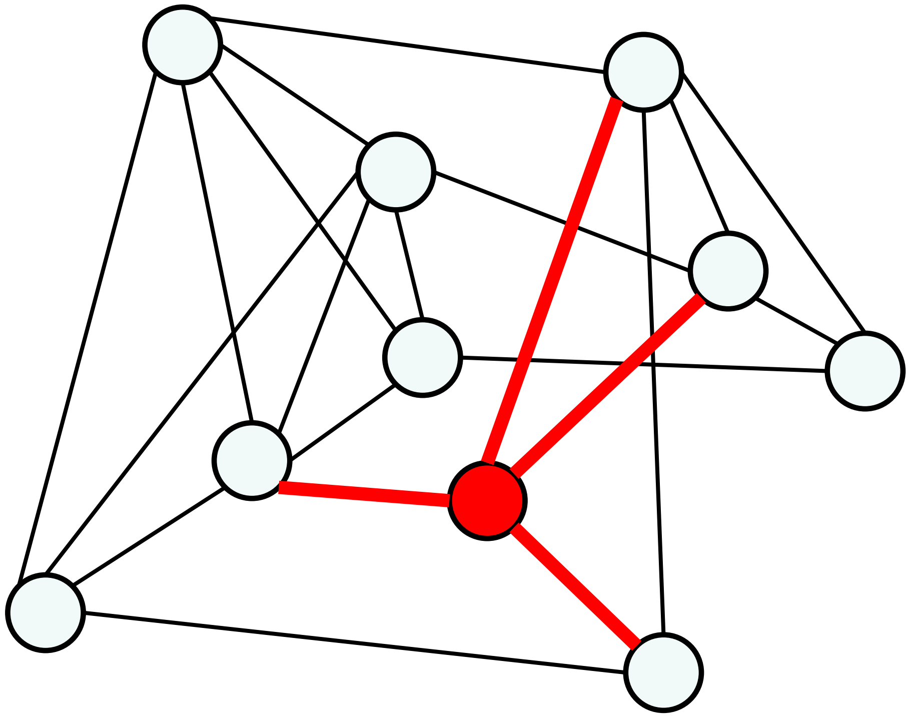

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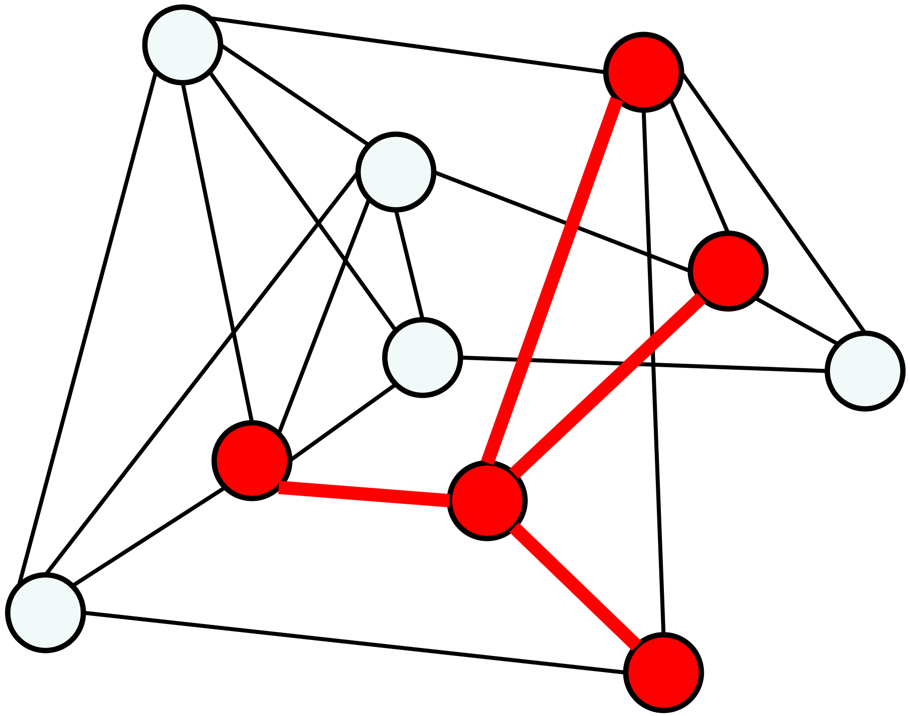

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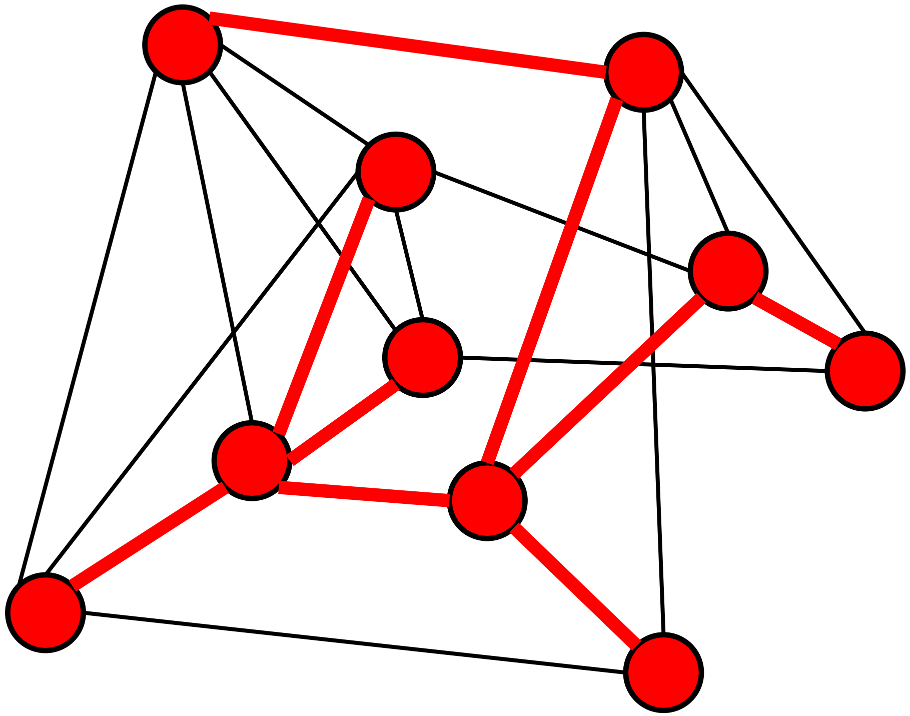

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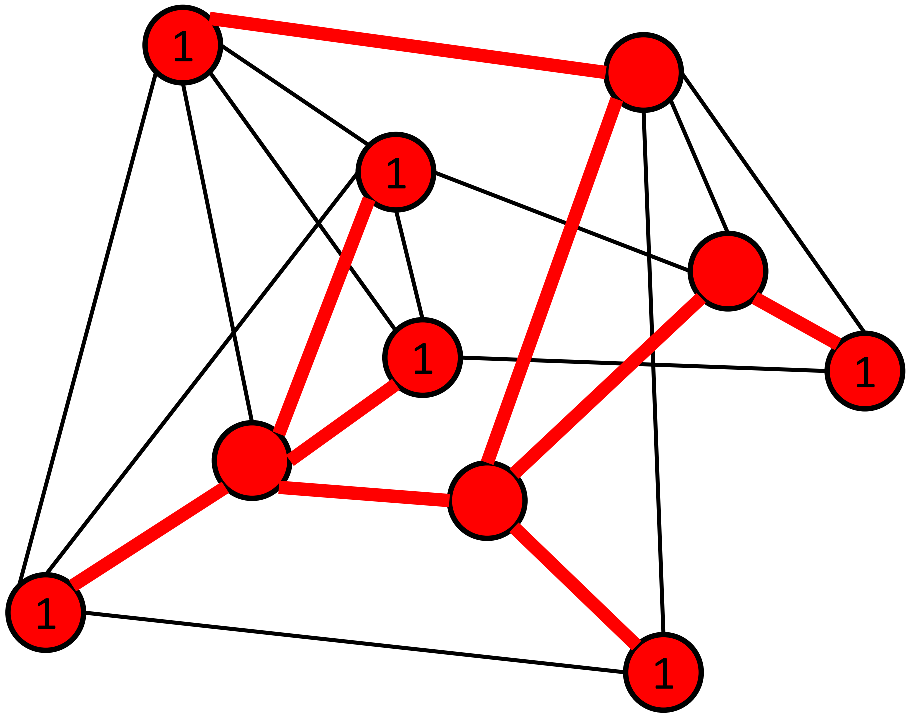

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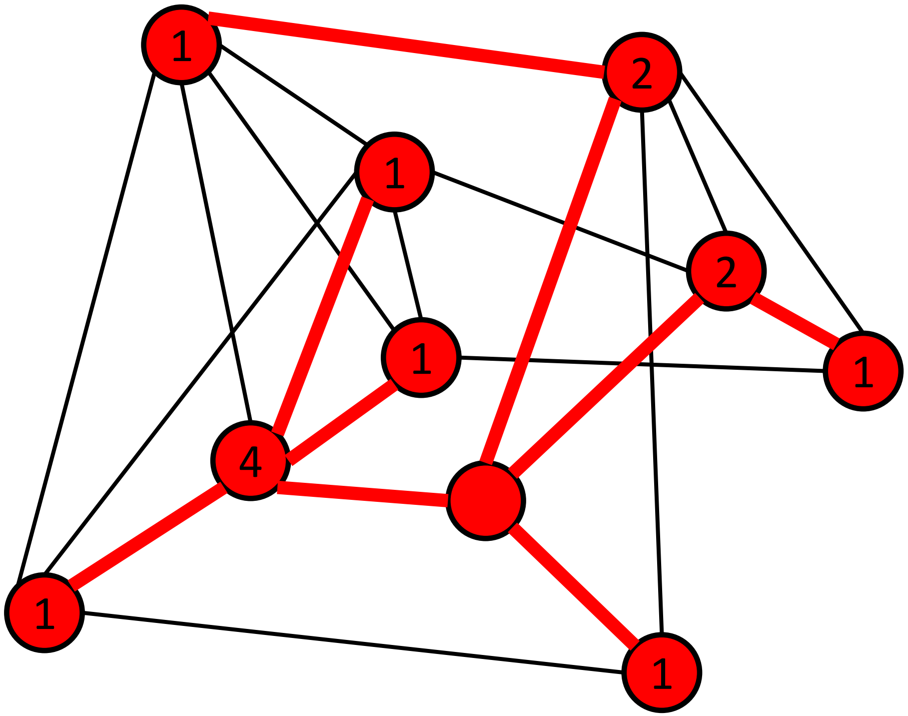

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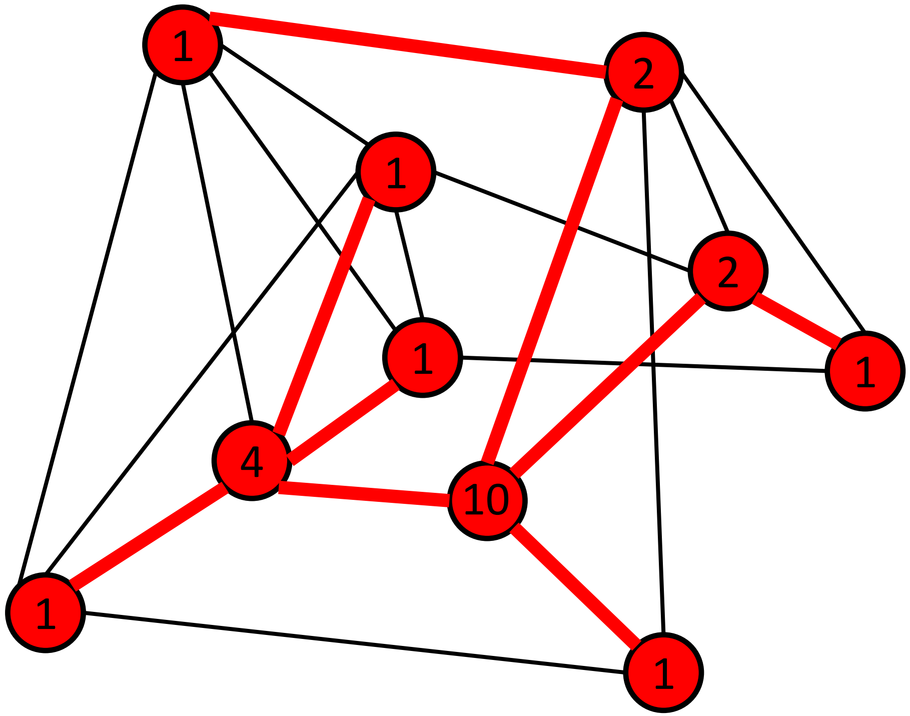
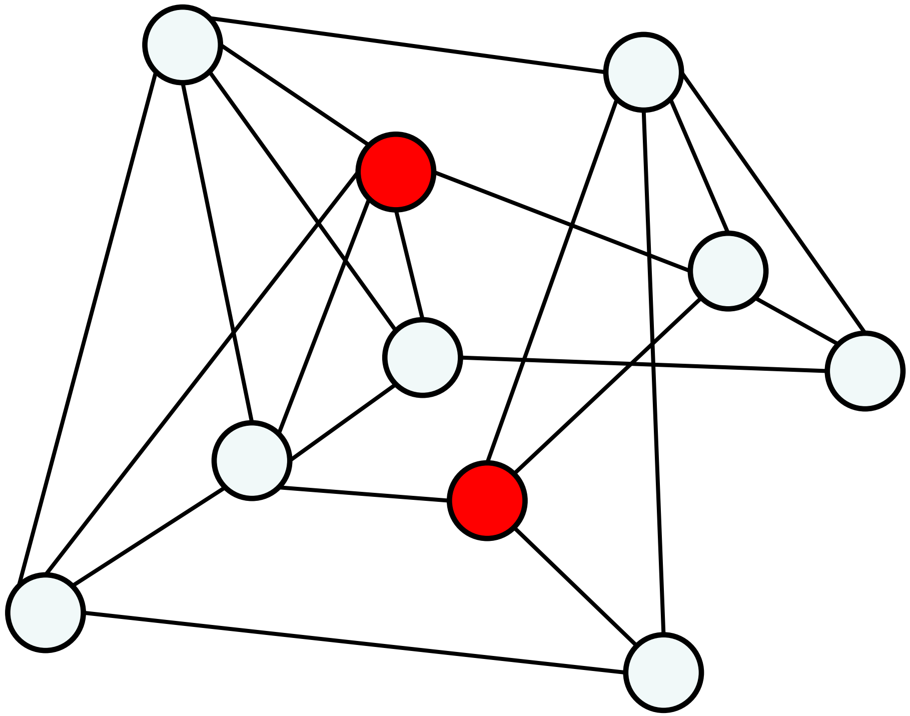


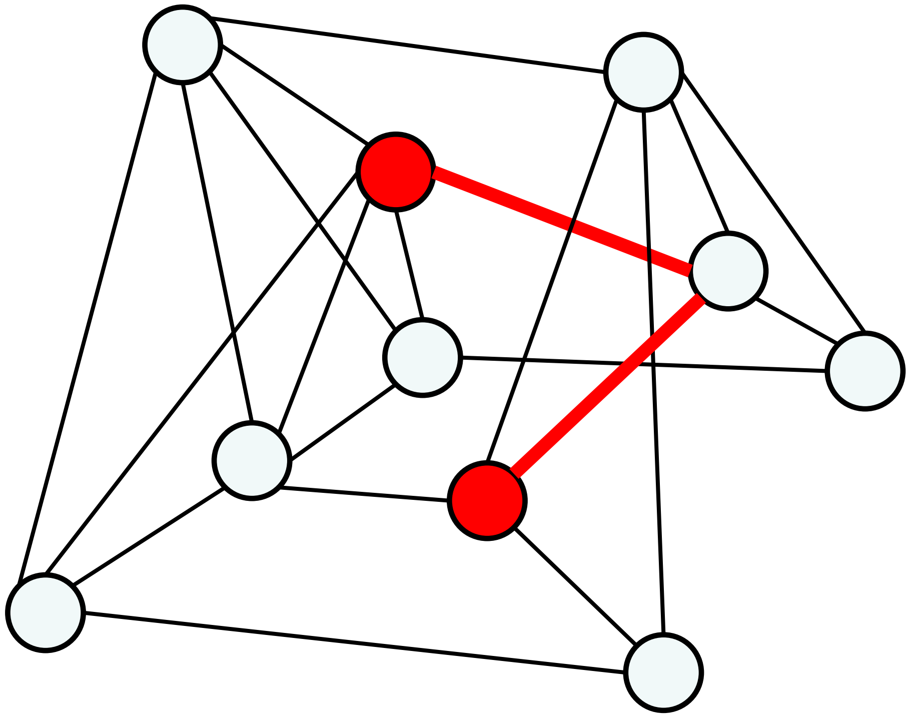
With a simple flooding/echo process, a network can find the number of nodes in time $O(D)$, where D is the diameter (size) of the network.

Diameter (Size) of Network?



- Distance between two nodes = Number of hops of shortest path

Diameter (Size) of Network?



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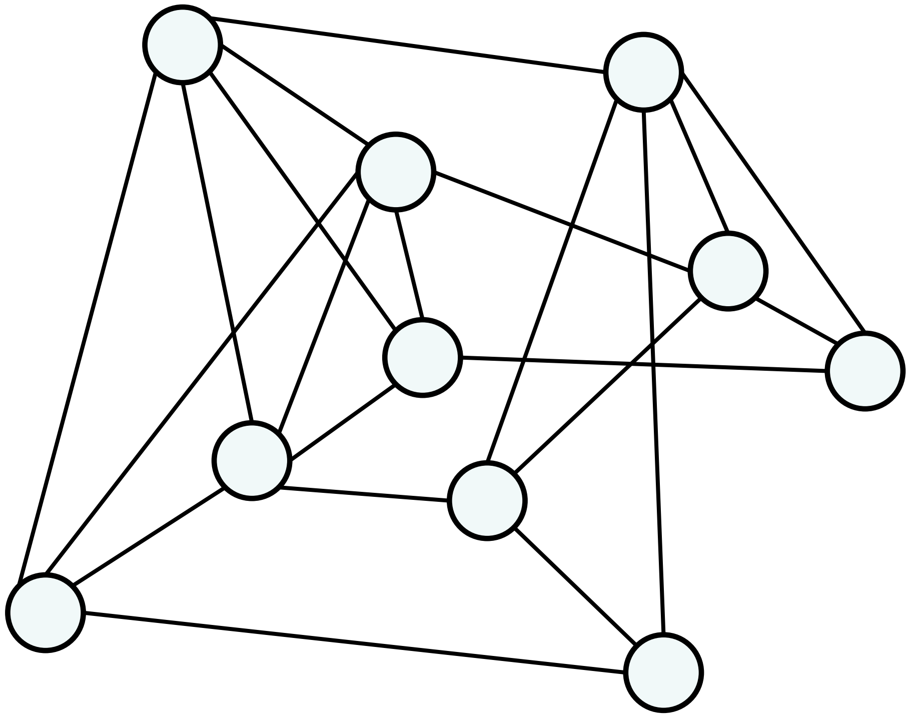
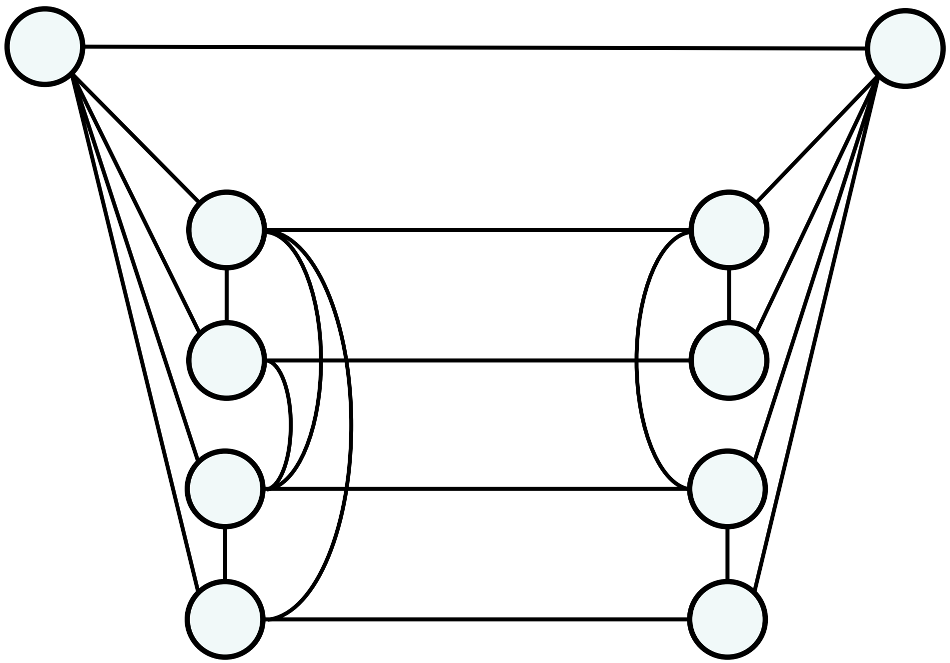
Diameter (Size) of Network?



- Distance between two nodes = Number of hops of shortest path
- Diameter of network = Maximum distance, between any two nodes

Networks Cannot Compute Their Diameter in Sublinear Time!

(even if diameter is just a small constant)



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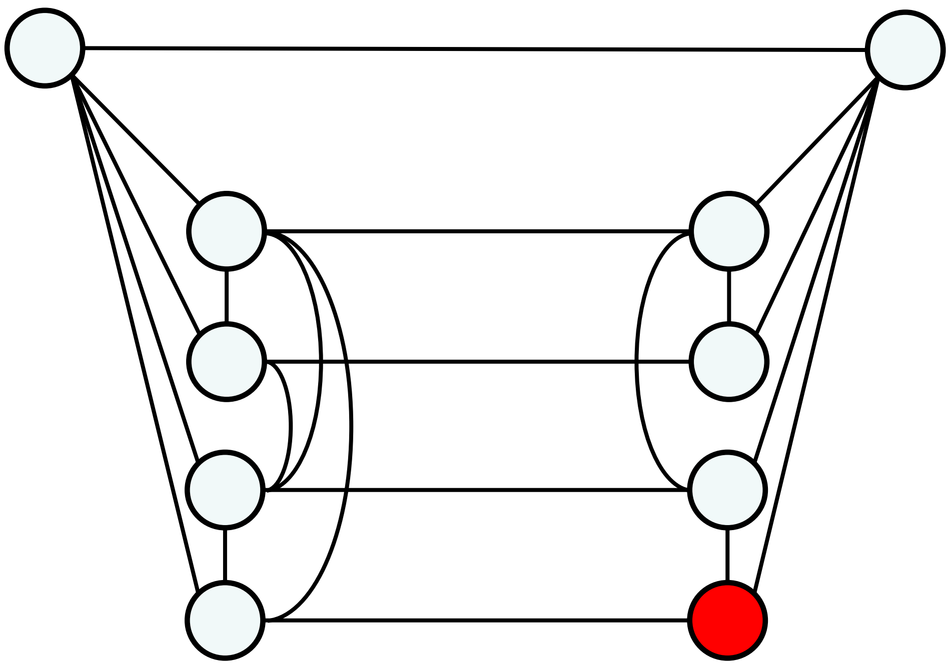

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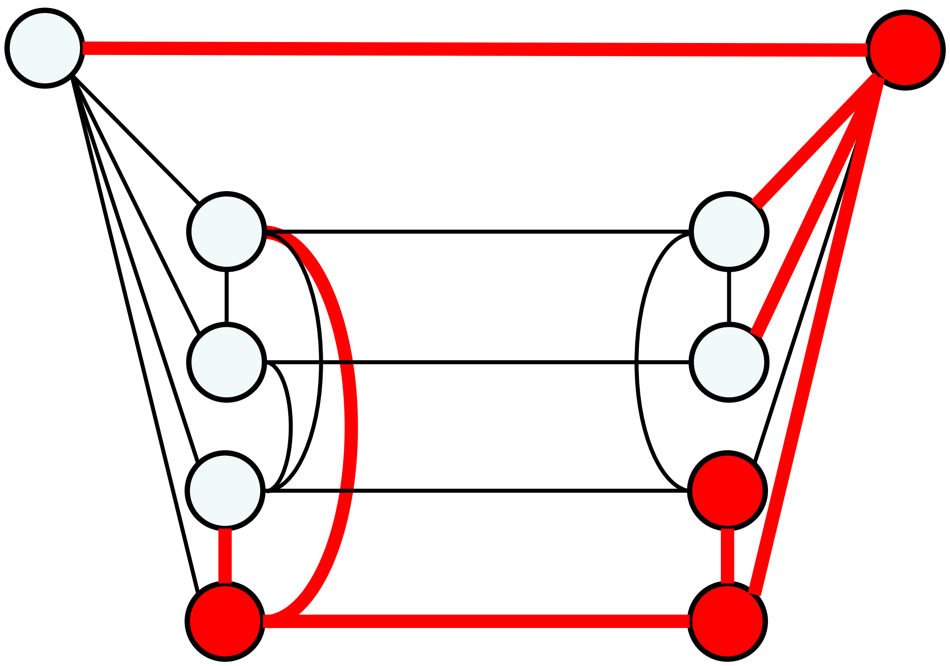
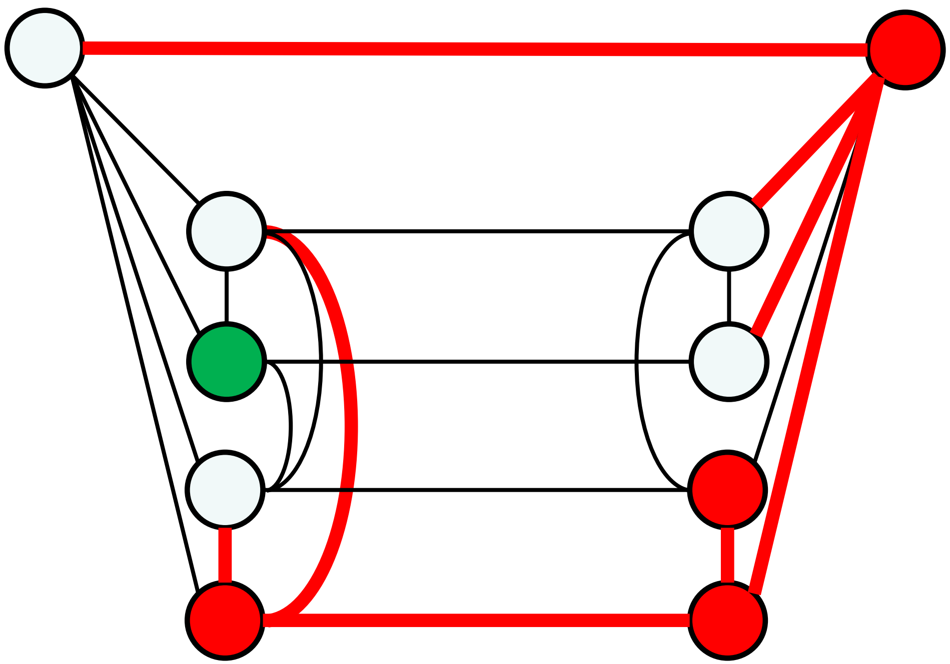
(even if diameter is just a small constant)



Networks Cannot Compute Their Diameter in Sublinear Time!

(even if diameter is just a small constant)



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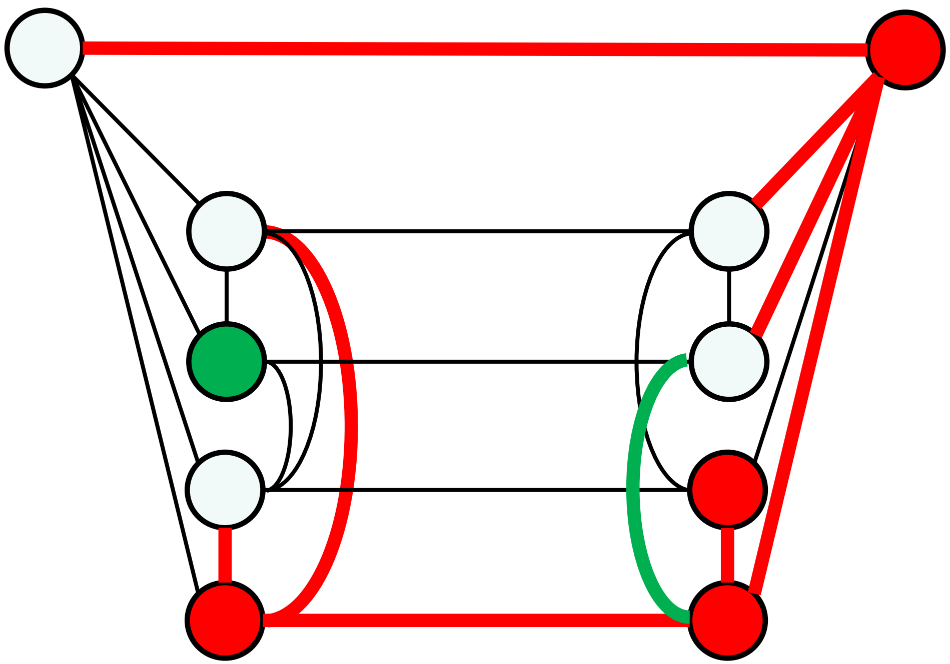

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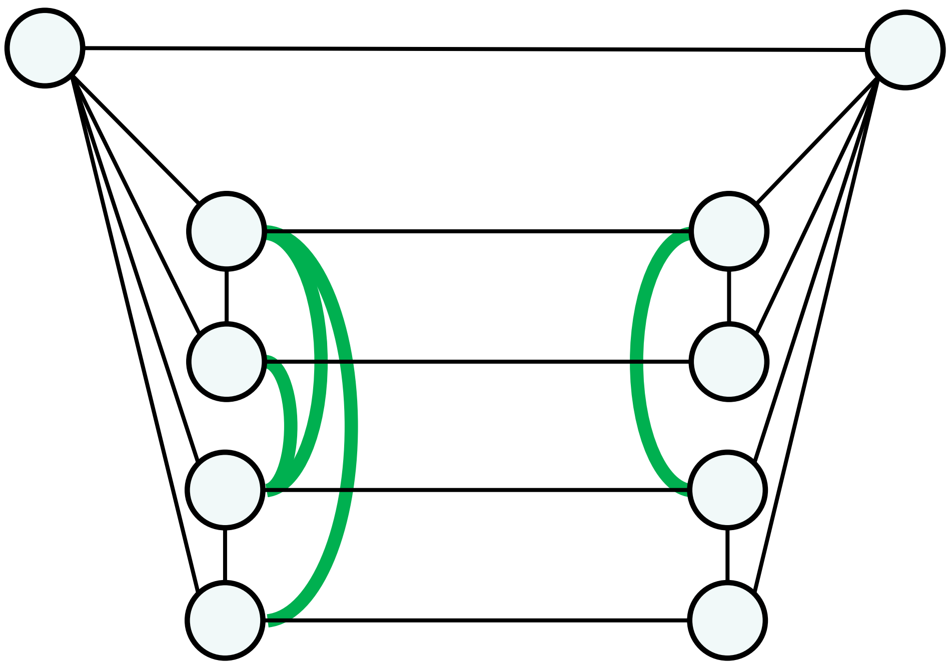

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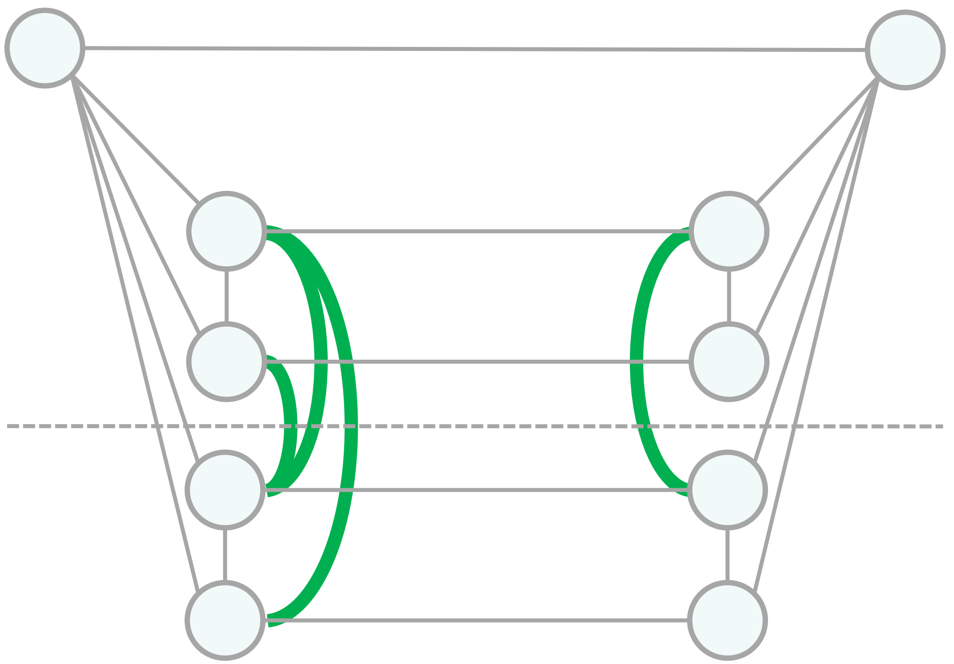

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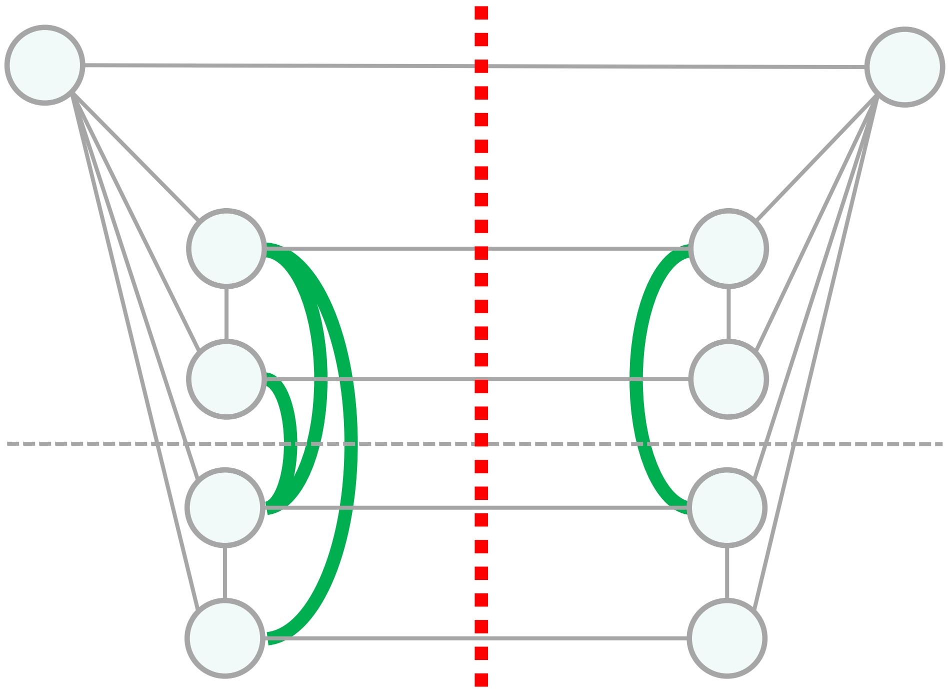

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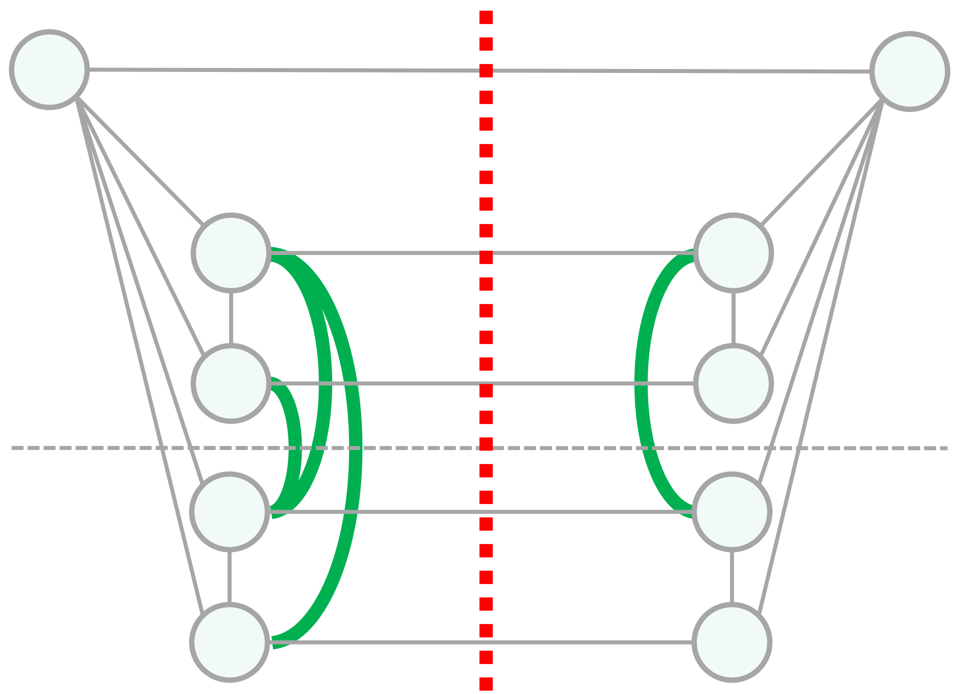
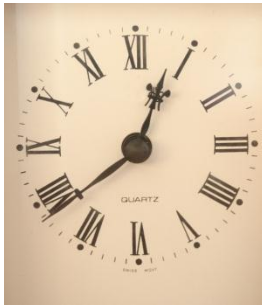
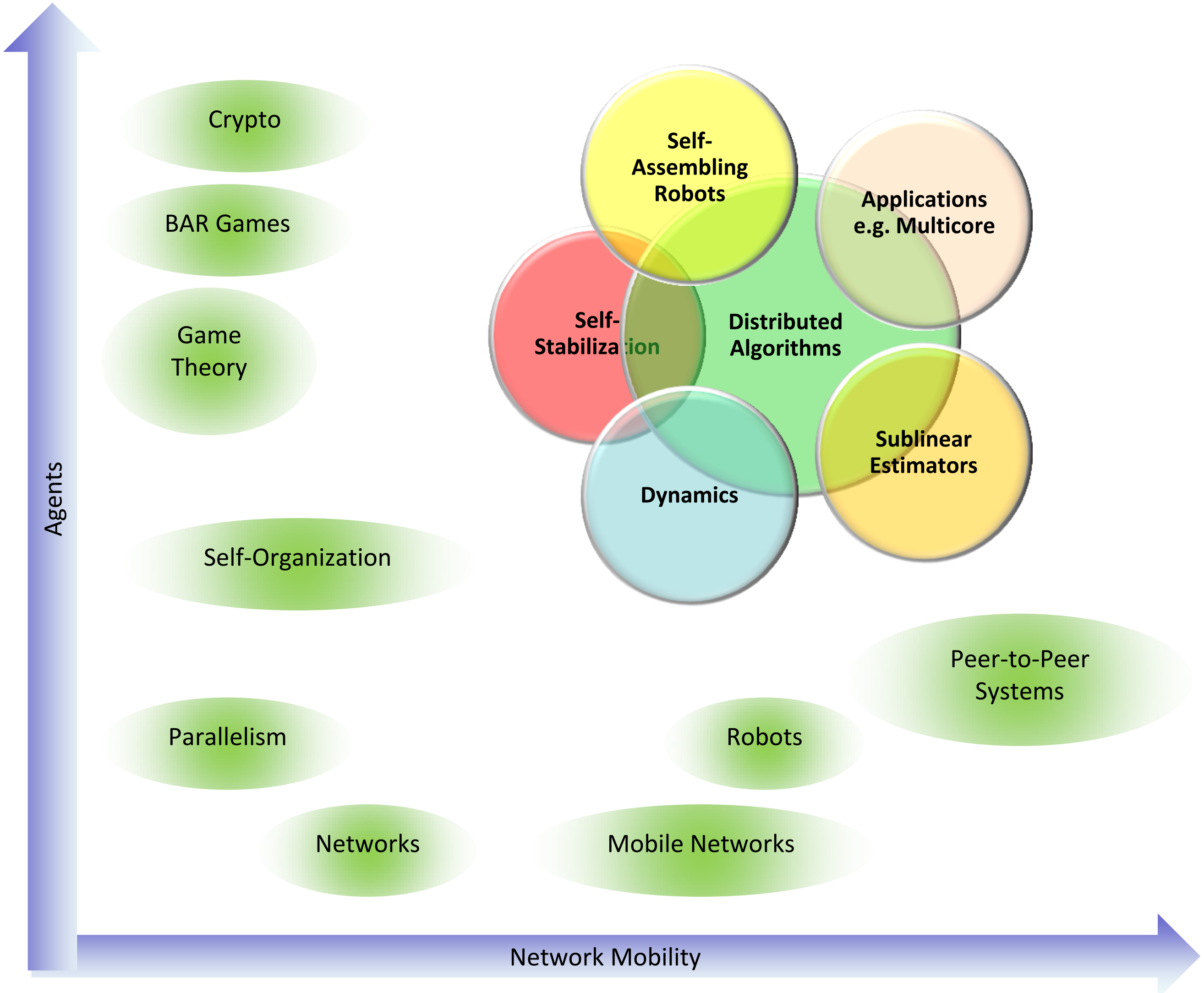


Pair of nodes not connected on both sides? We have $\Theta(n^2)$ information that has to be transmitted over $O(n)$ edges, which takes $\Omega(n)$ time!

[Frischknecht, Holzer, W, 2012]

Summary

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Self-Assembling Robots
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Dynamics

Thank You!

Questions & Comments?

Thanks to my co-authors
Silvio Frischknecht
Stephan Holzer
Christoph Lenzen
Thomas Moscibroda
Thomas Locher
Philipp Sommer

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