Ad Hoc Networks: Pushing Mobile and Wireless Communication (Since 1970)

Roger Wattenhofer


Packet
Radio

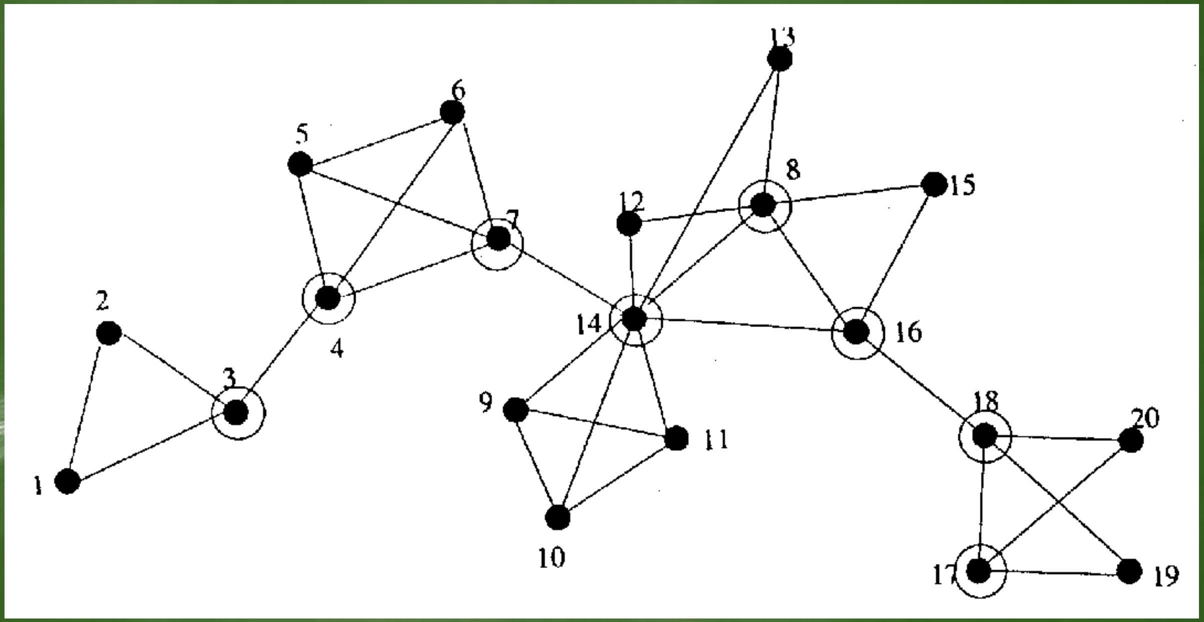
Why Do You Study Ad Hoc Networks?


CHECKLIST
important applications
it’s fun
for the money


CHECKLIST, really
mobile
wireless
energy

Mobile Networks?

Distributed Control!



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Complexity Theory

Can a Computer Solve Problem P in Time t?

Distributed

Complexity Theory

Network

Can a ~~Computer~~ Solve Problem *P* in Time *t*?

Network

~~Distributed~~

Complexity Theory

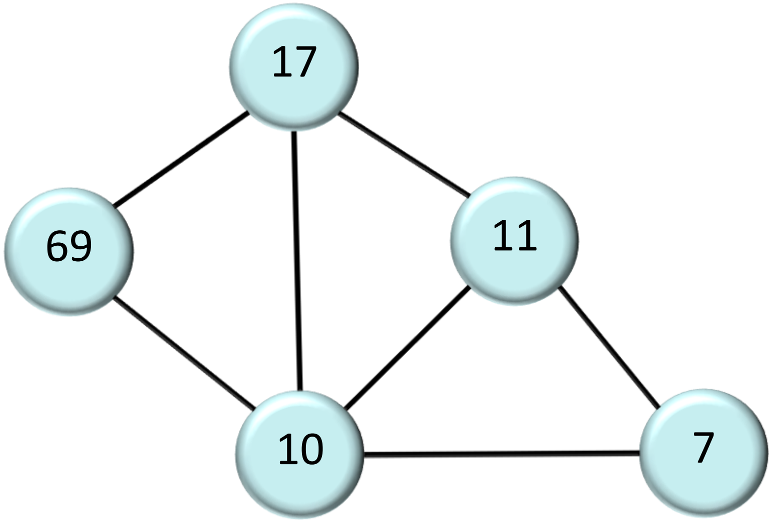
Network

Can a ~~Computer~~ Solve

Problem *P* in Time *t*?

Distributed (Message-Passing) Algorithms

- Nodes are agents with unique ID's that can communicate with neighbors by sending messages. In each synchronous round, every node can send a (different) message to each neighbor.



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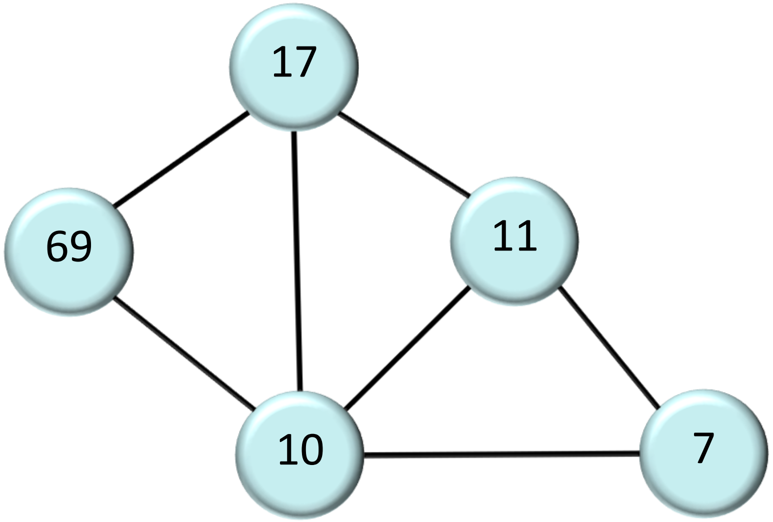


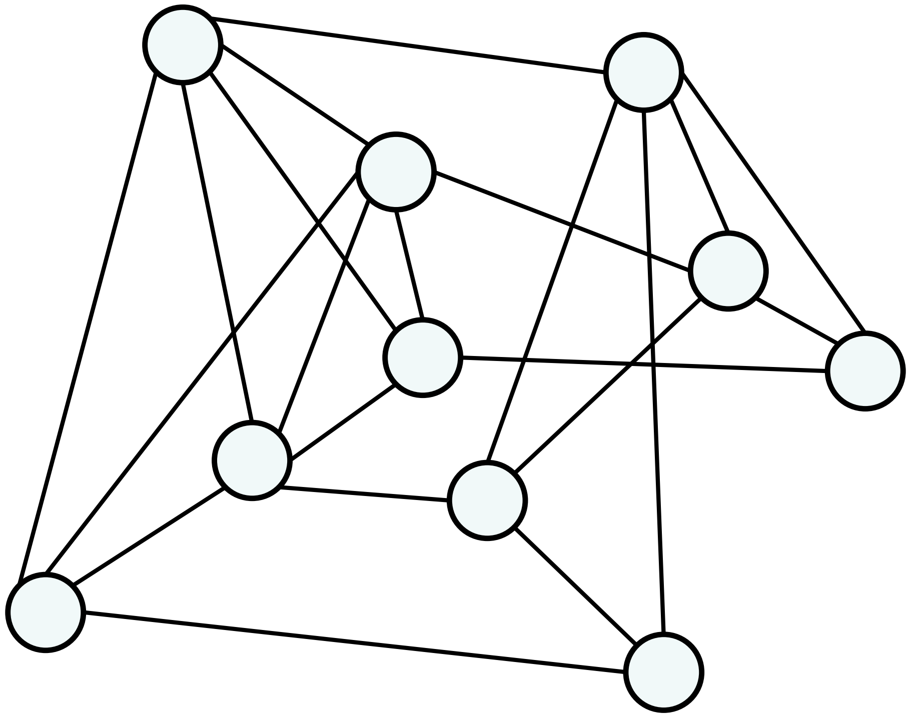

```
each round:
every node:
1. send msgs
2. rcv msgs
3. compute
```

- Distributed (Time) Complexity: How many rounds does problem take?

An Example

each round:
every node:
1. send msgs
2. rcv msgs
3. compute

How Many Nodes in Network?



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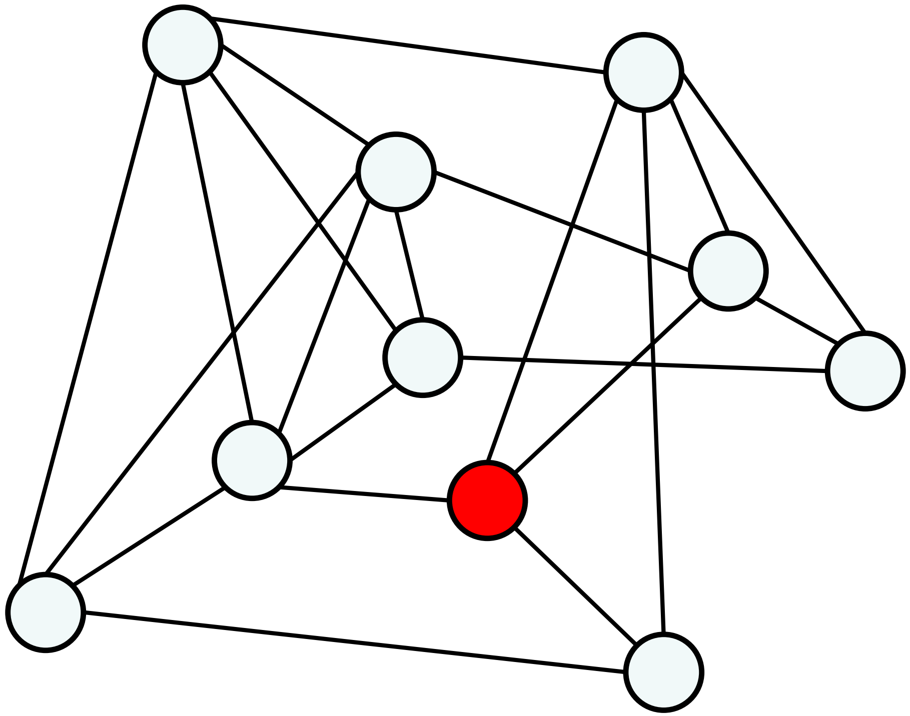

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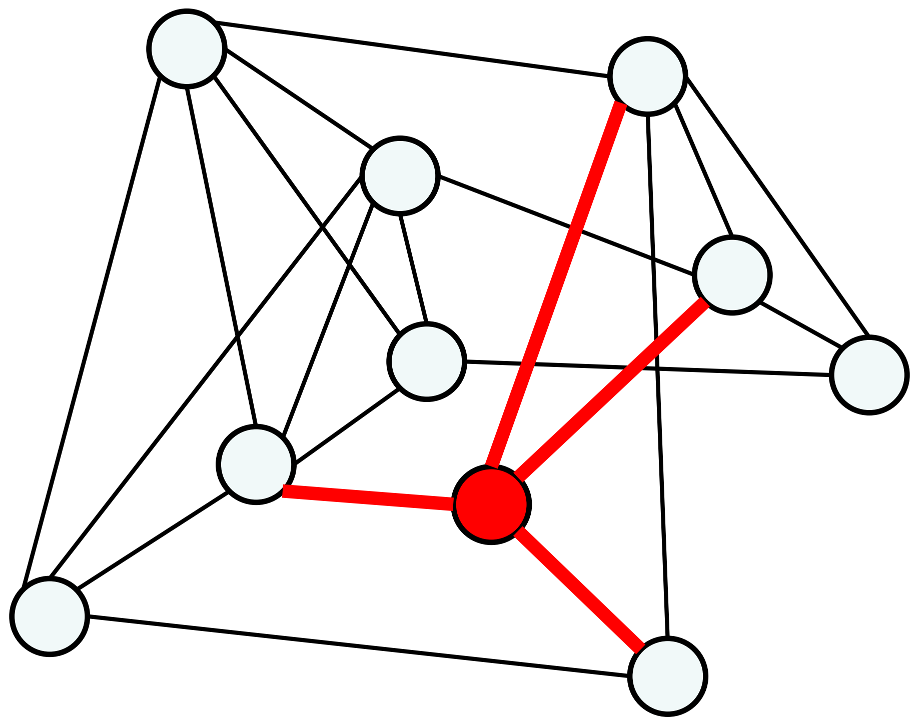

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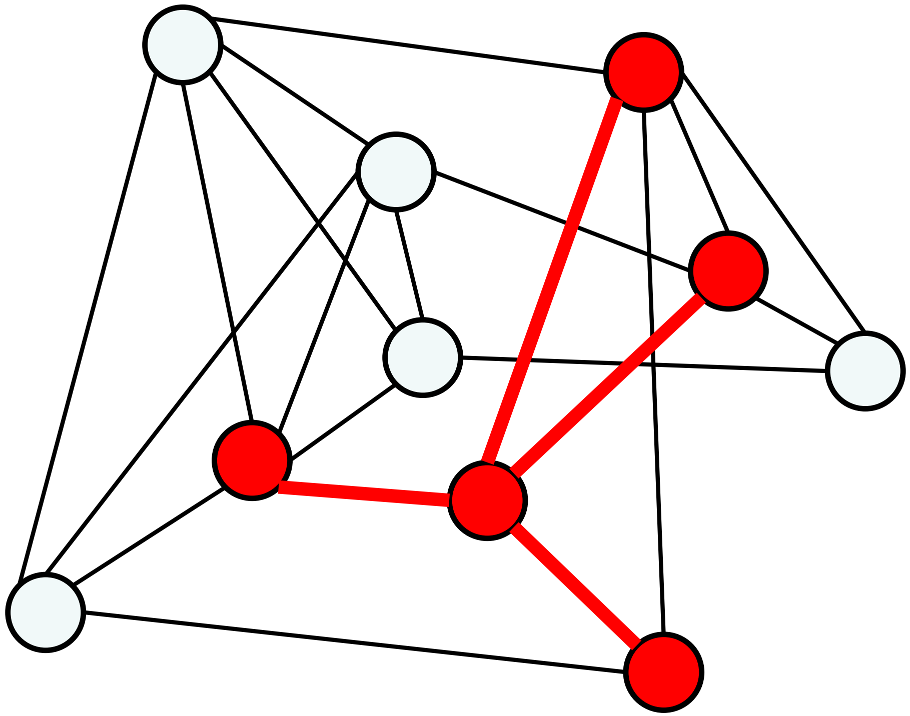

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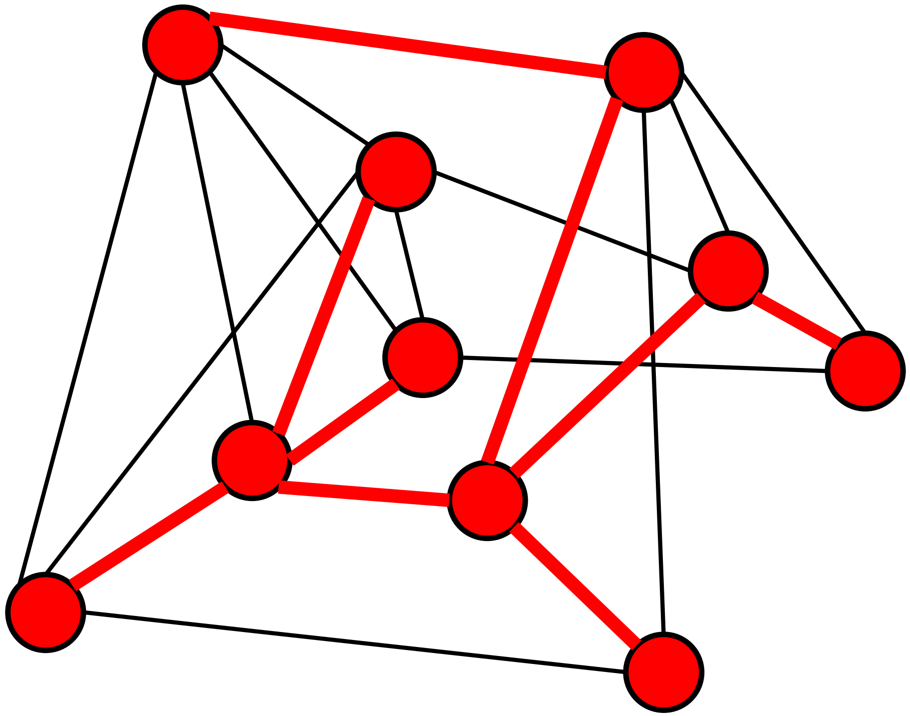

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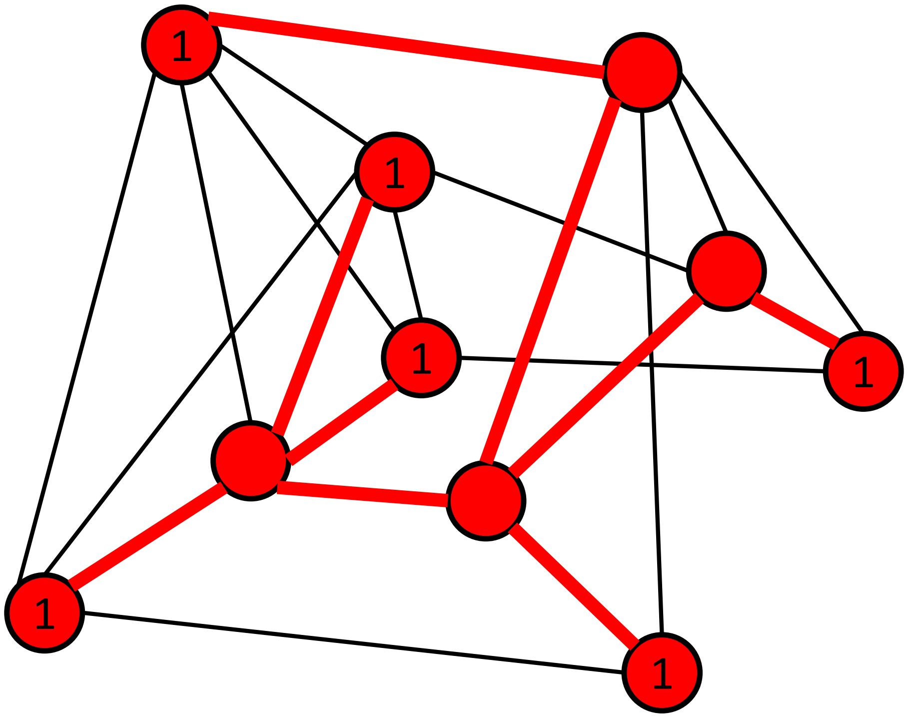

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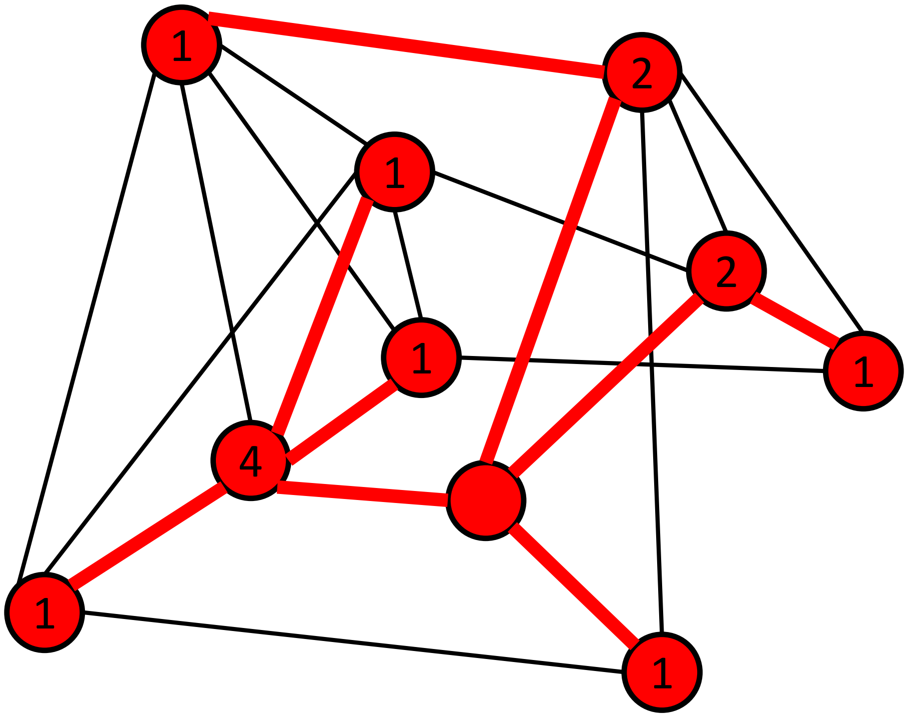

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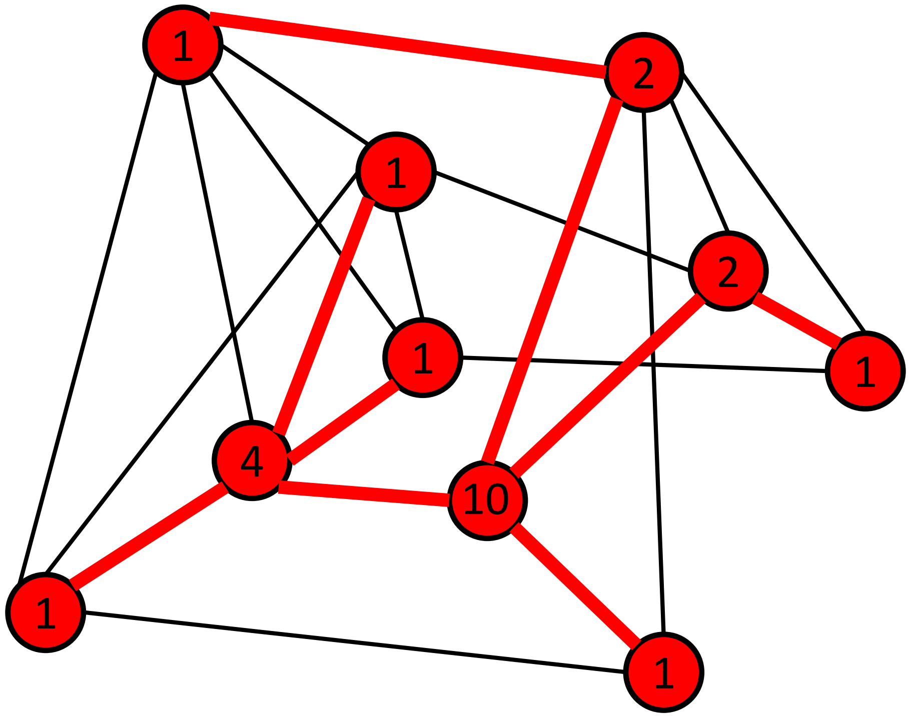
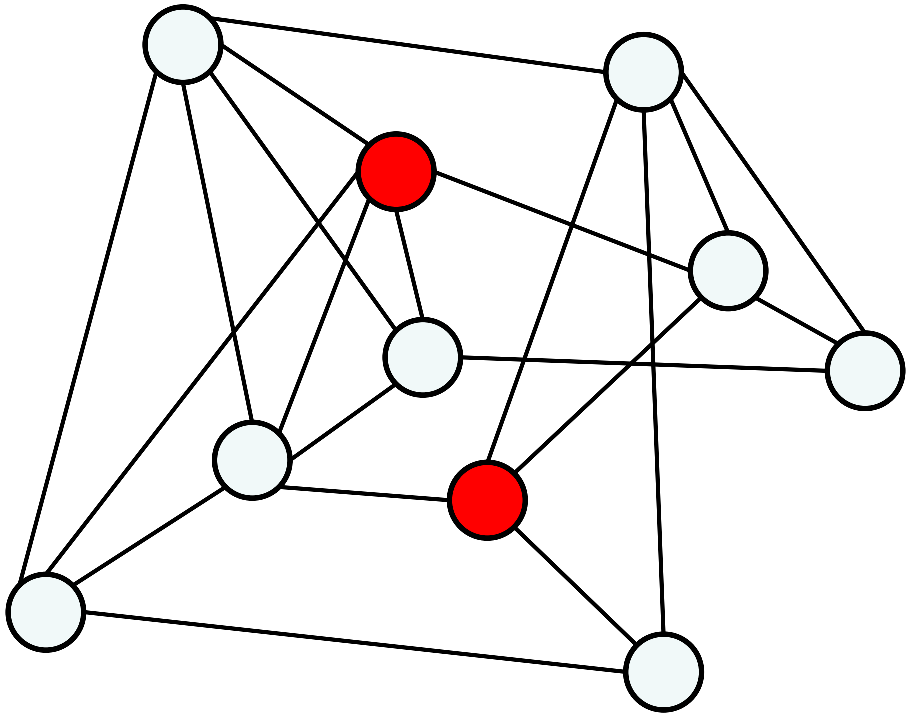


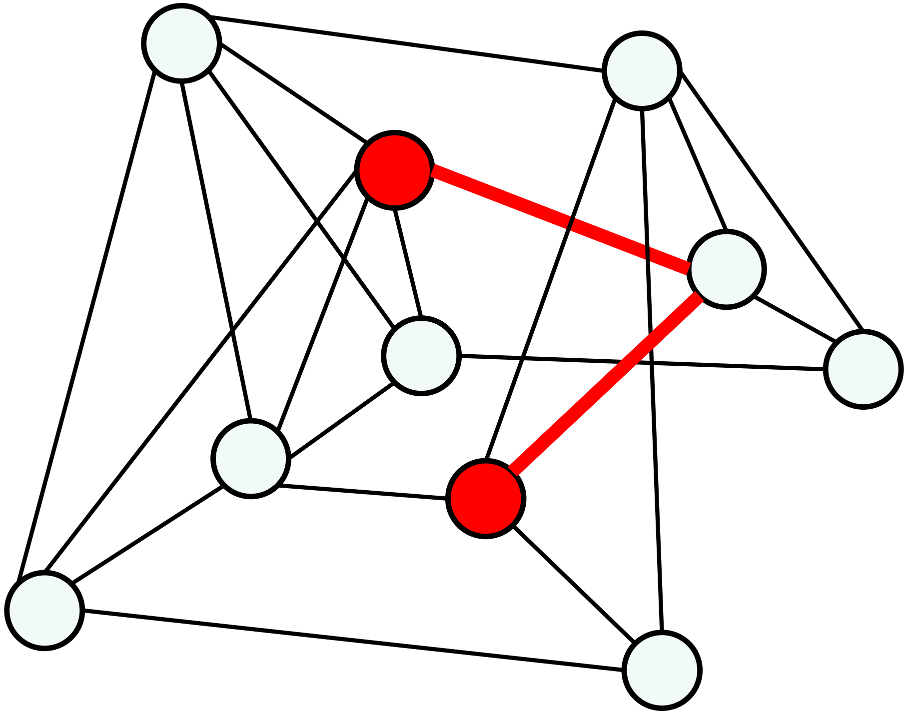
With a simple flooding/echo process, a network can find the number of nodes in time $O(D)$, where D is the diameter (size) of the network.

Diameter of Network?



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

Diameter of Network?



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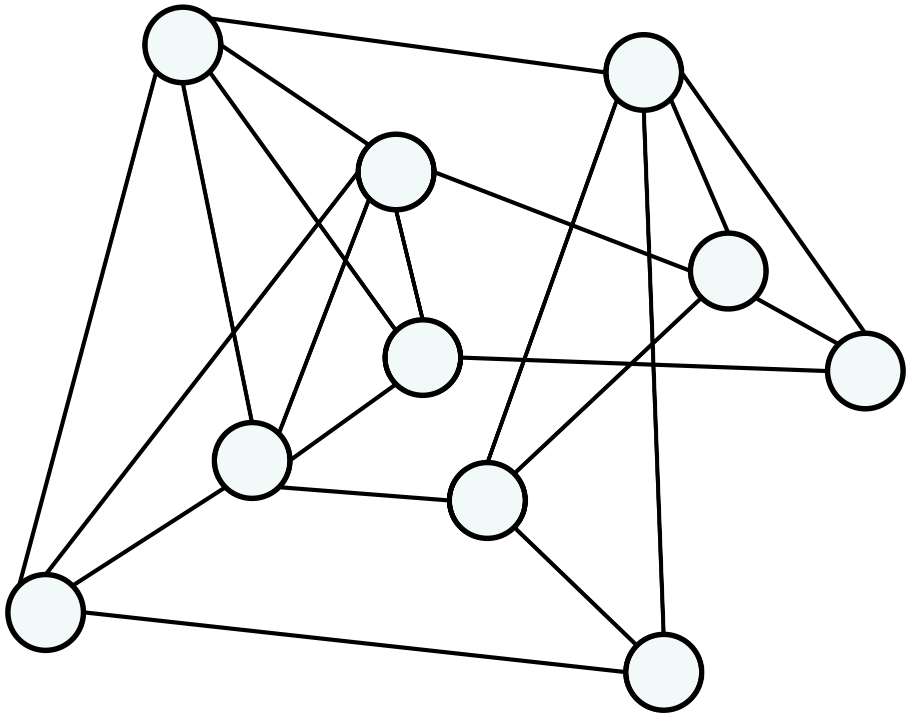
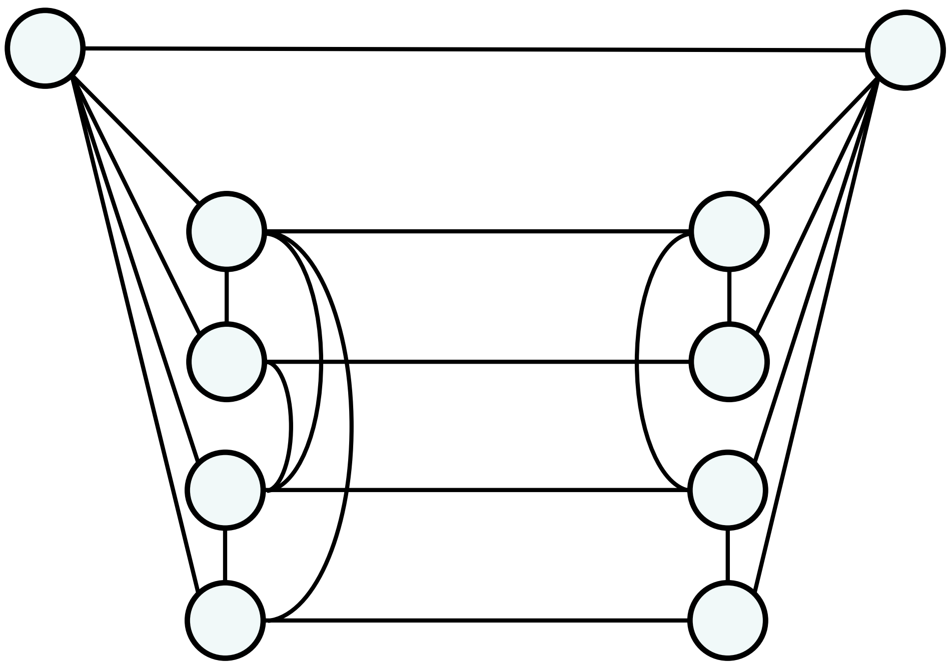
Diameter of Network?



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

Diameter of Network?



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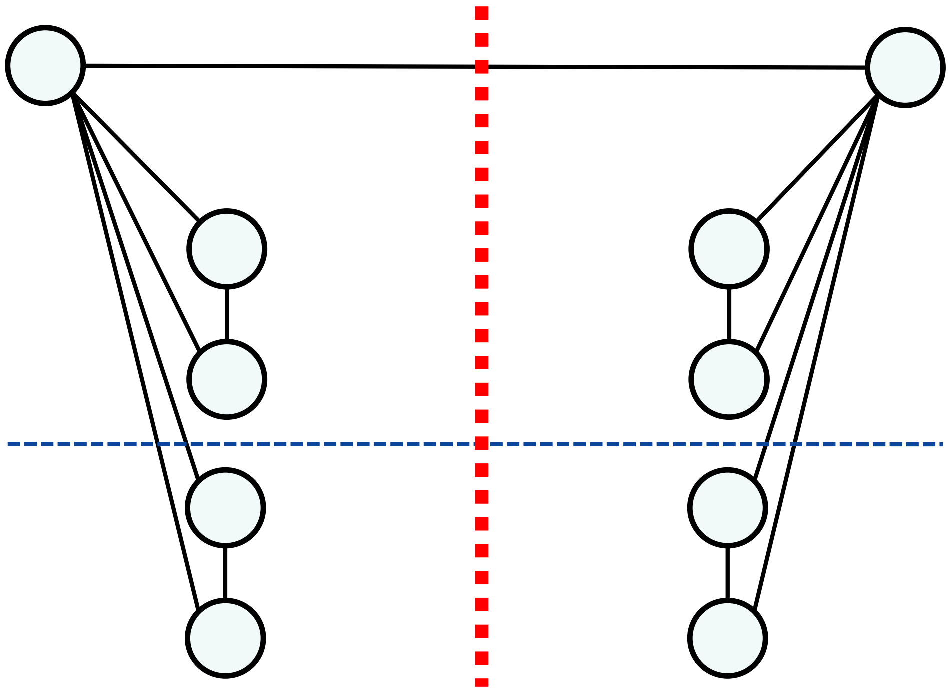

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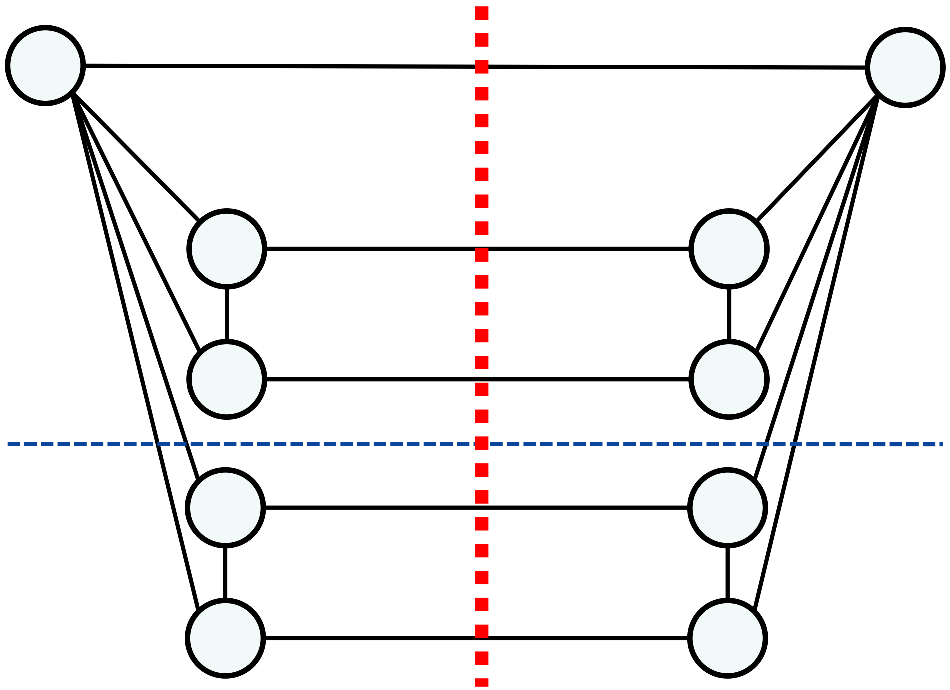

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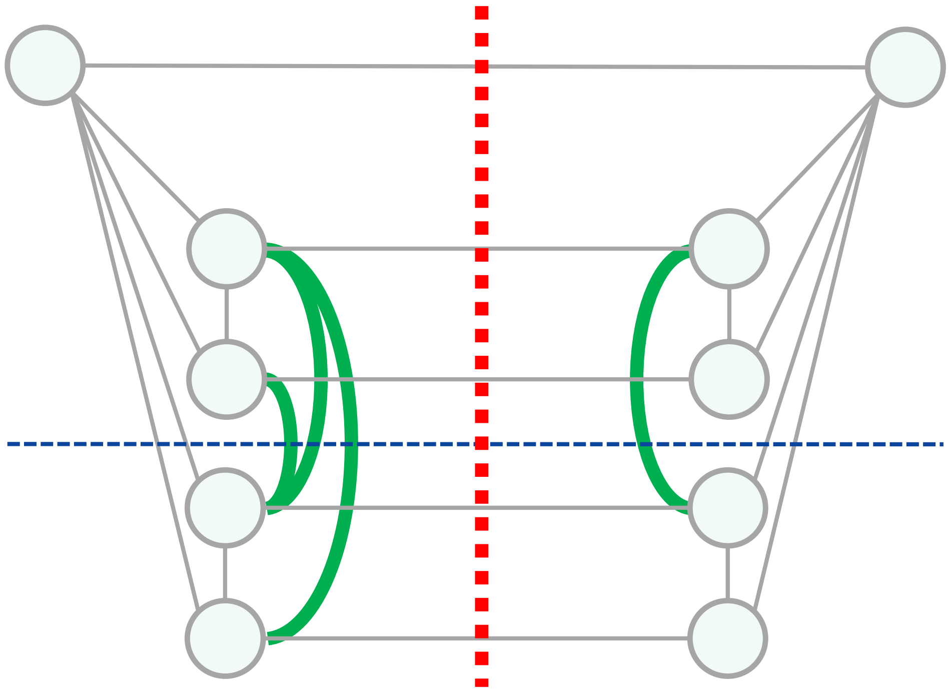

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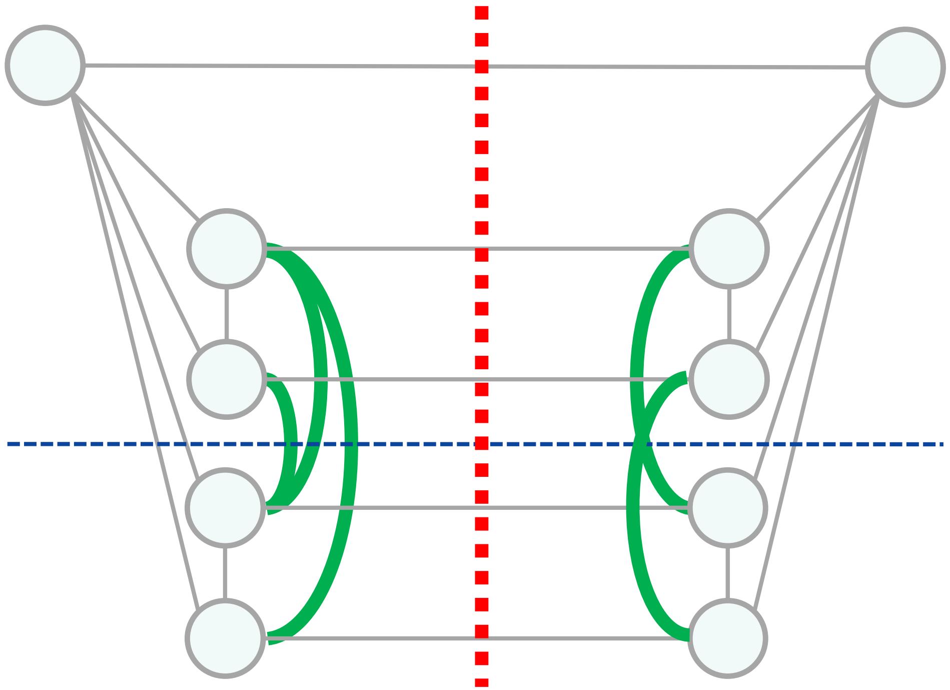

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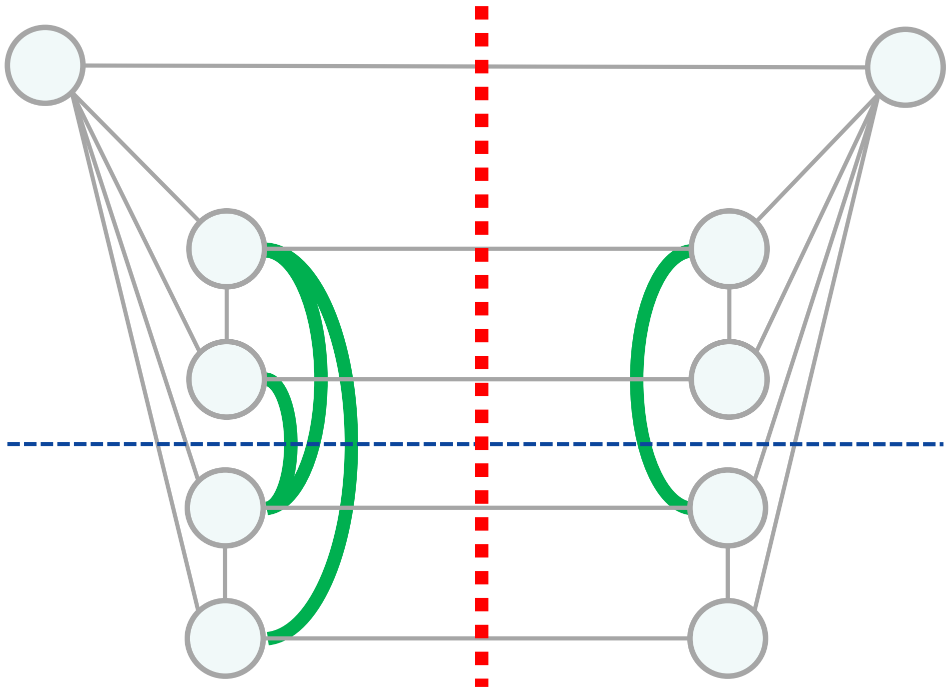
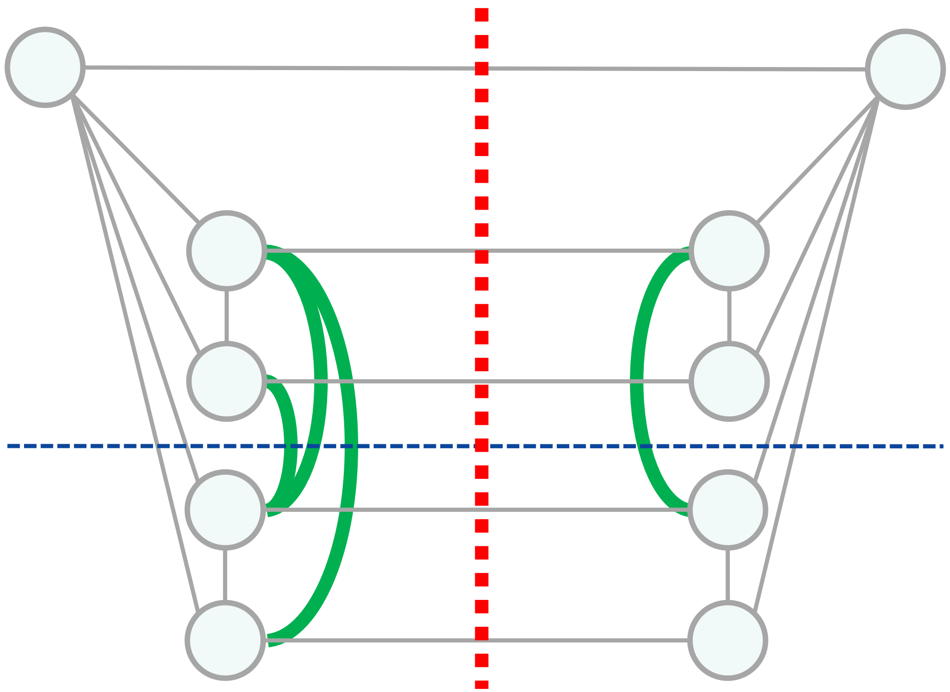


Networks Cannot Compute Their Diameter in Sublinear Time!

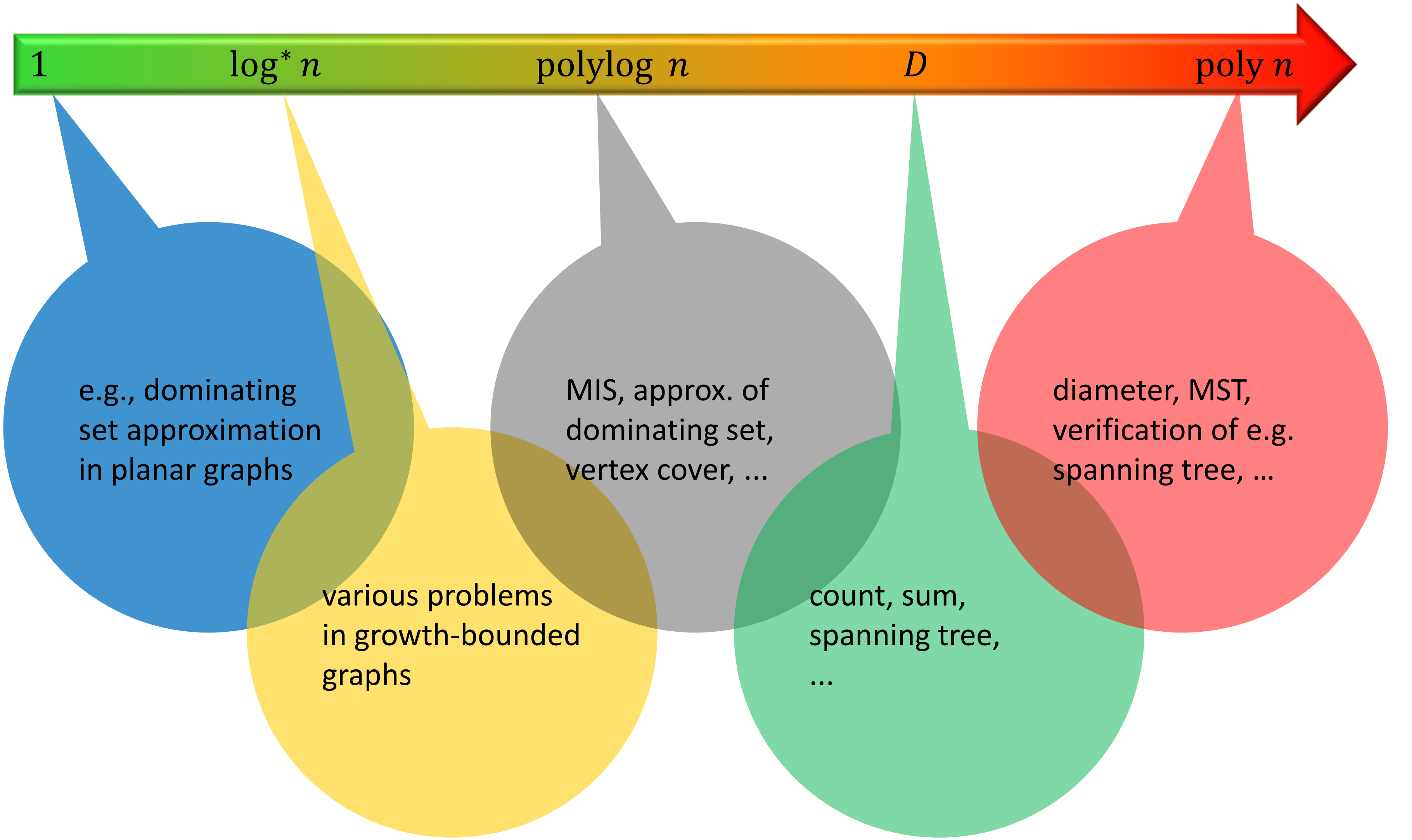
(even if diameter is just a small constant)



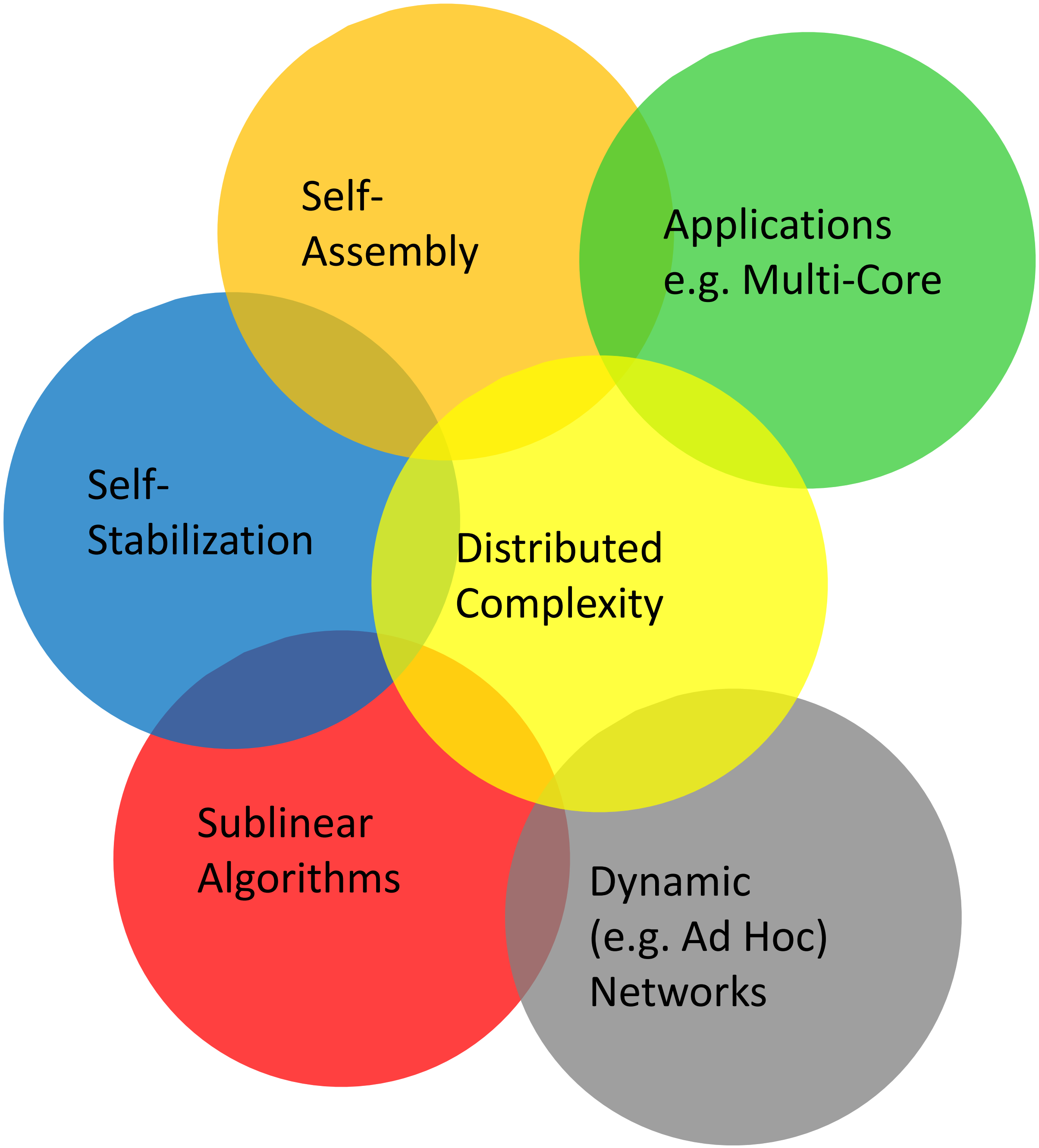
Pair of rows connected neither left nor right? Communication complexity:
Transmit $\Theta(n^2)$ information over $O(n)$ edges → $\Omega(n)$ time!

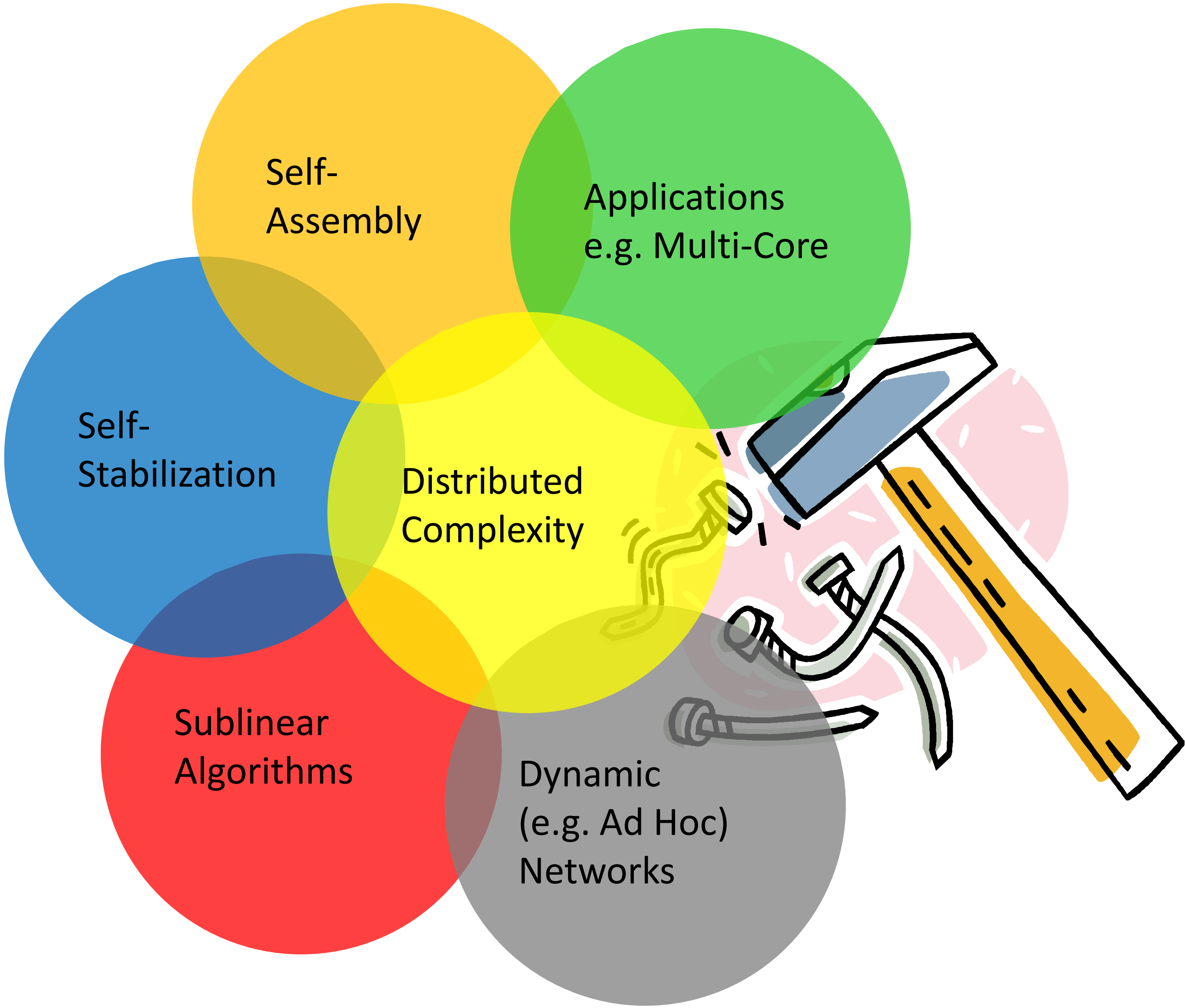
[Frischknecht, Holzer, W, 2012]

Distributed Complexity Classification



e.g., [Kuhn, Moscibroda, W, 2014]


Self-
Assembly
Applications
e.g. Multi-Core
Self-
Stabilization
Distributed
Complexity
Sublinear
Algorithms
Dynamic
(e.g. Ad Hoc)
Networks


Self-
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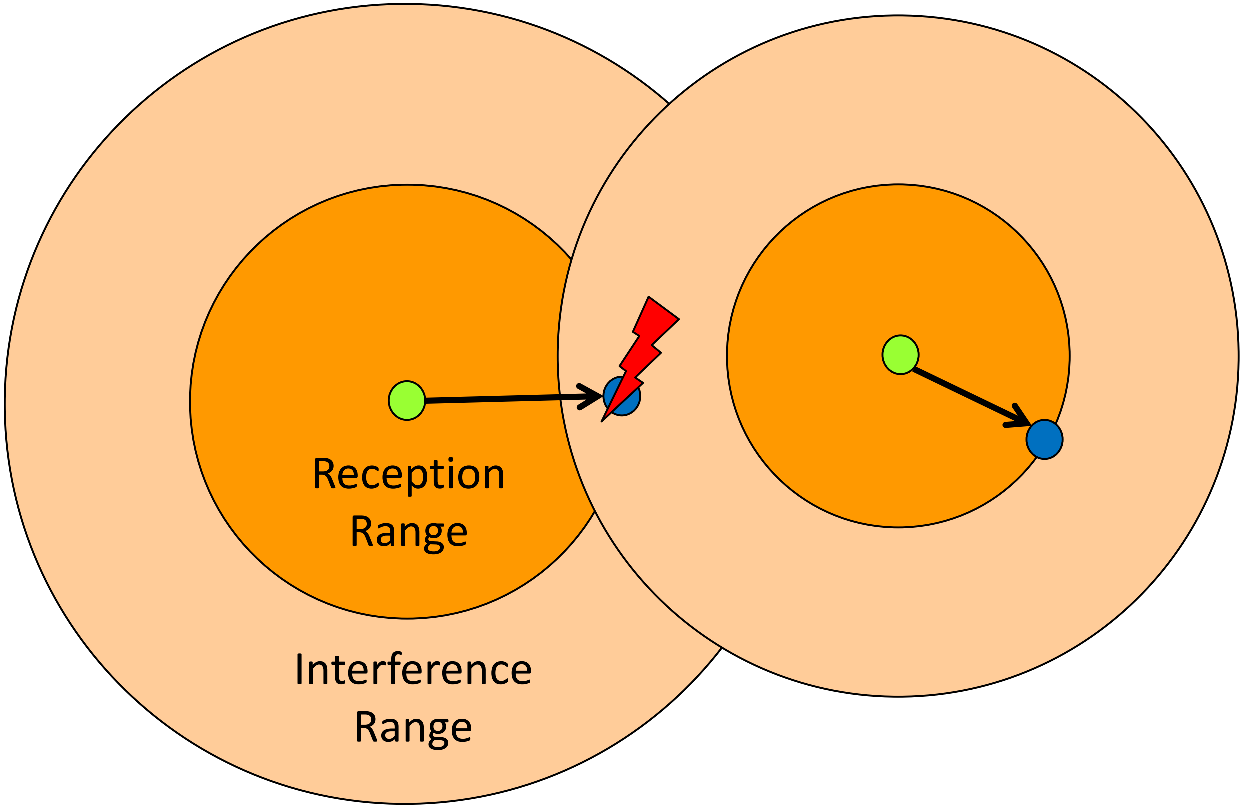
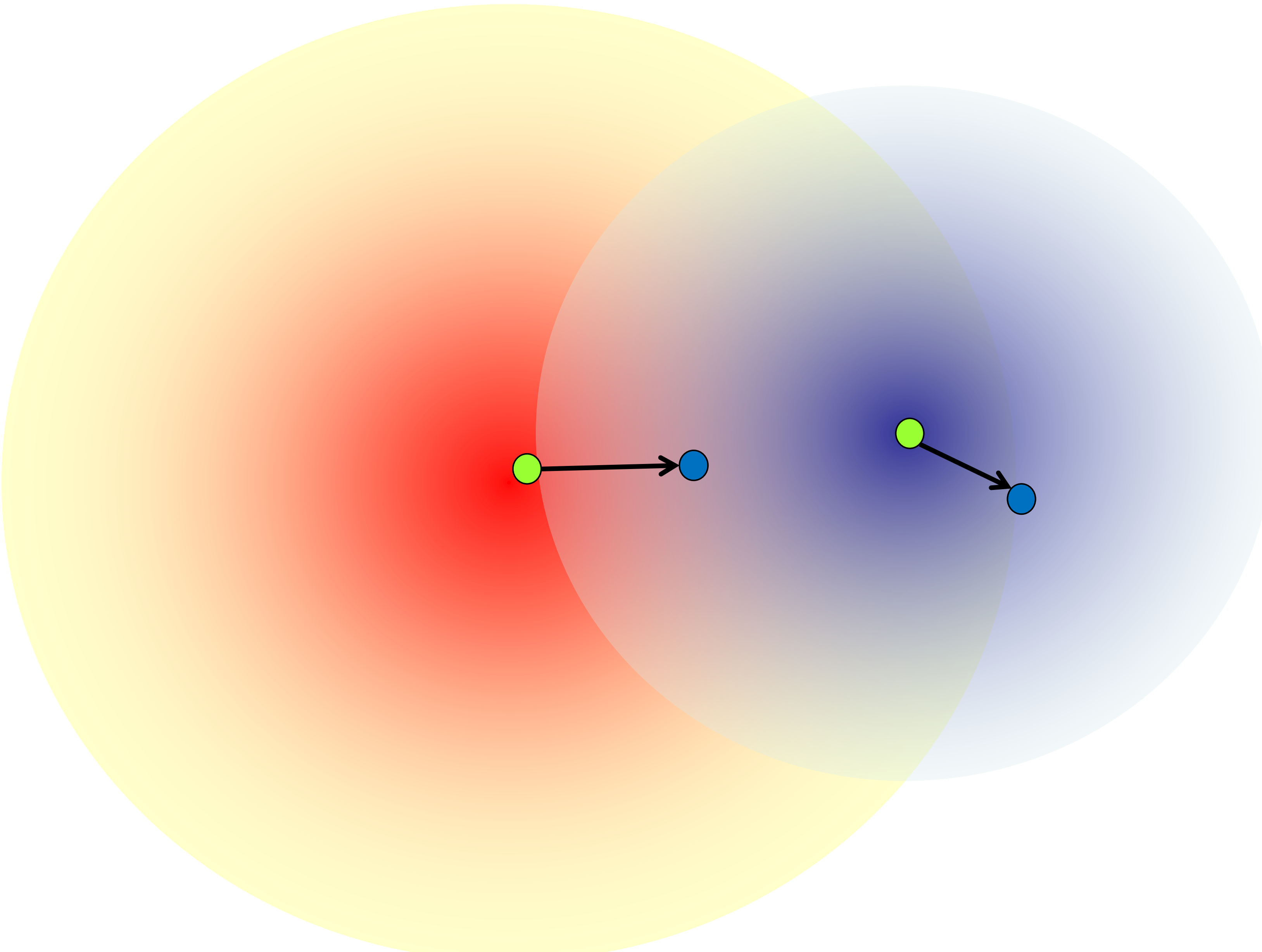
Wireless Communication?

Capacity!

Protocol Model



Physical (SINR) 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

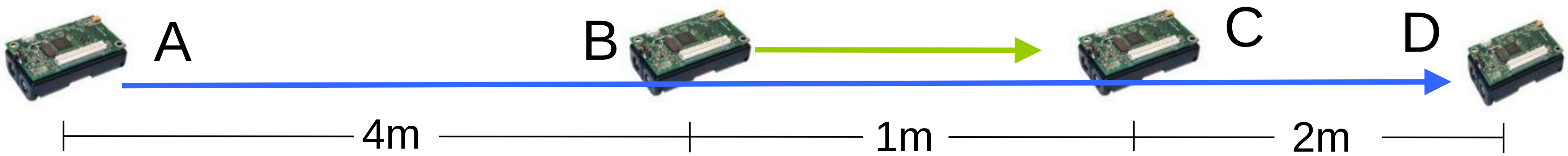
Noise

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

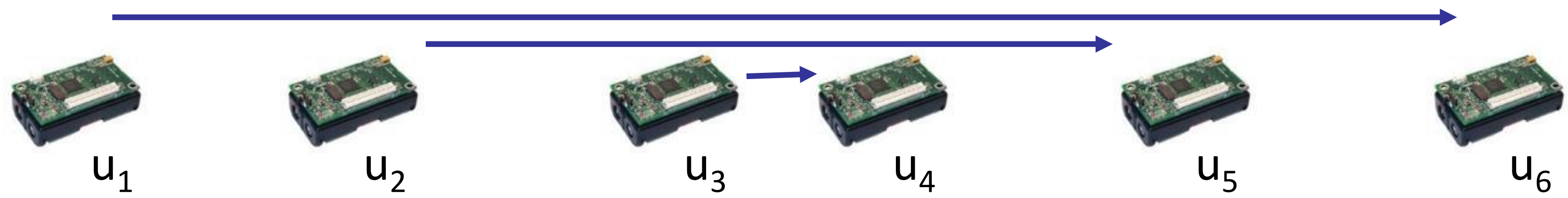
Transmission powers: P_B= -15 dBm and P_A= 1 dBm

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



Time for transmitting 20‘000 packets:

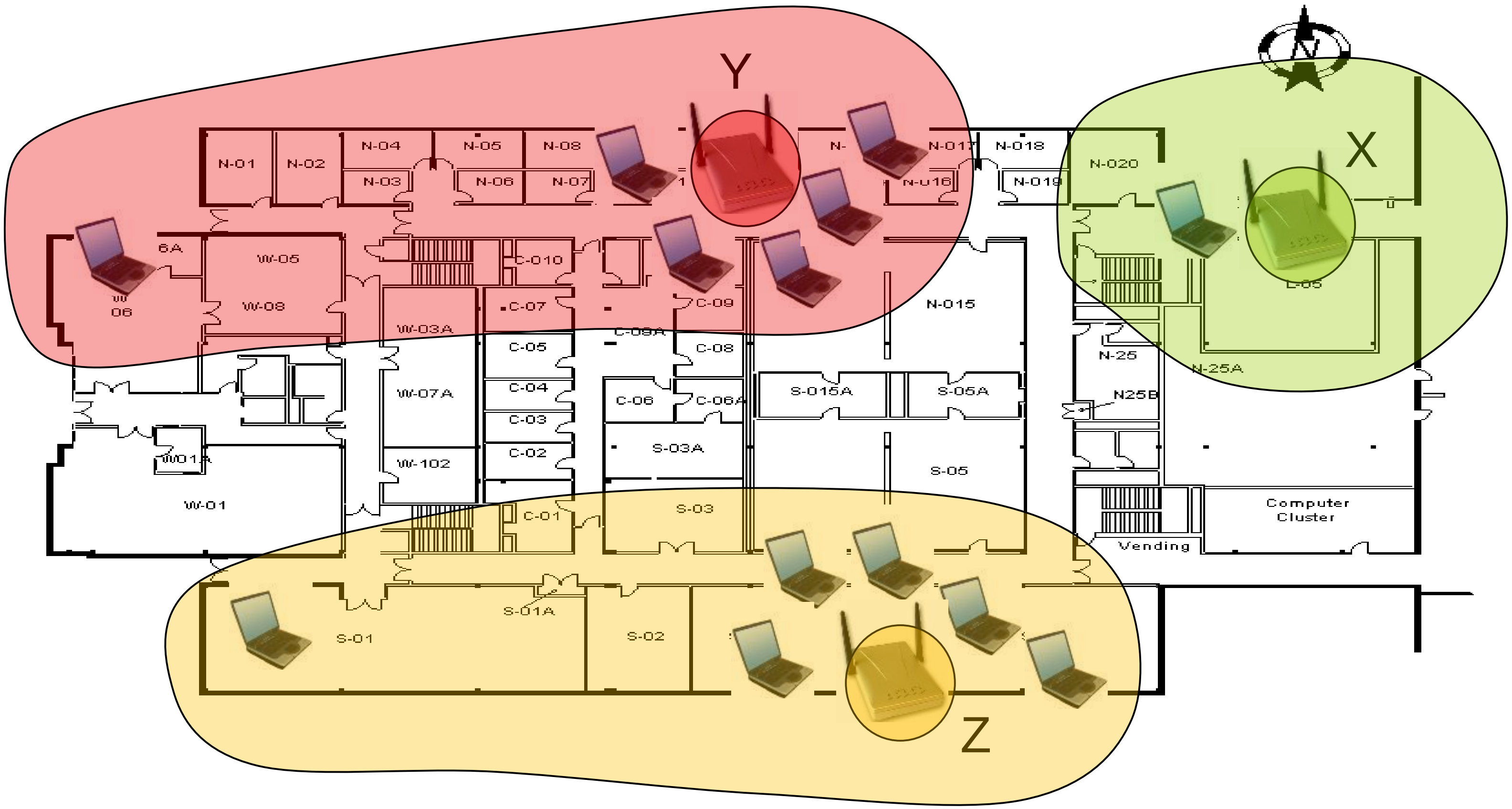
	Time required	
	standard MAC	“SINR-MAC”
Node u_1	$721s$	$267s$
Node u_2	$778s$	$268s$
Node u_3	$780s$	$270s$

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

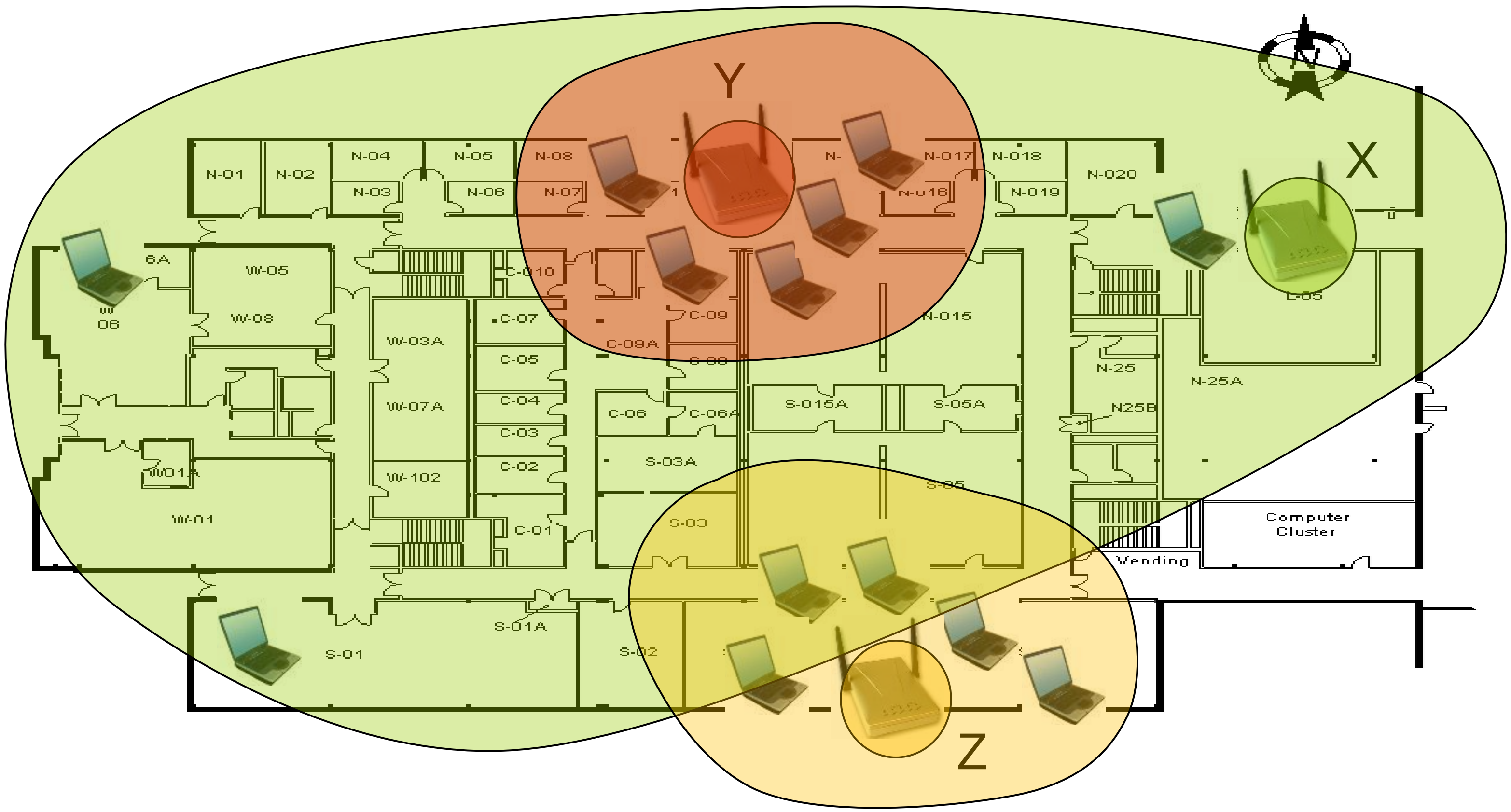
Speed-up is almost a factor 3

[Moscibroda, W, Weber, Hotnets 2006]

Possible Application – Hotspots in WLAN



Possible Application – Hotspots in WLAN



The Capacity of a Network

(How many concurrent wireless transmissions can you have)

Convergecast Capacity in Wireless (Sensor) Networks

[Moscibroda, W, 2006]

Worst-Case Capacity

[Giridhar, Kumar, 2005]

Classic Capacity

Topology / 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)	$\Omega(1/\log^3 n)$	$\Omega(1/\log n)$

Capacity of a Network

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?

Core Capacity Problems

Given a set of arbitrary communication links

One-Shot Problem

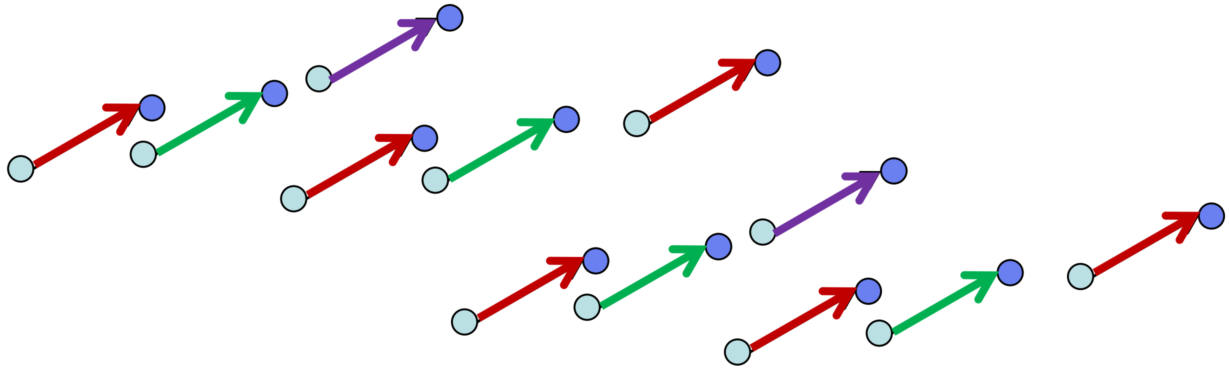
Find the maximum size feasible subset of links

O(1) approximations for uniform power [Goussevskaia, Halldorsson, W, 2009 & 2014] as well as arbitrary power [Kesselheim, 2011]

Scheduling Problem

Partition the links into fewest possible slots, to minimize time

Open problem: Only $O(\log n)$ approximation using the one-shot subroutine



Energy Efficiency?

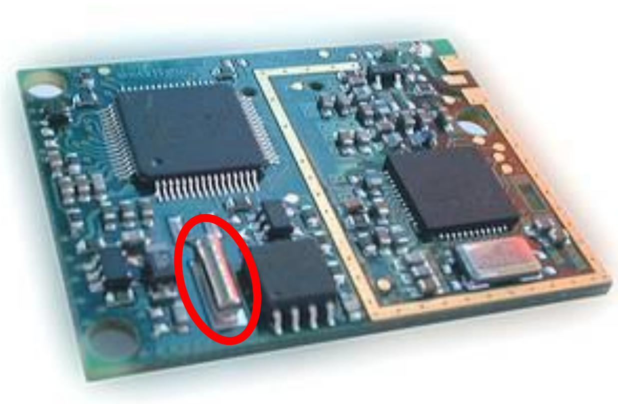
Clock Synchronization!

Clock Synchronization Example: Dozer

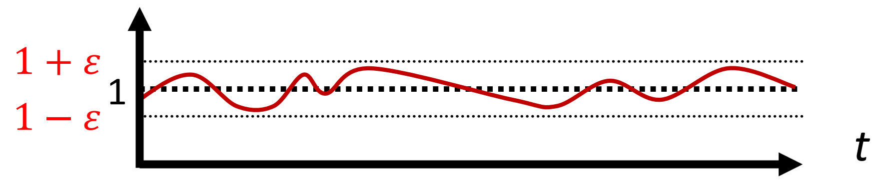
- Multi-hop sensor network with duty cycling
- 10 years of network life-time, mean energy consumption: 0.066mW
- High availability, reliability (99.999%)
- Many different applications use Dozer: TinyNode, PermaSense, etc.

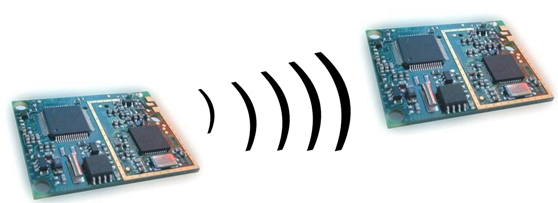
[Burri, von Rickenbach, W, 2007]

Problem: Physical Reality

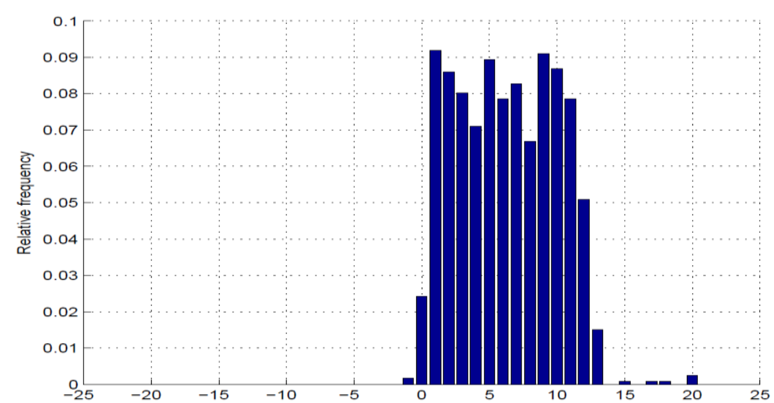


clock rate





message delay

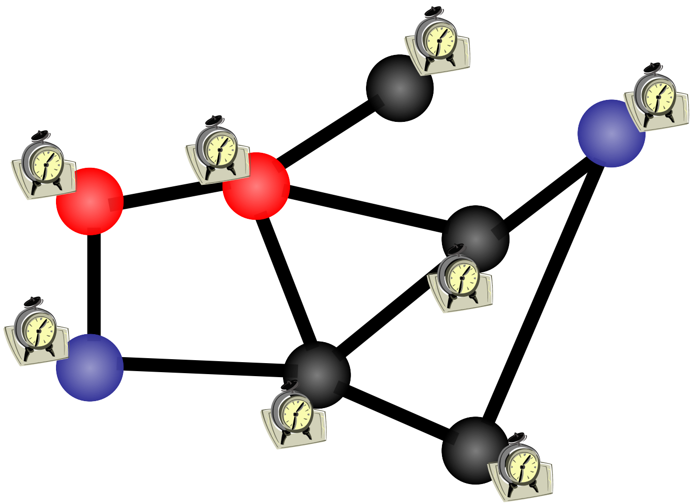


Clock Synchronization in Theory?

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")

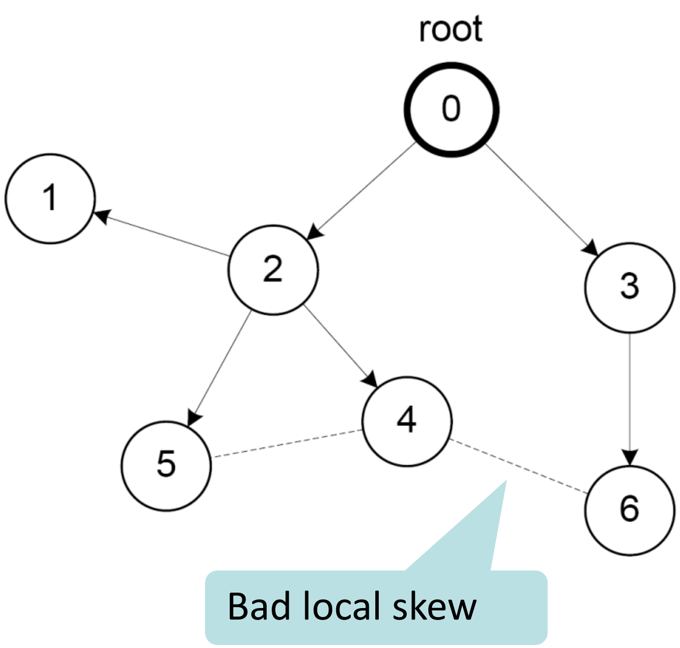
- Both global and local synchronization!

Time Must Behave!

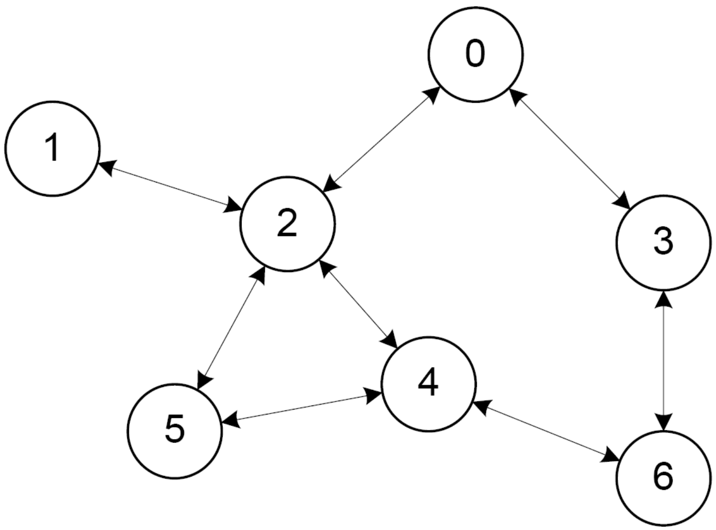
- Time (logical clocks) should not be allowed to stand still or jump

Local Skew

Tree-based Algorithms
e.g. FTSP

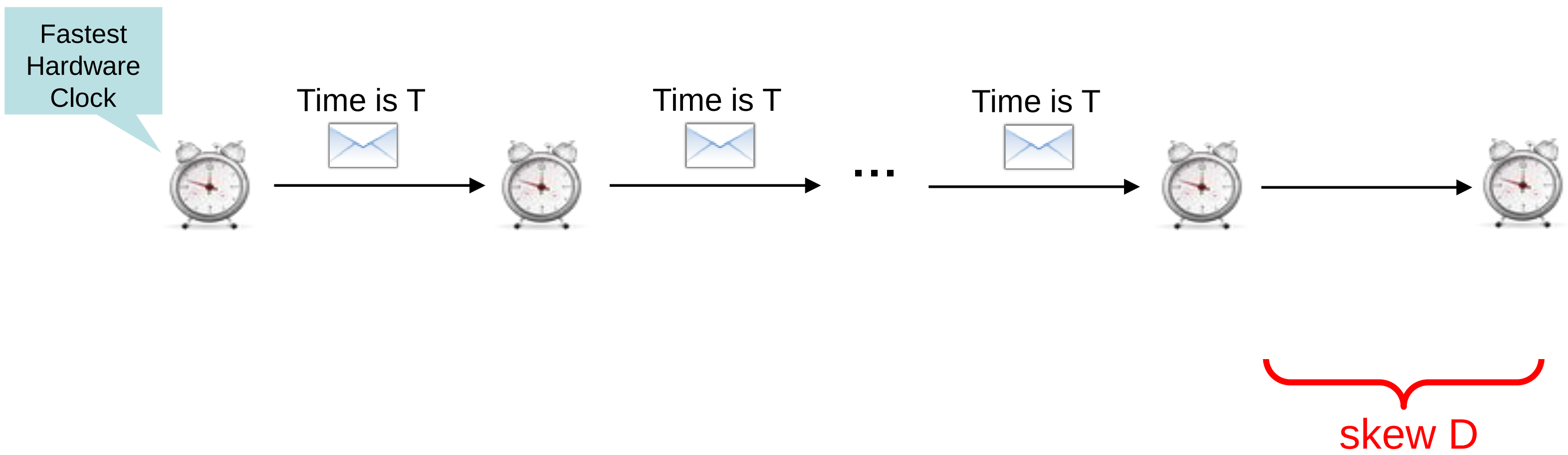


Neighborhood Algorithms
e.g. GTSP

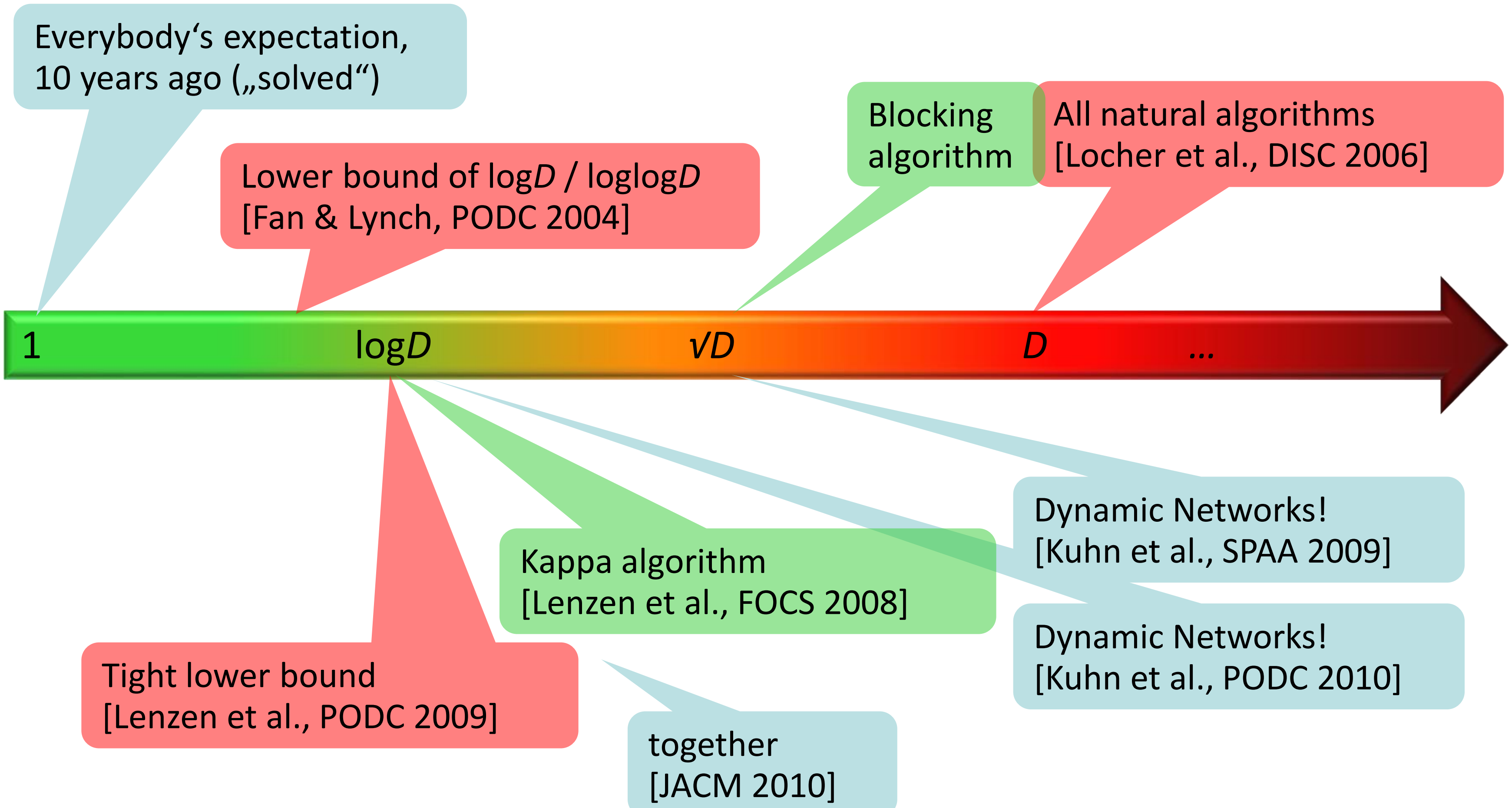


Synchronization Algorithms: An Example ("A^{max}")

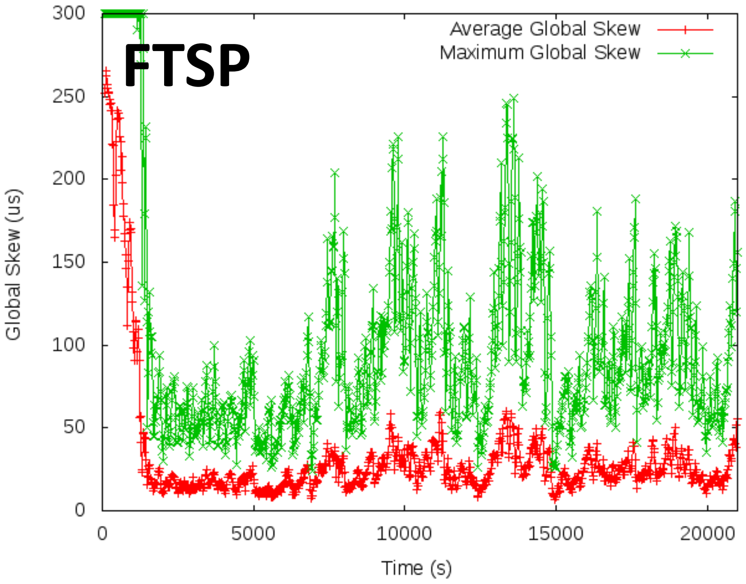
- Question: How to update the logical clock based on the messages from the neighbors?
- Idea: Minimizing the skew to the fastest neighbor
  - Set clock to maximum clock value you know, forward new values immediately
- First all messages are slow (1), then suddenly all messages are fast (0)!

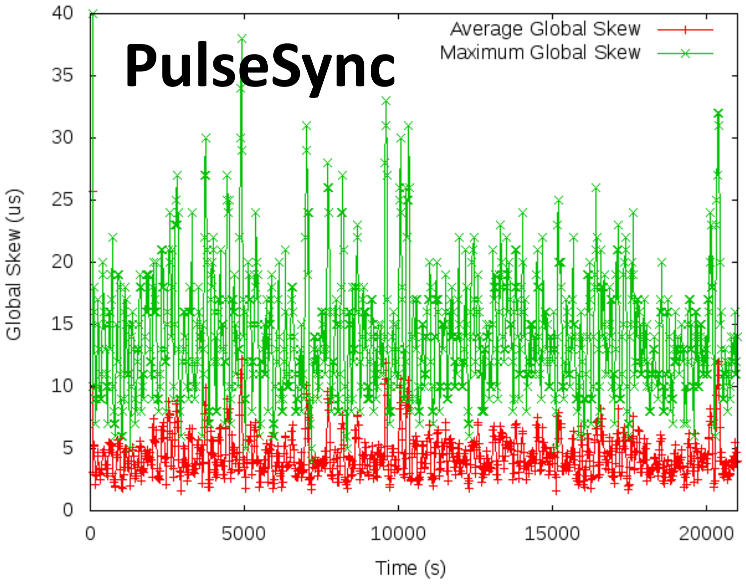


Local Skew: Overview of Results



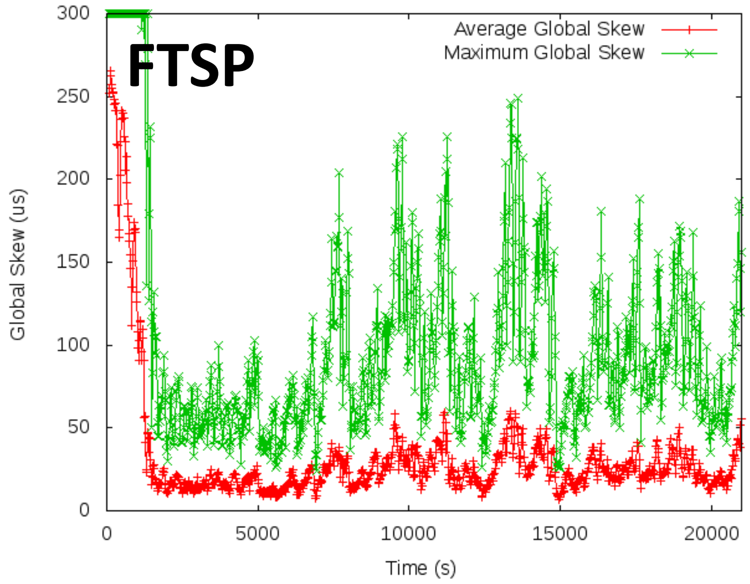
Experimental Results for Global Skew

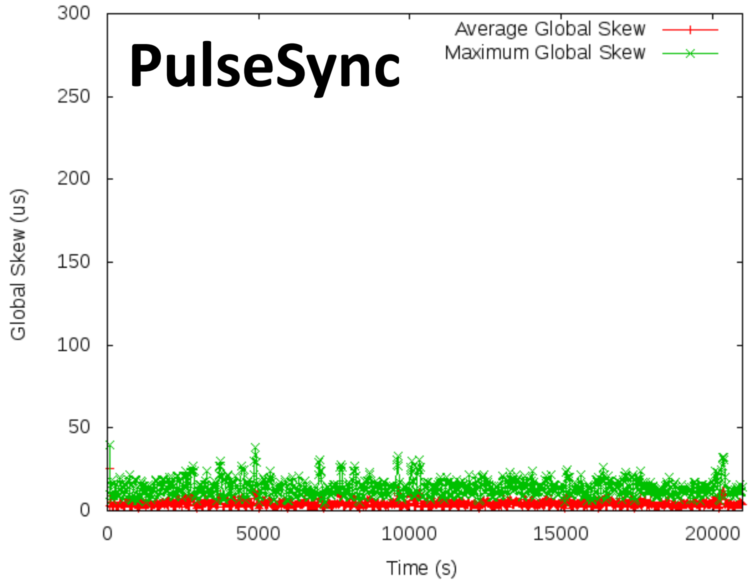




[Lenzen, Sommer, W, 2009]

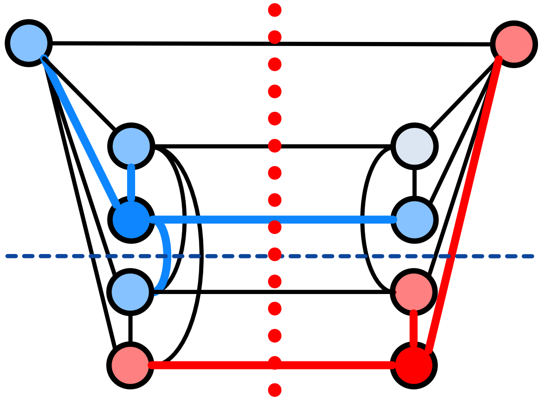
Experimental Results for Global Skew

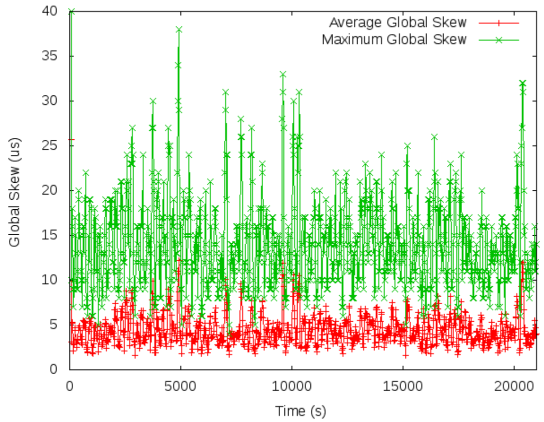




[Lenzen, Sommer, W, 2009]

Summary




Average Global Skew
Maximum Global Skew
Global Skew (us)
Time (s)
0
5
10
15
20
25
30
35
40
0
5000
10000
15000
20000


CHECKLIST, really
mobile
wireless
hard problems

Thank You!

Questions & Comments?

Thanks to my co-authors, mostly
Silvio Frischknecht
Magnus Halldorsson
Stephan Holzer
Christoph Lenzen
Thomas Moscibroda
Philipp Sommer

www.disco.ethz.ch