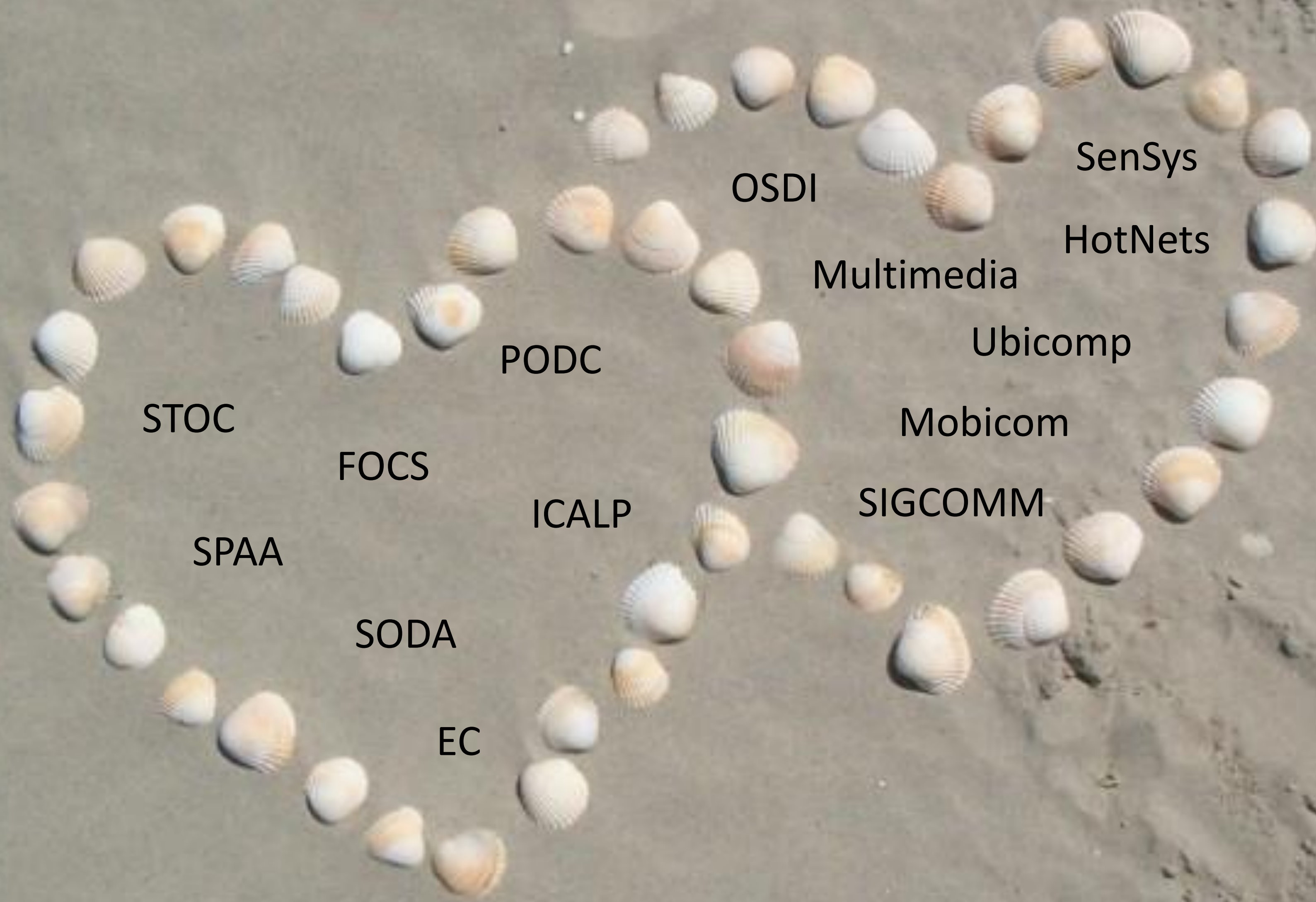
Sensor Networks
Where Theory Meets Practice

Roger Wattenhofer

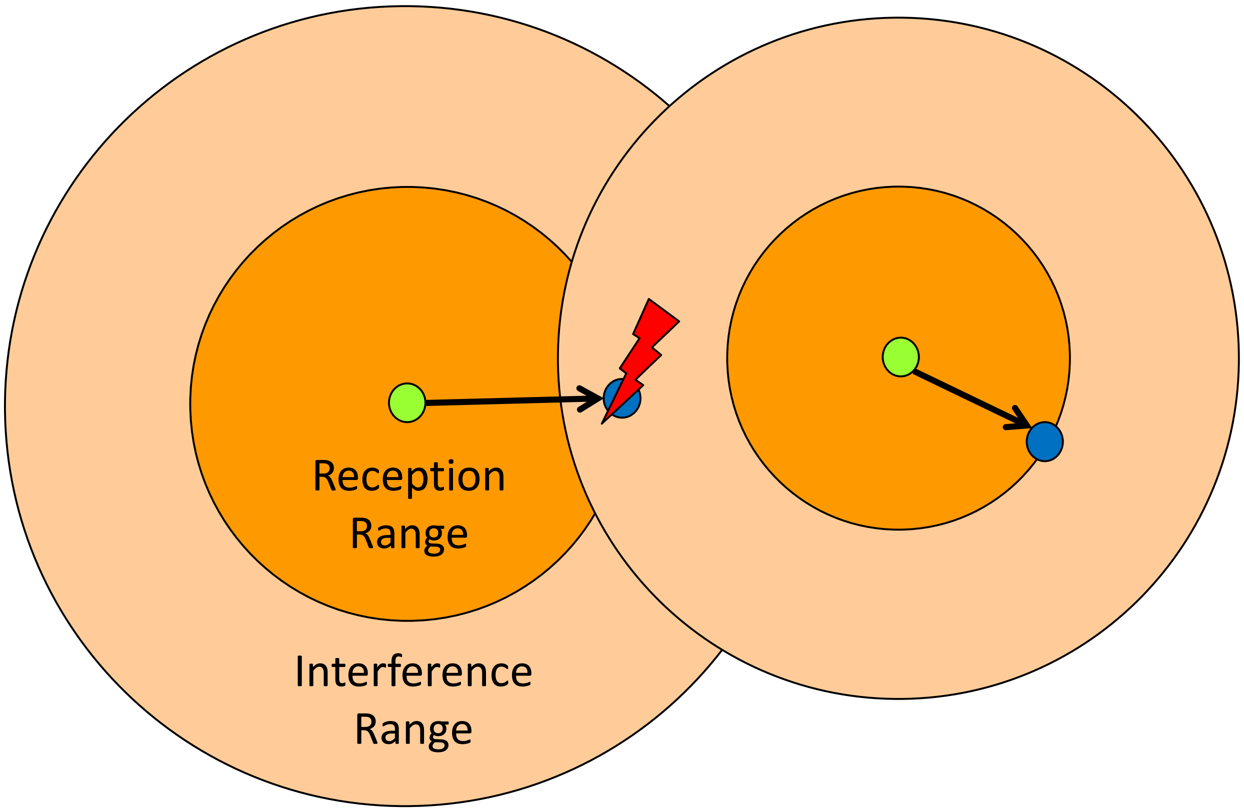
Theory Meets Practice



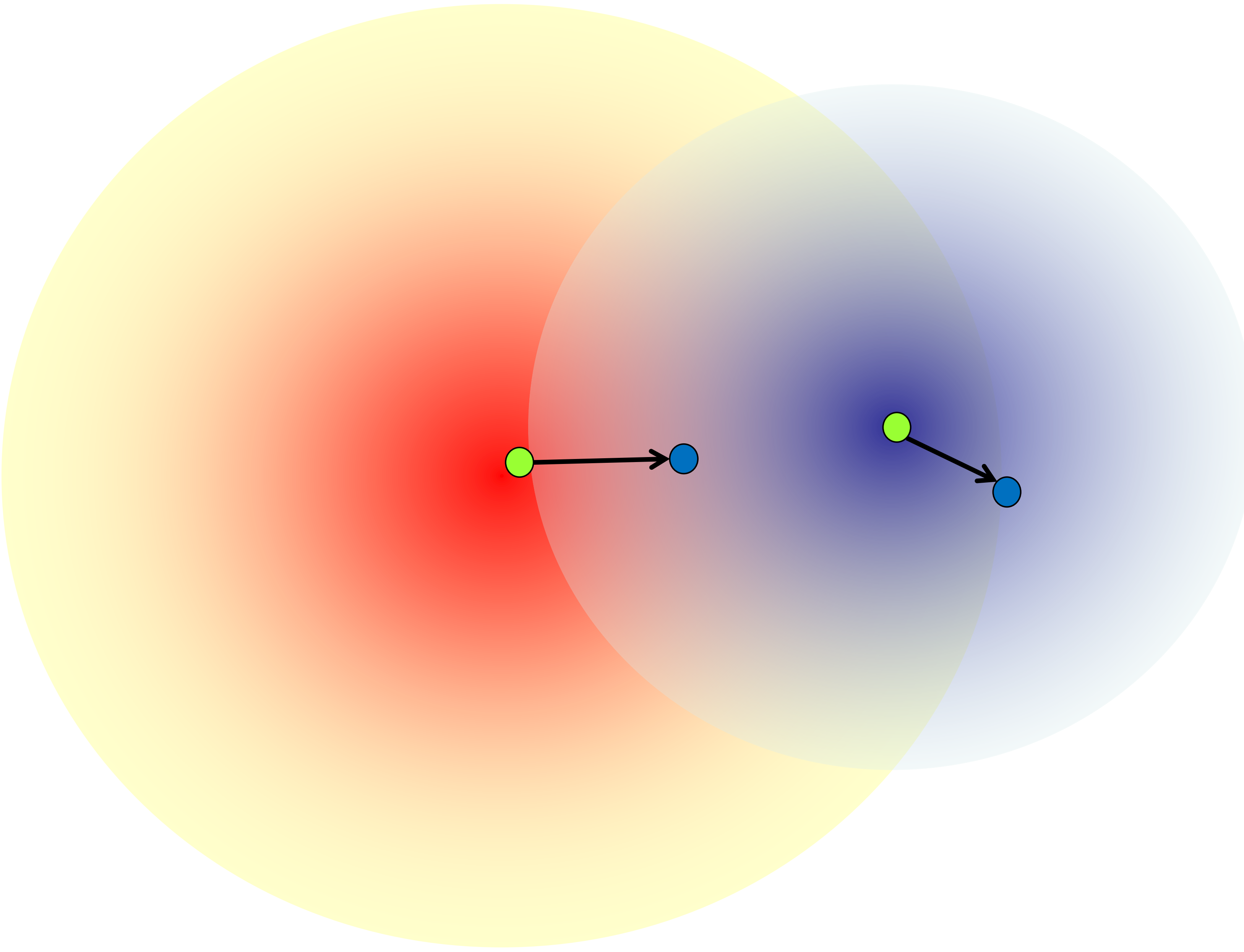
Wireless Communication?

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

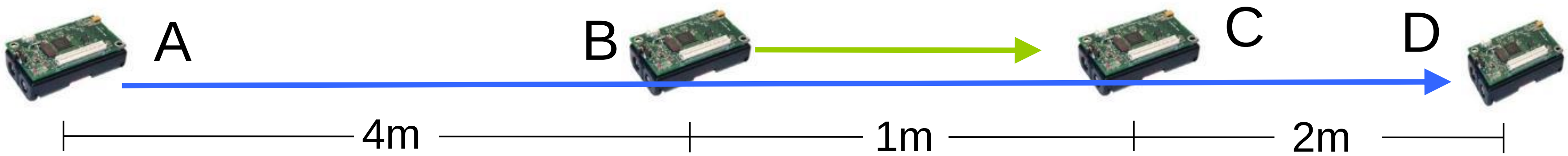
Noise

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

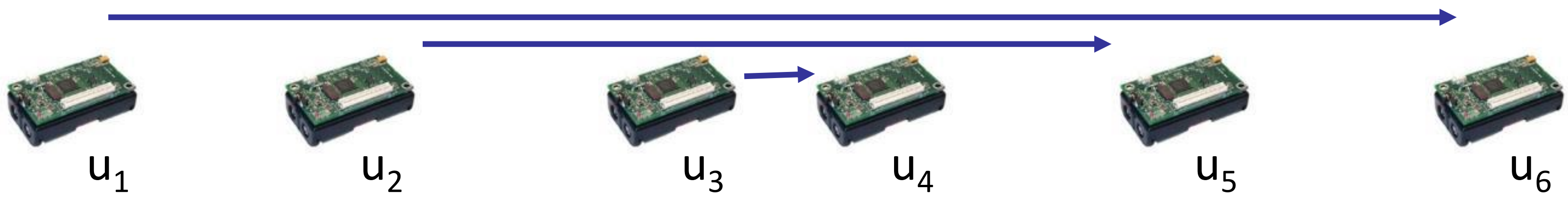
Transmission powers: P_B= -15 dBm and P_A= 1 dBm

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:

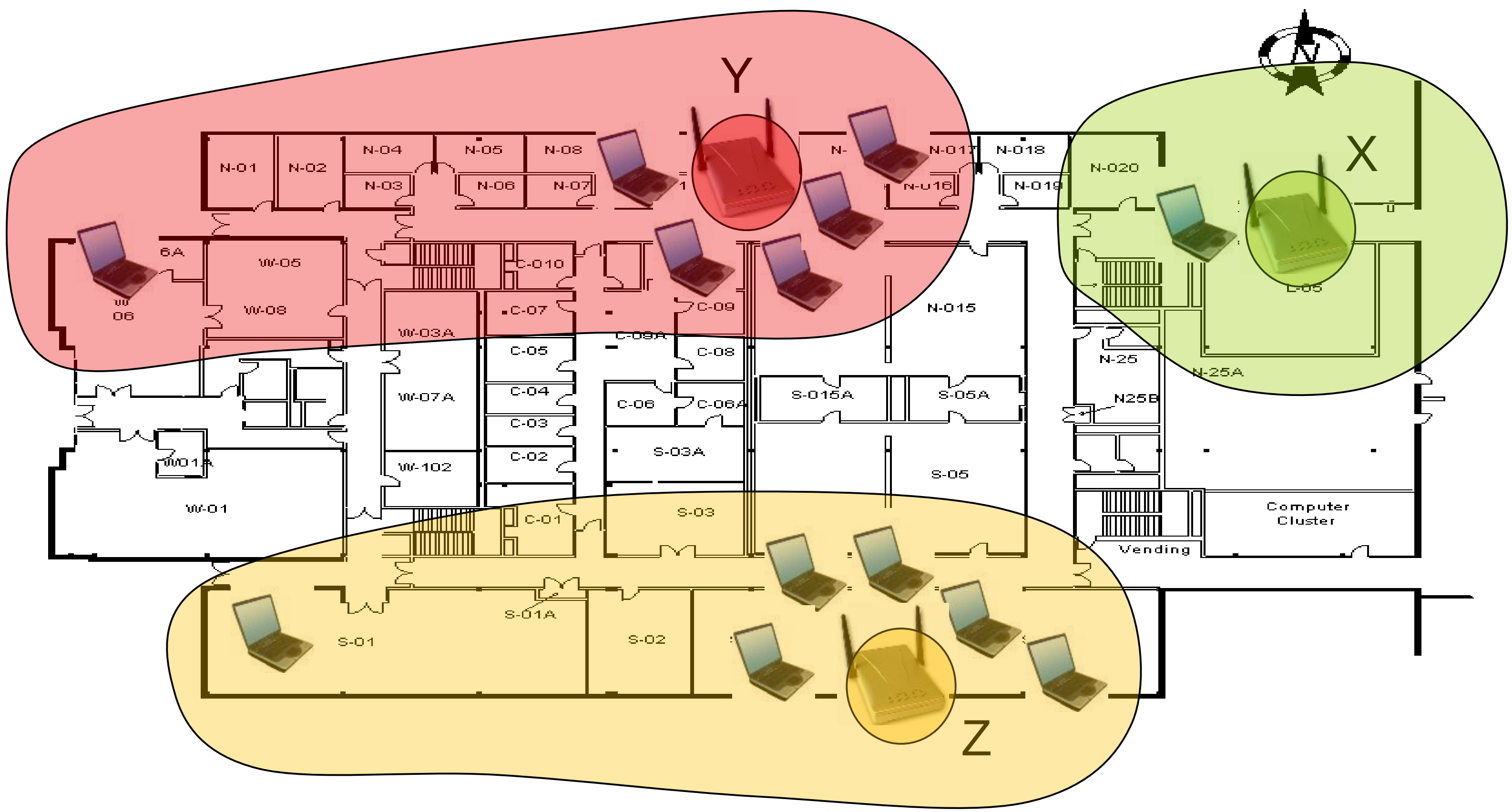
	Time required	
	standard MAC	“SINR-MAC”
Node u_1	$721s$	$267s$
Node u_2	$778s$	$268s$
Node u_3	$780s$	$270s$

	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



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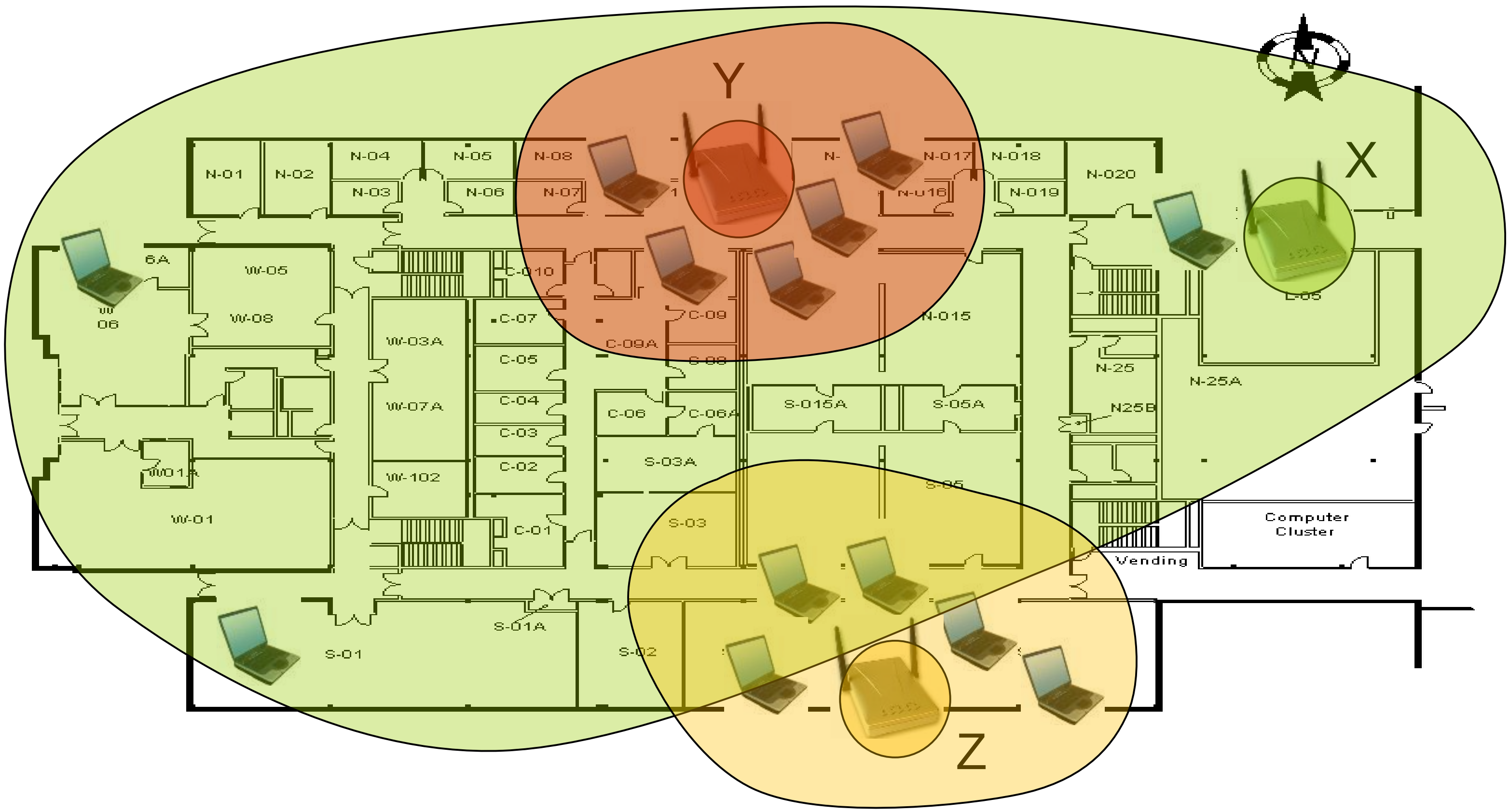


The Capacity of a Network

(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

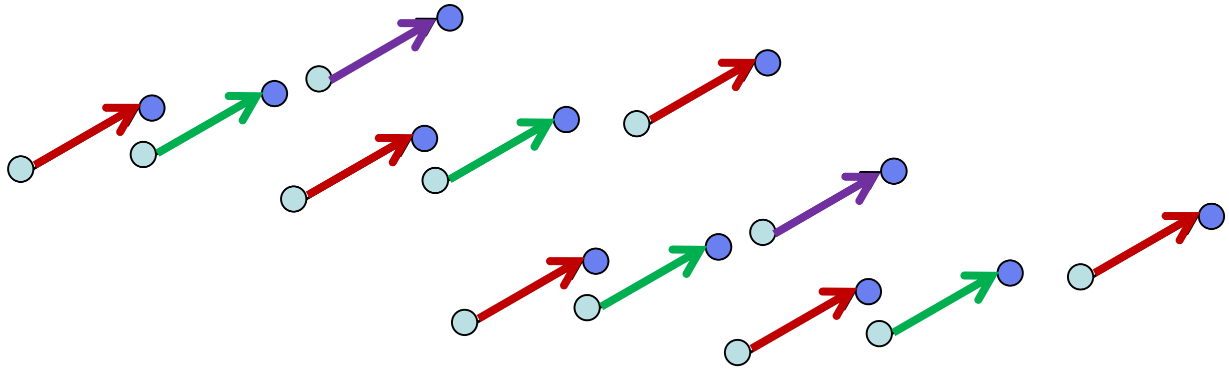
Find the maximum size feasible subset of links

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

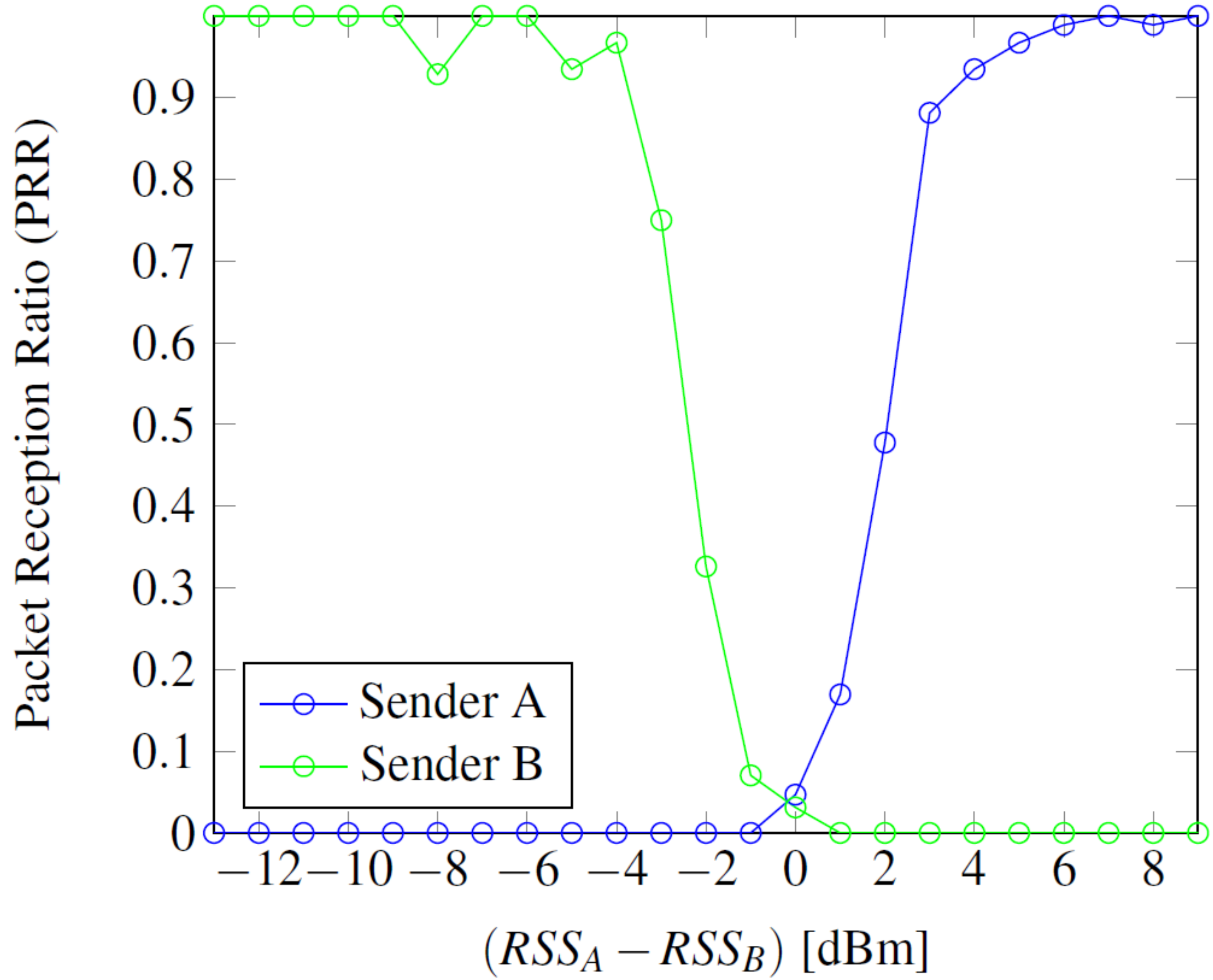
Scheduling Problem

Partition the links into fewest possible slots, to minimize time

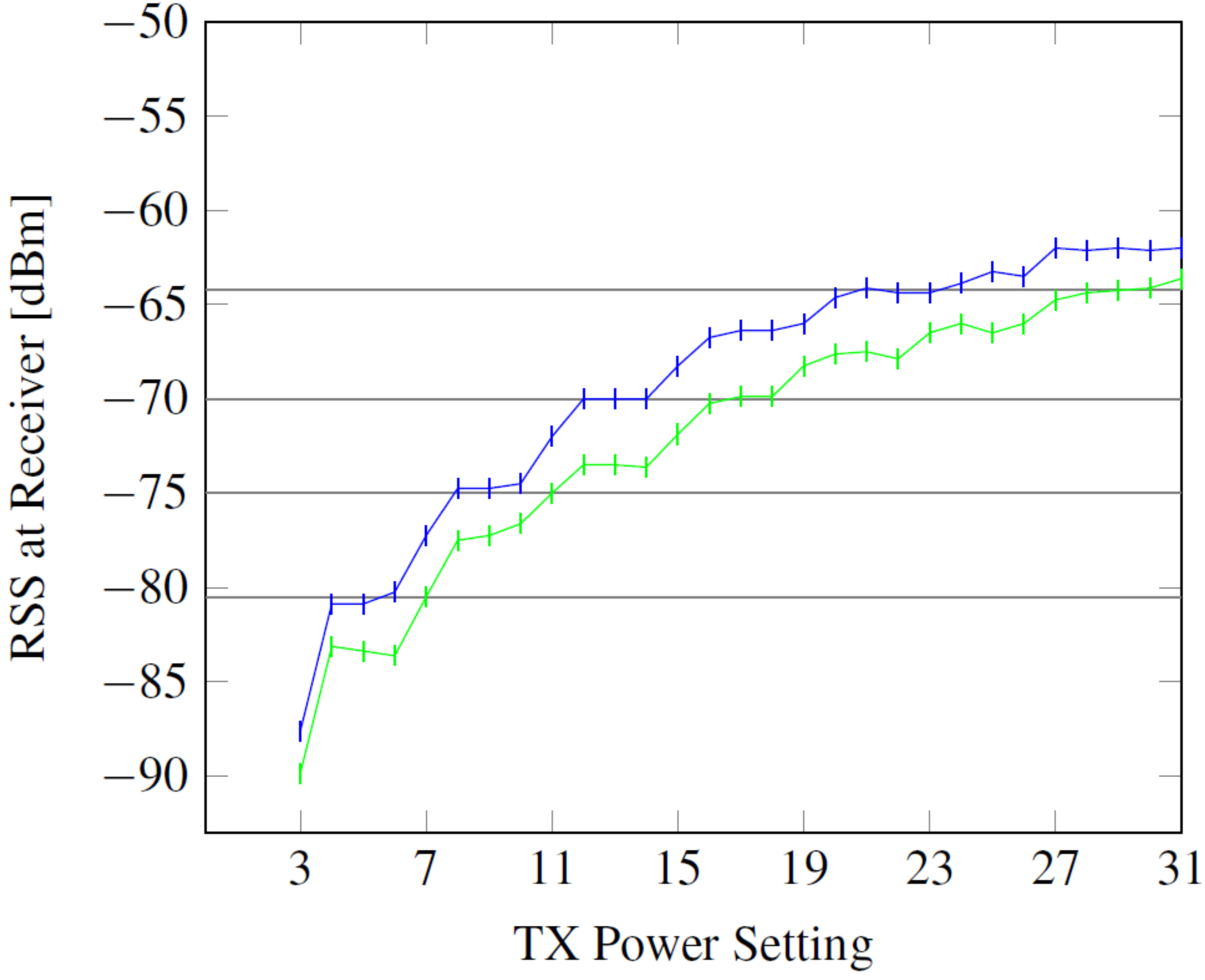
Open problem: Only $O(\log n)$ approximation using the one-shot subroutine



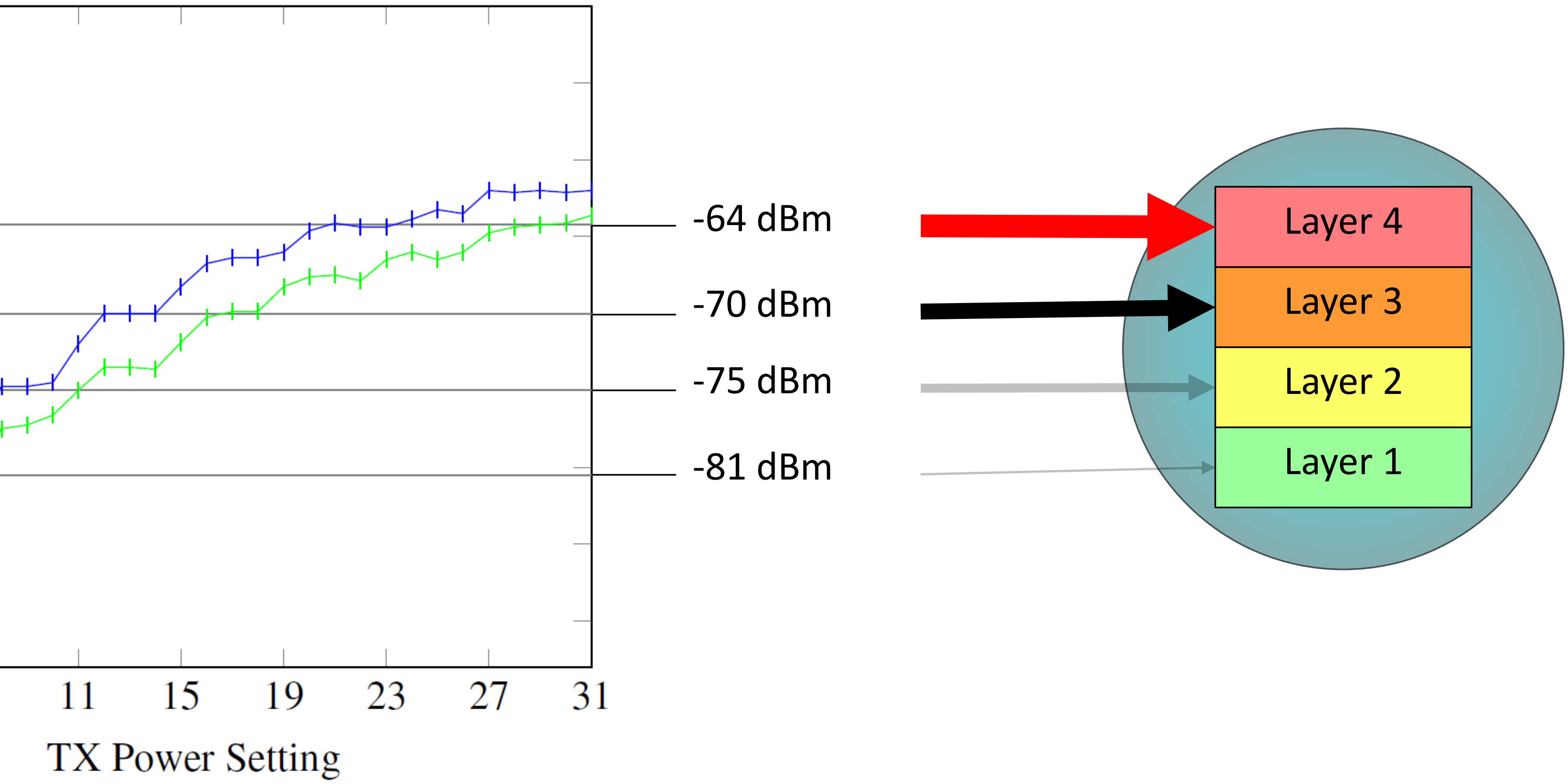
The Capture Effect



Receiving Different Senders

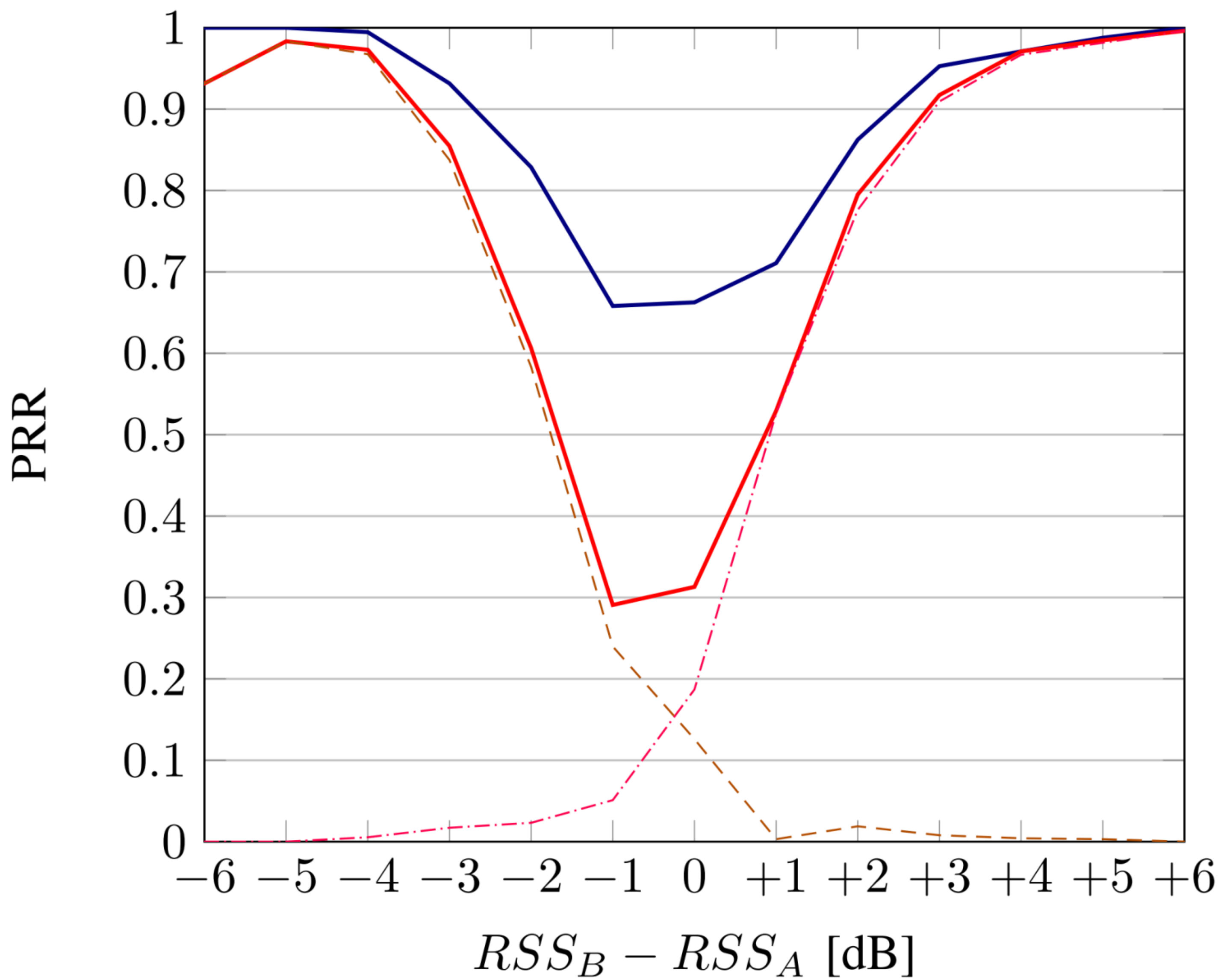


“Layer” Abstraction



[König, W, 2016]

Constructive Interference



Energy Efficiency?

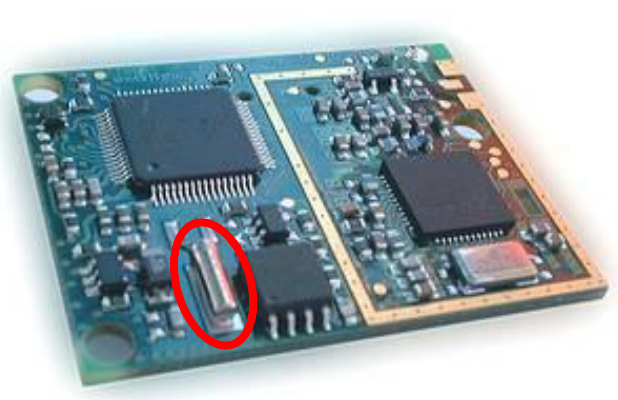
Clock Synchronization!

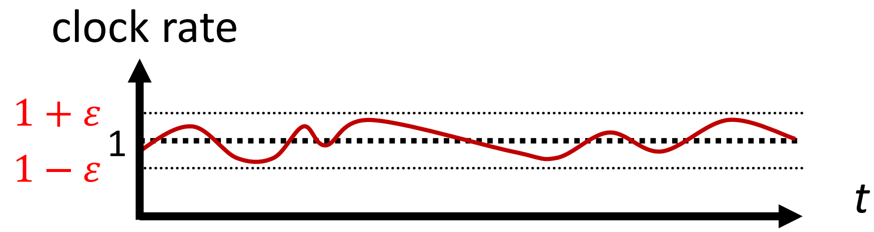
Clock Synchronization Example: Dozer

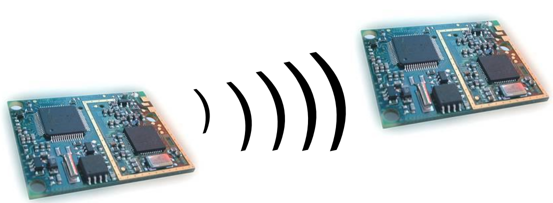
- Multi-hop sensor network with duty cycling
- 10 years of network life-time, mean energy consumption: 0.066mW
- High availability, reliability (99.999%)
- Many different applications use Dozer: TinyNode, PermaSense, etc.

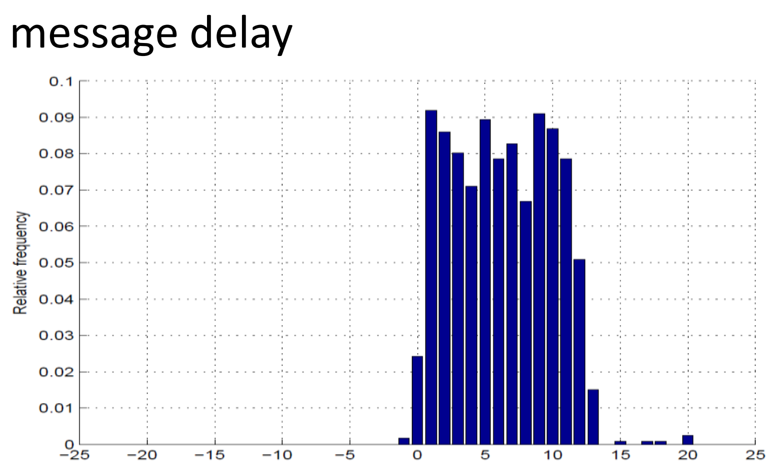
[Burri, von Rickenbach, W, 2007]

Problem: Physical Reality







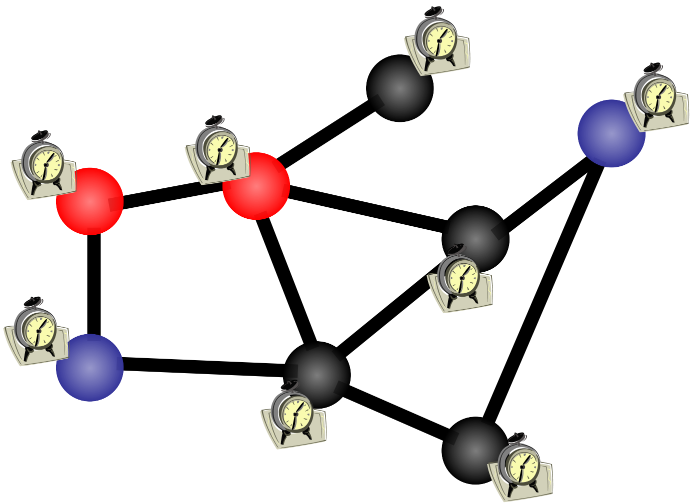


Clock Synchronization in Theory?

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!

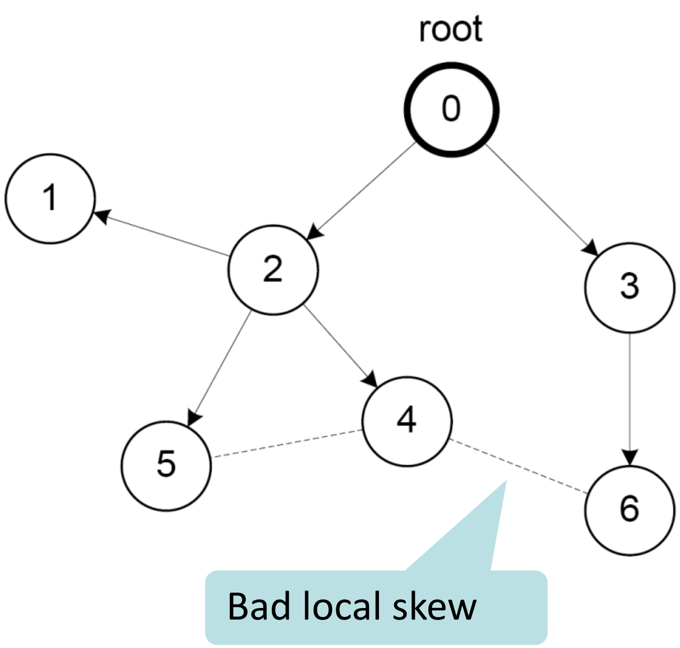
Time Must Behave!

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

Local Skew

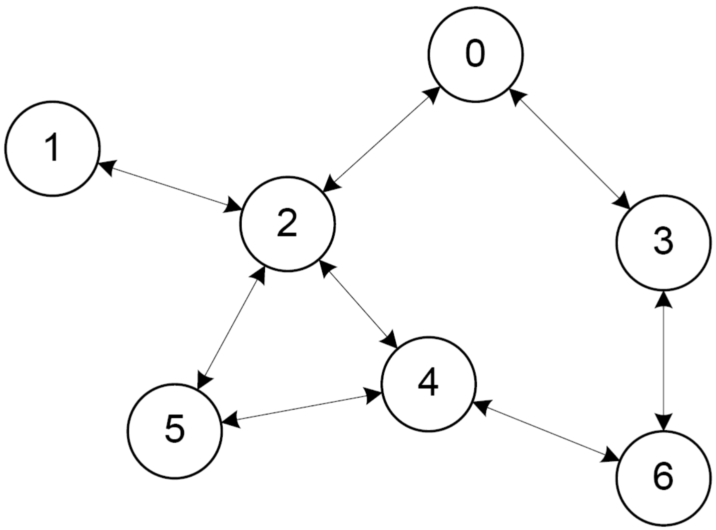
Tree-based Algorithms

e.g. FTSP



Neighborhood Algorithms

e.g. GTSP

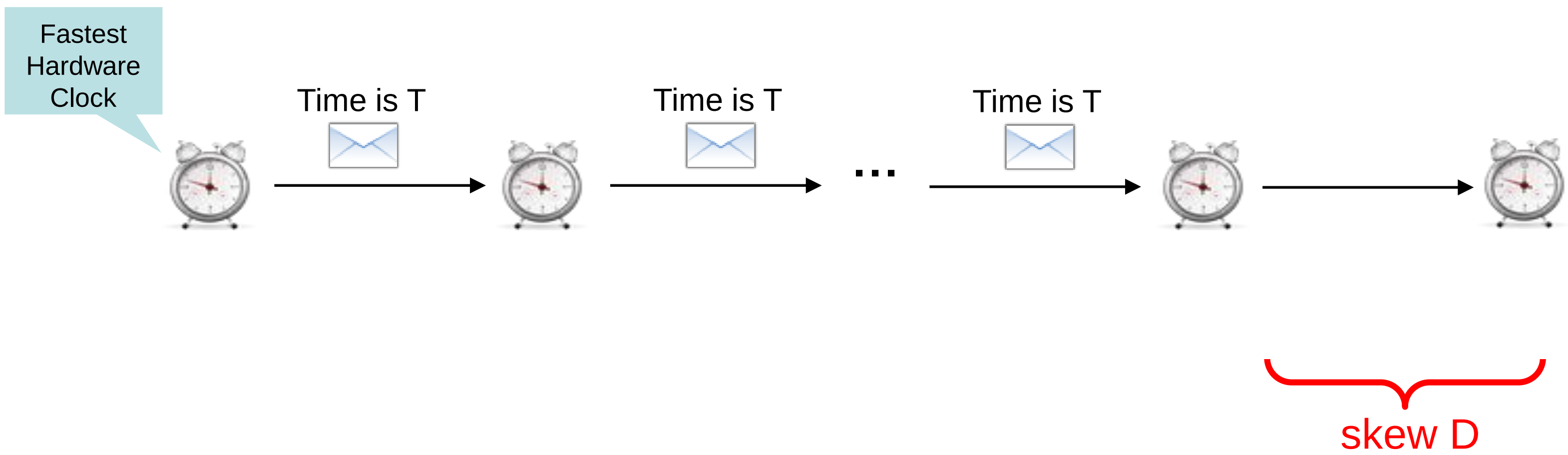


Synchronization Algorithms: An Example ("A^{max}")

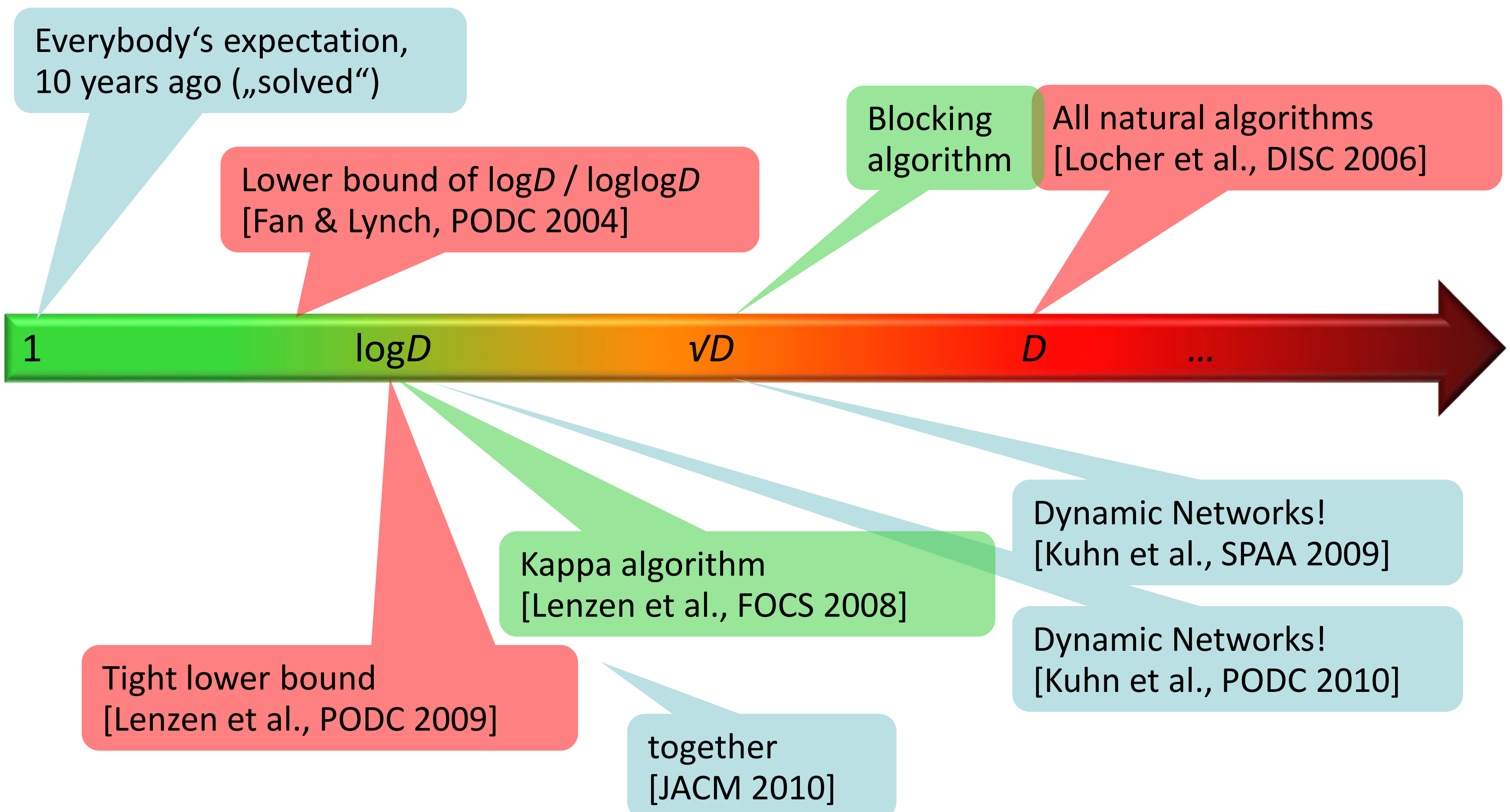
- Question: How to update the logical clock based on the messages from the neighbors?

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

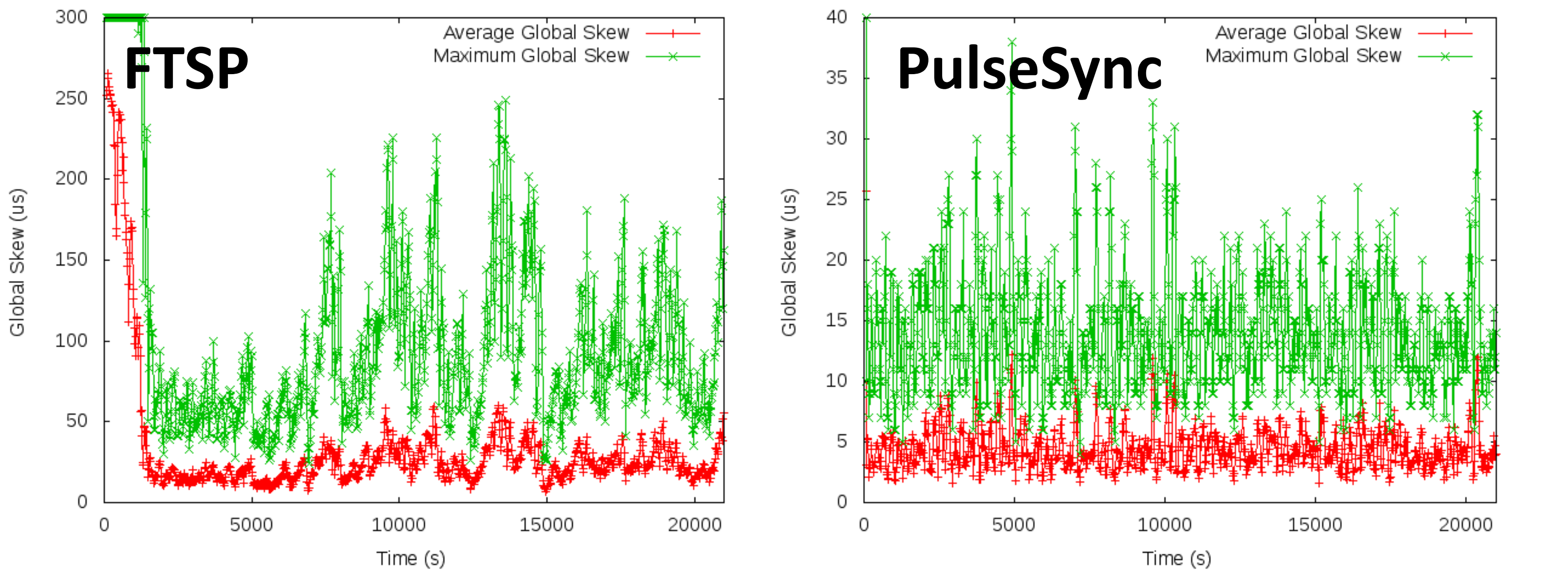
- First all messages are slow (1), then suddenly all messages are fast (0)!



Local Skew: Overview of Results



Experimental Results for Global Skew



[Lenzen, Sommer, W, 2014]

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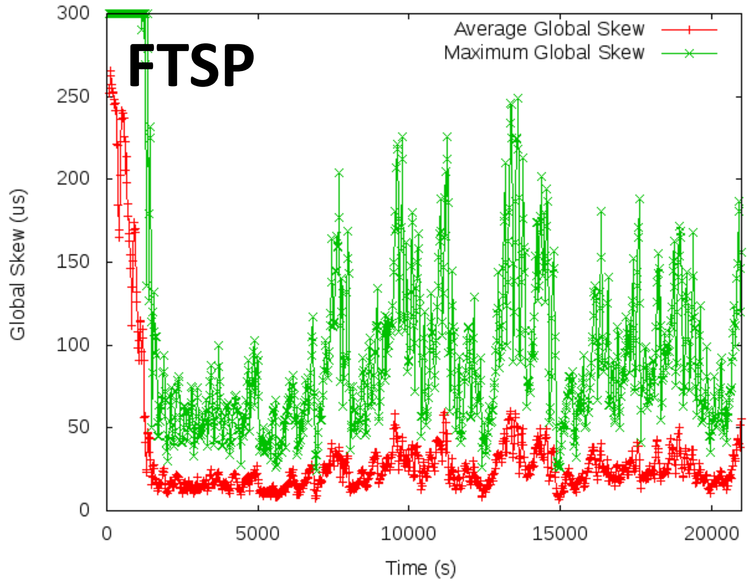
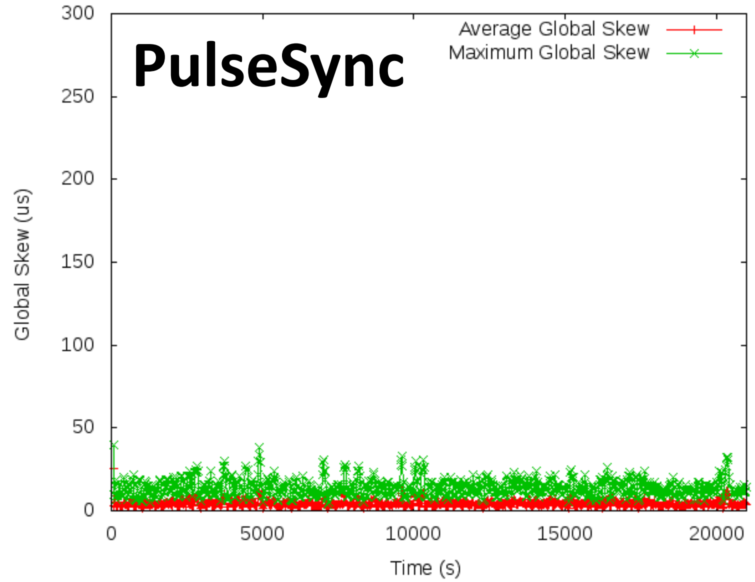
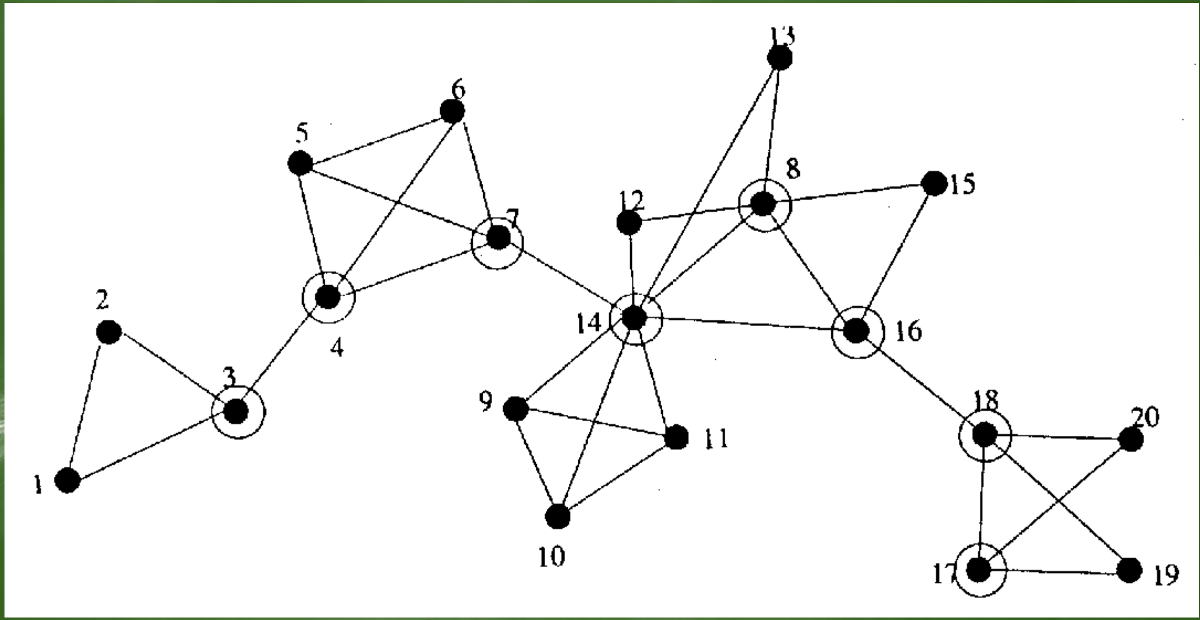




[Lenzen, Sommer, W, 2014]

Network Dynamics?

Distributed Control!


1
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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

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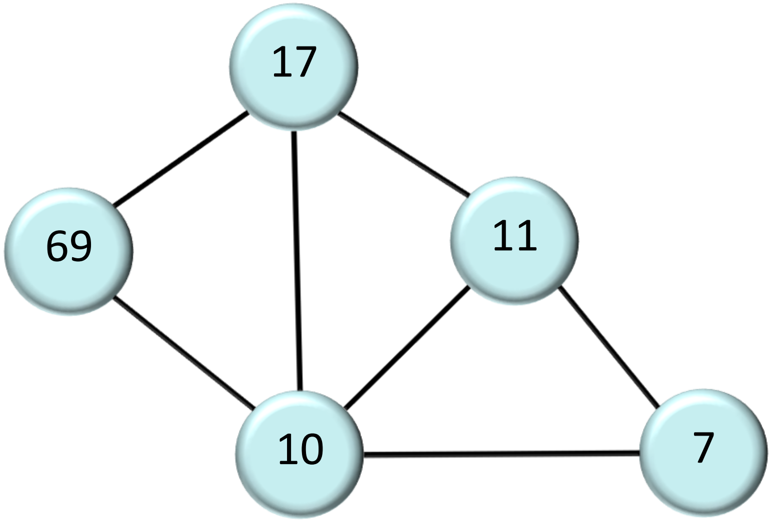
Distributed (Message-Passing) Algorithms

- 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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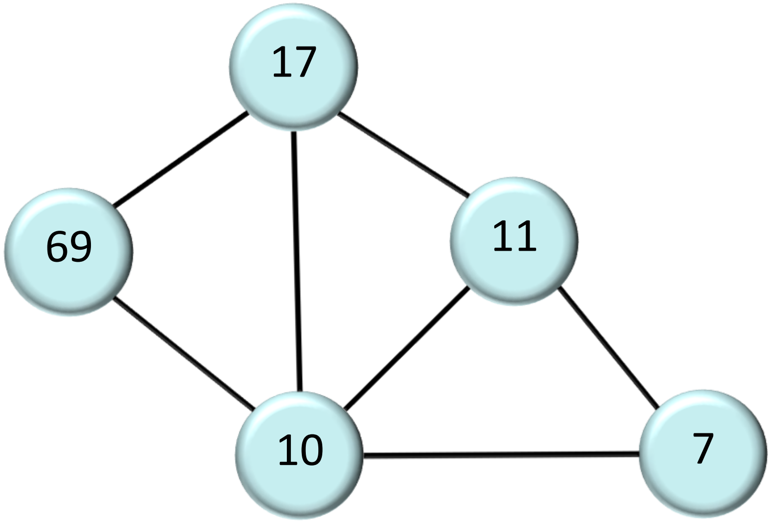


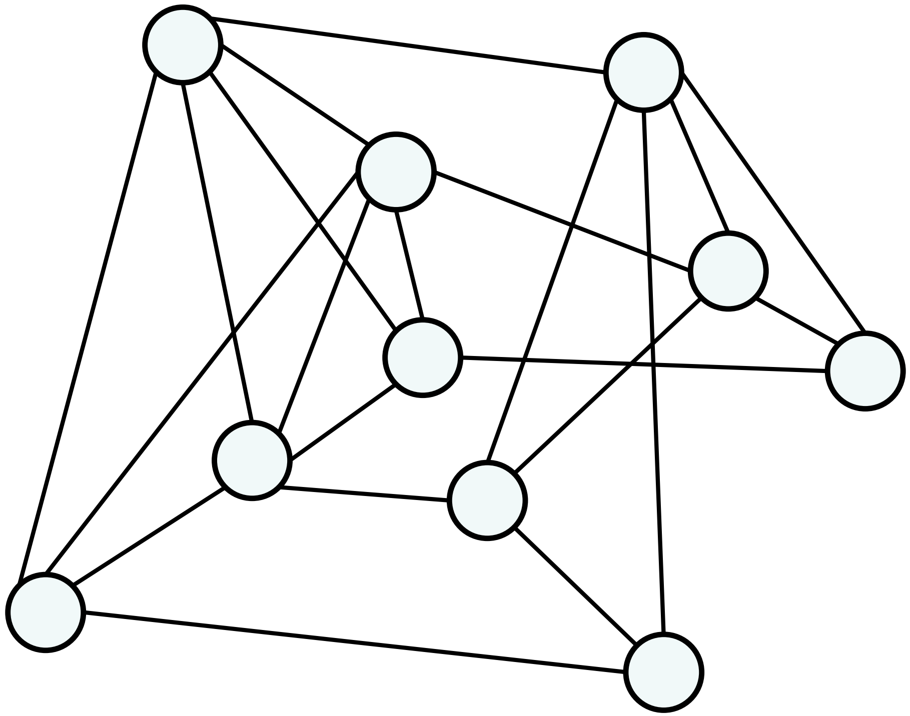

```
each round:
every node:
1. send msgs
2. rcv msgs
3. compute
```

- 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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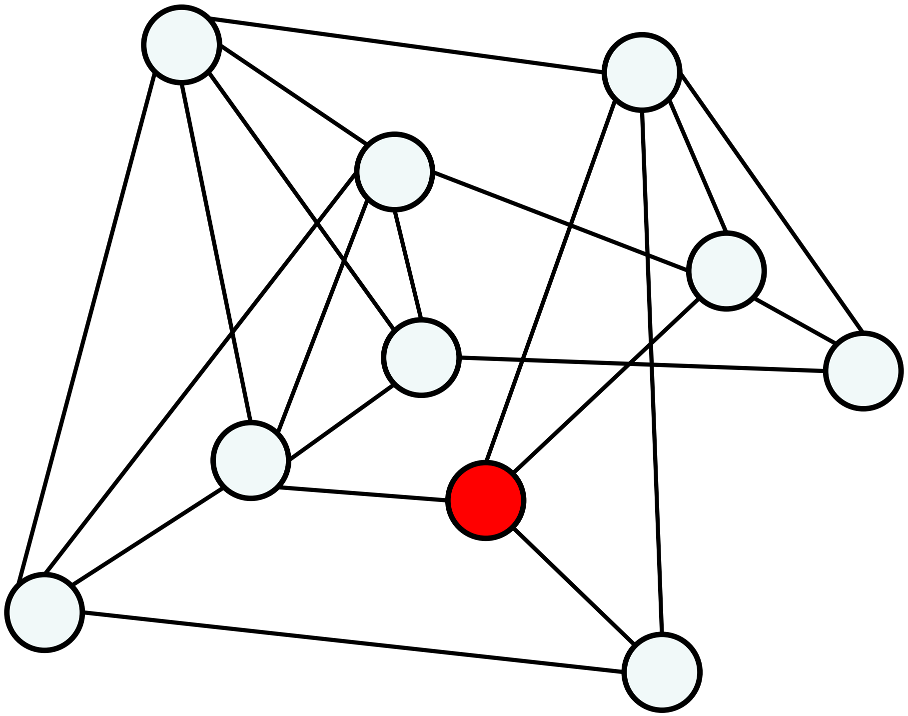

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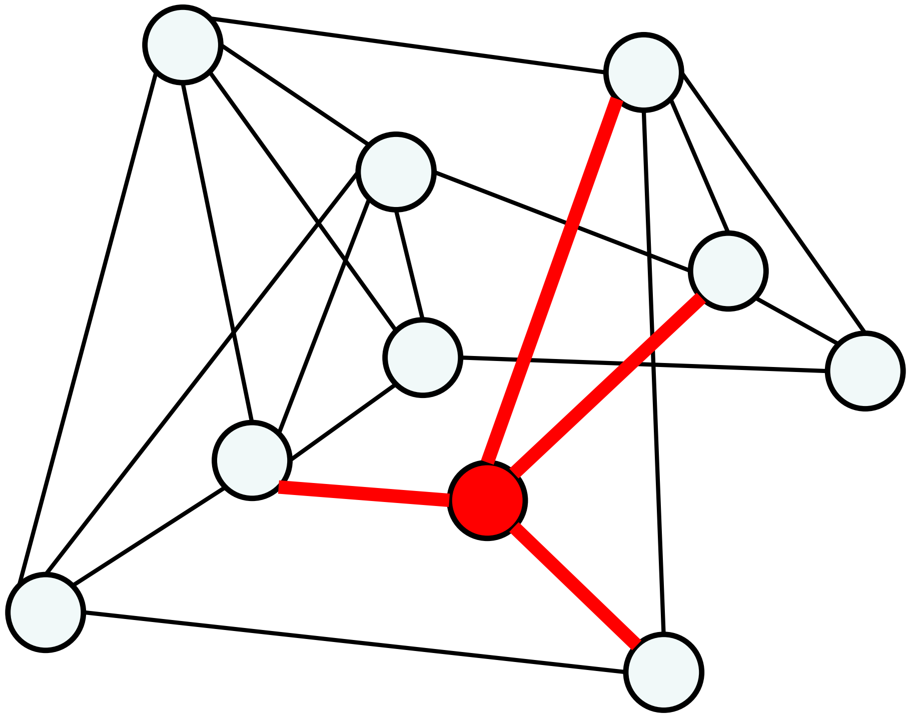

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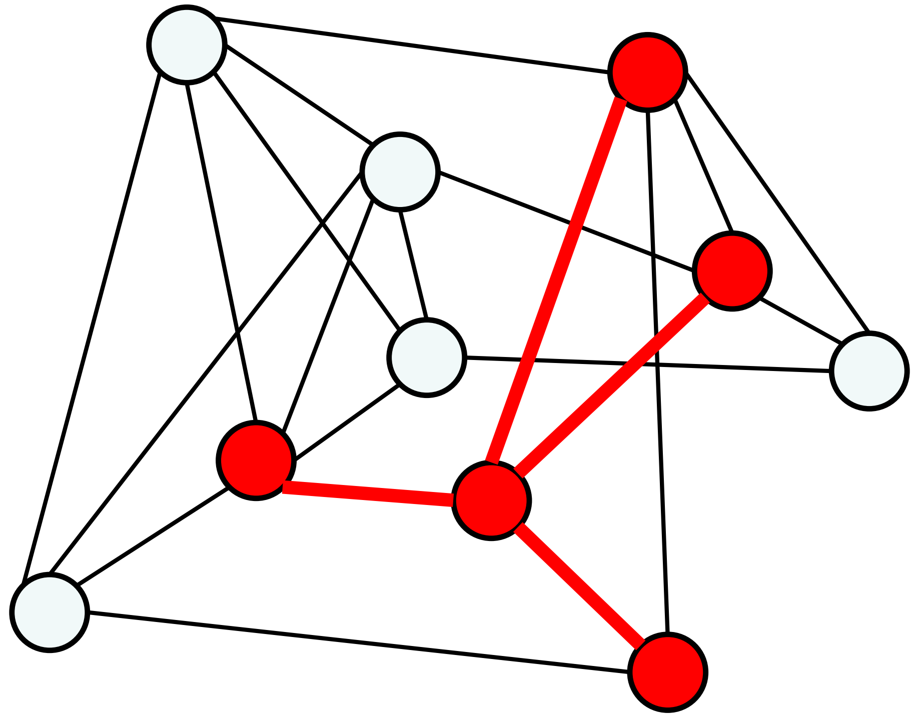

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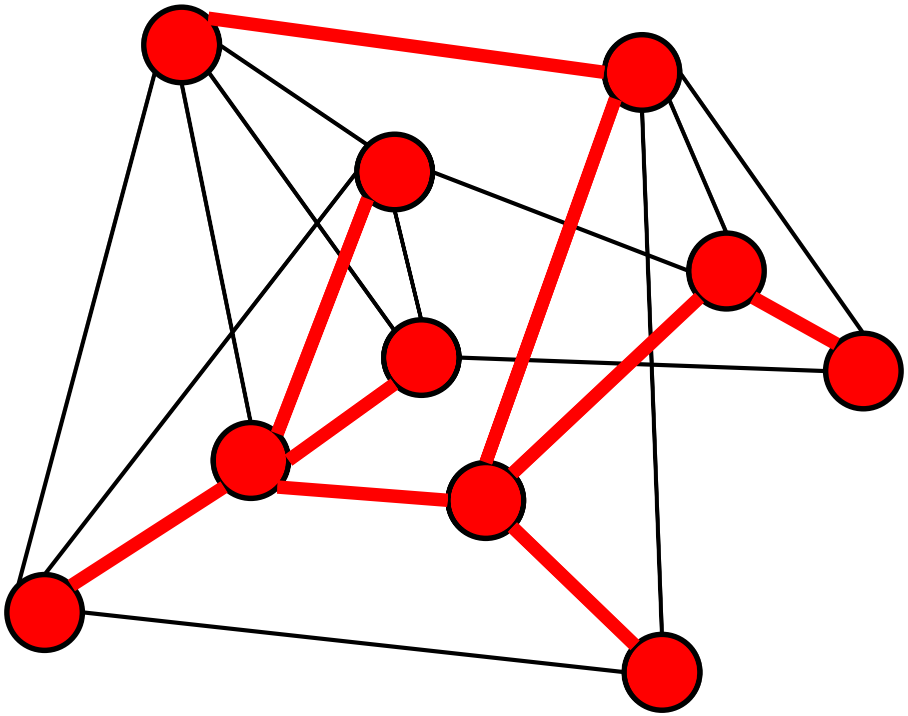

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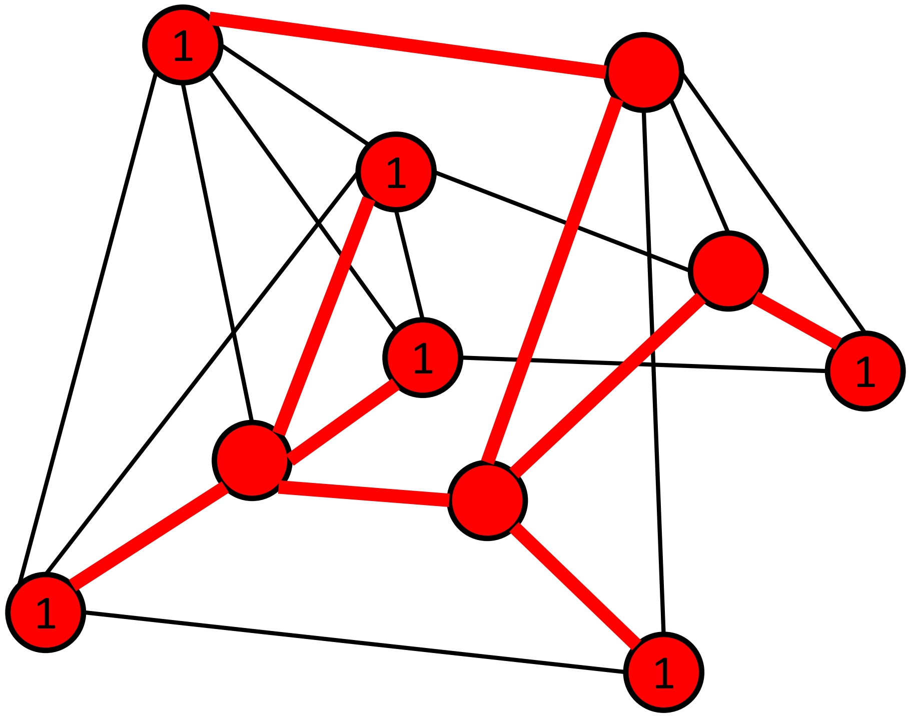

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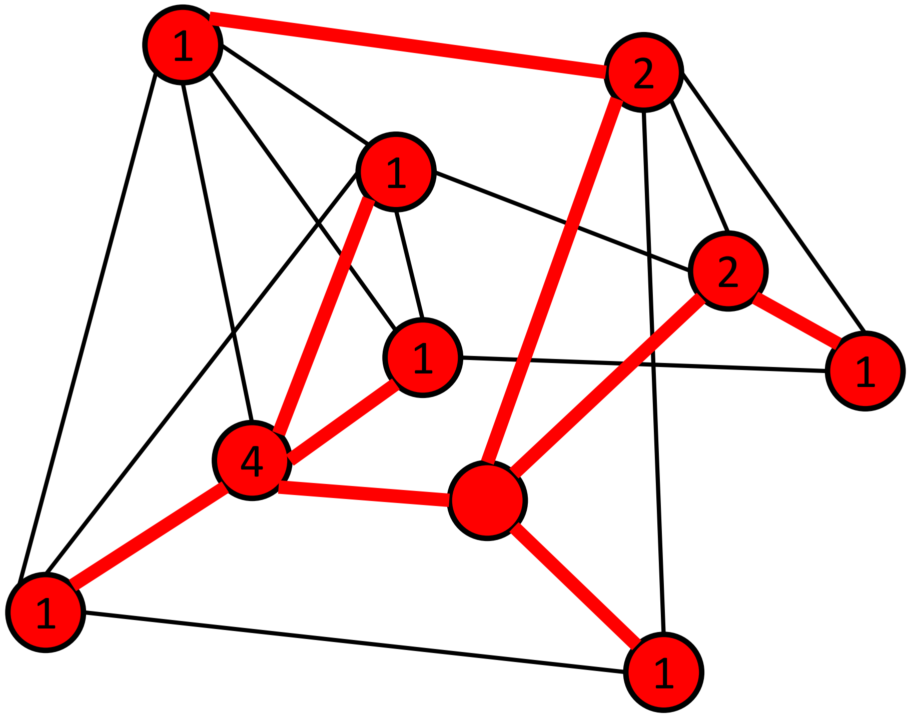

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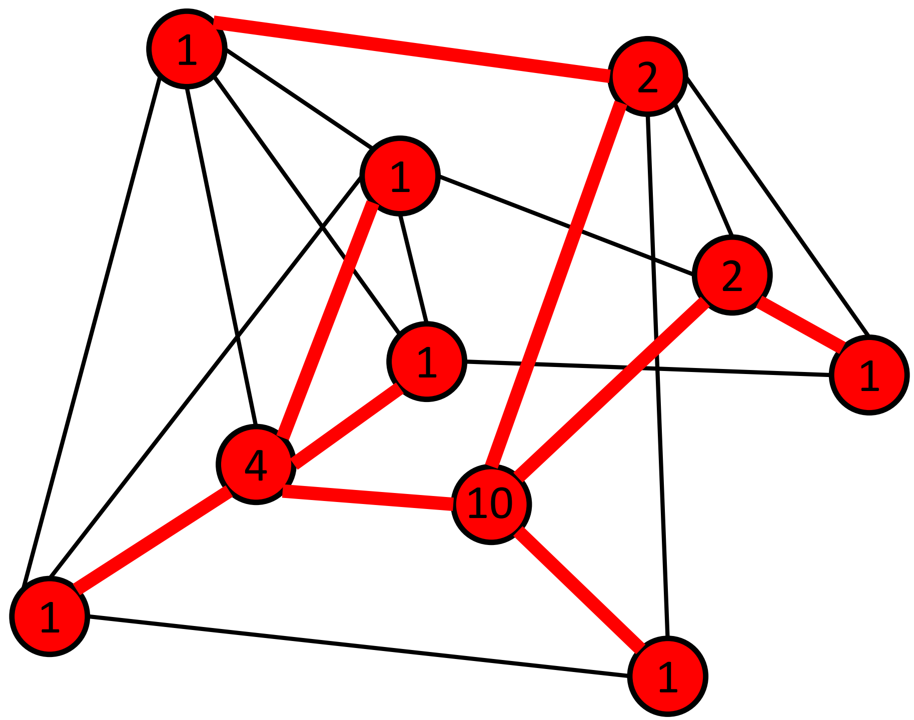
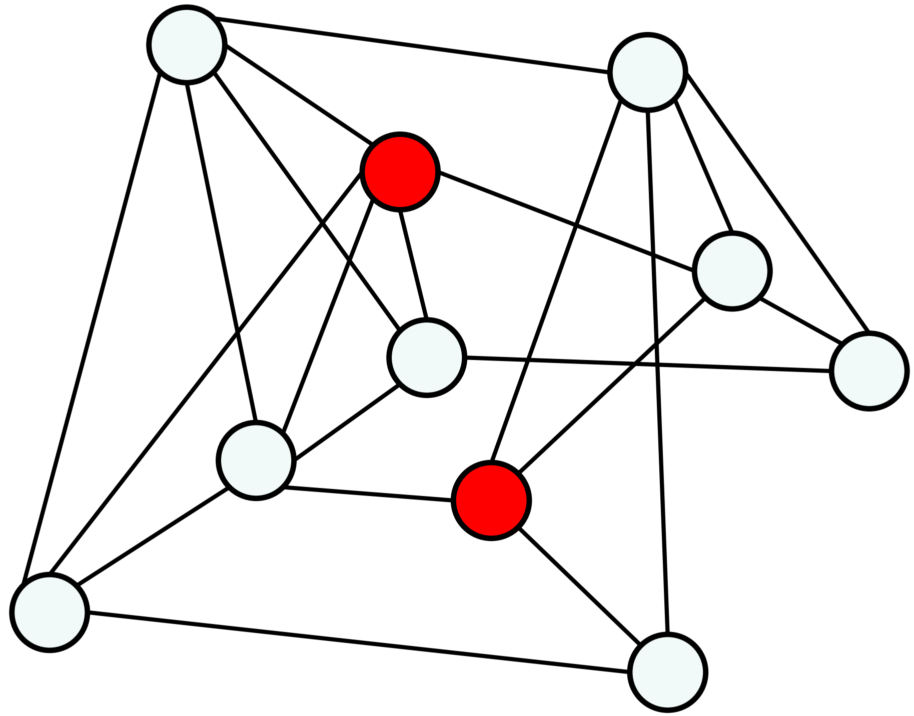


With a simple flooding/echo process, a network can find the number of nodes in time $O(D)$, where D is the diameter (size) of the network.

Diameter of Network?



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

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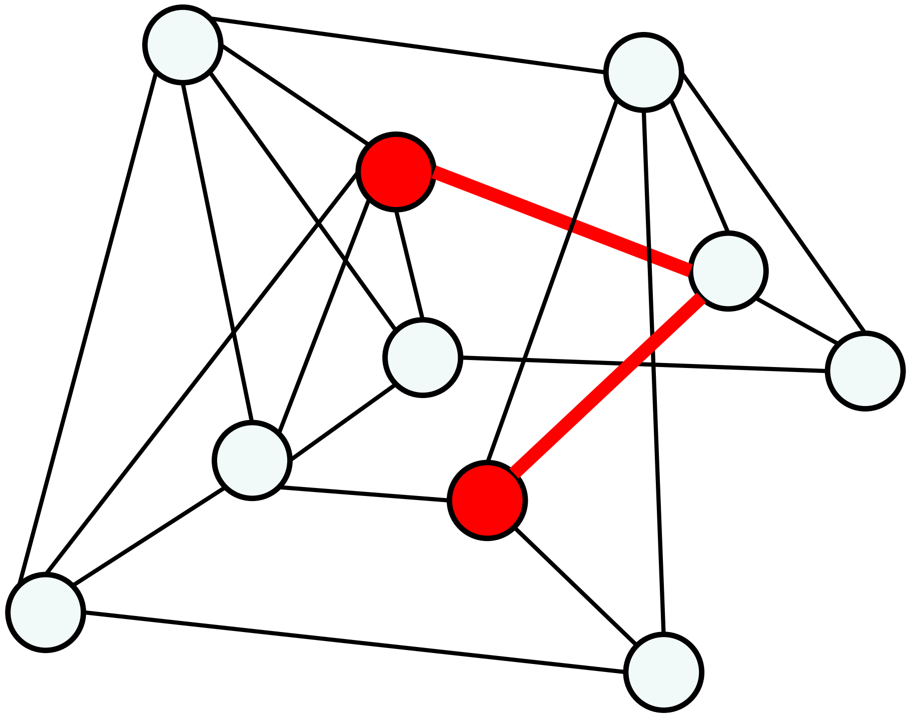

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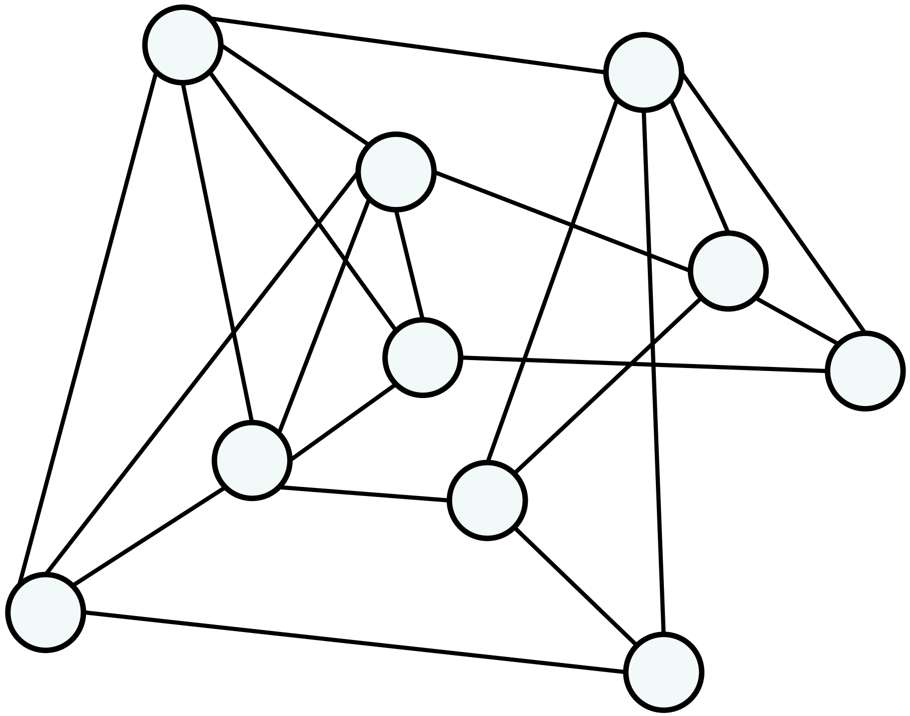
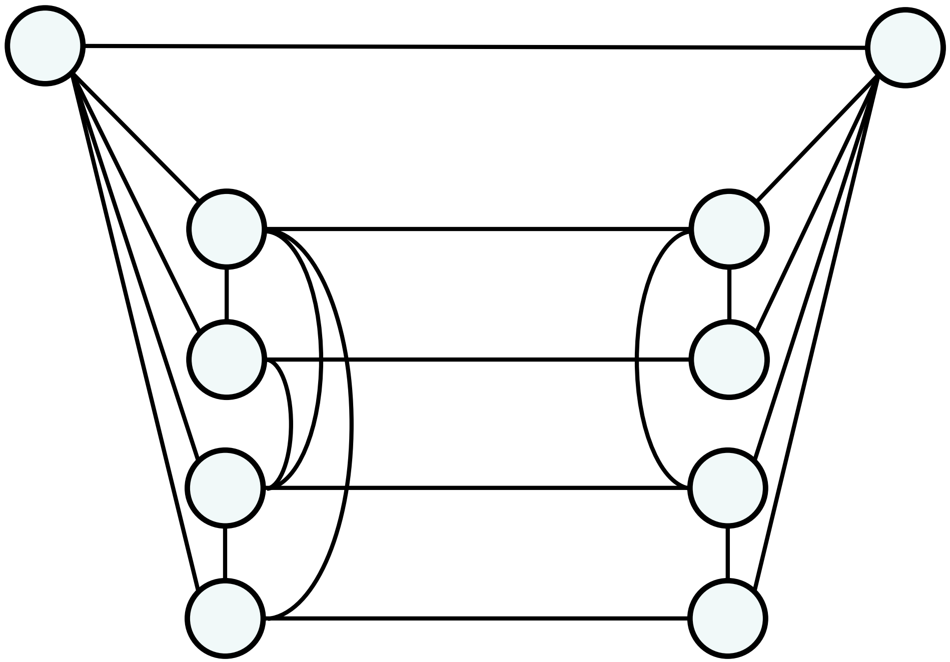


- Distance between two nodes = Number of hops of shortest path
- Diameter of network = Maximum distance, between any two nodes

Diameter of Network?



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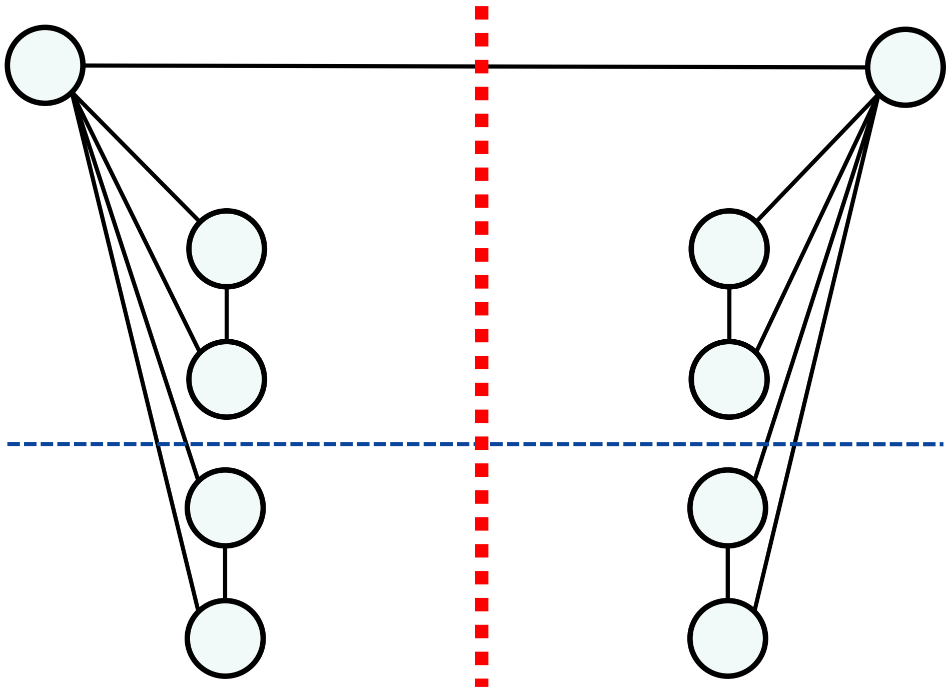

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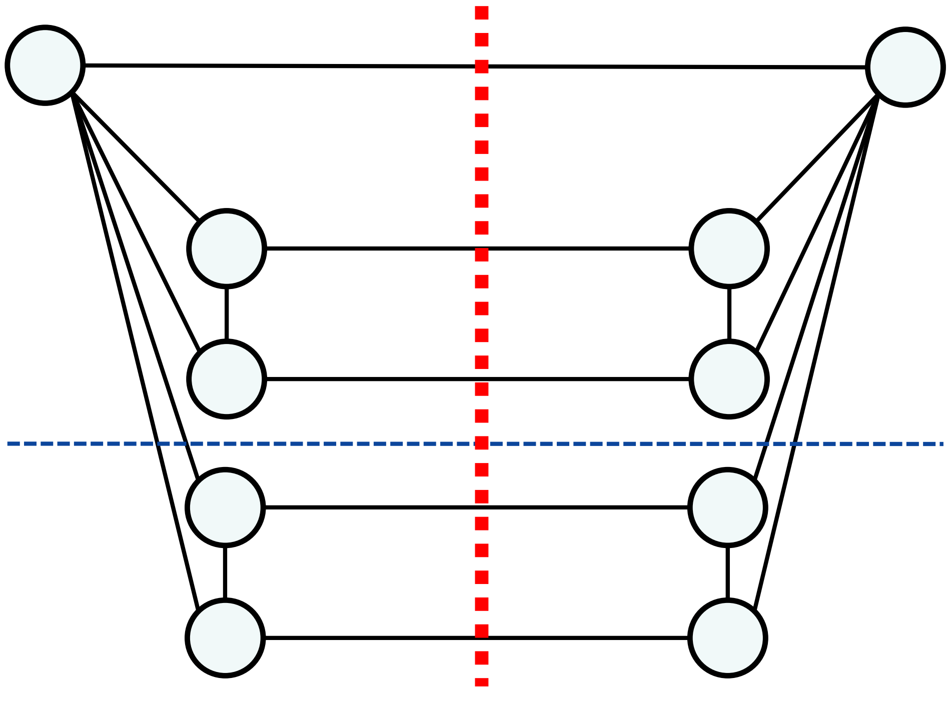

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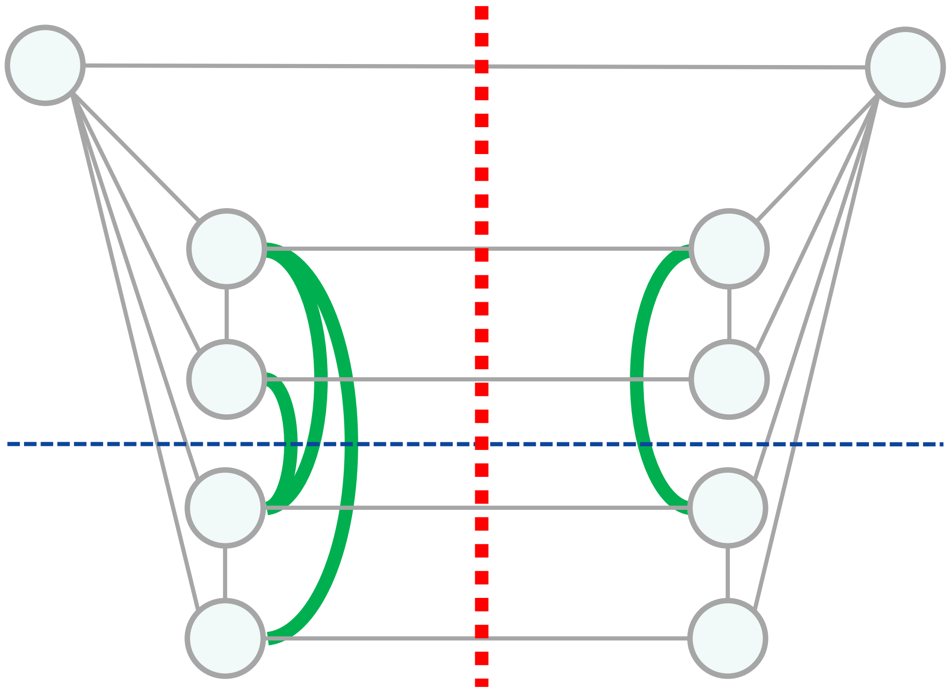

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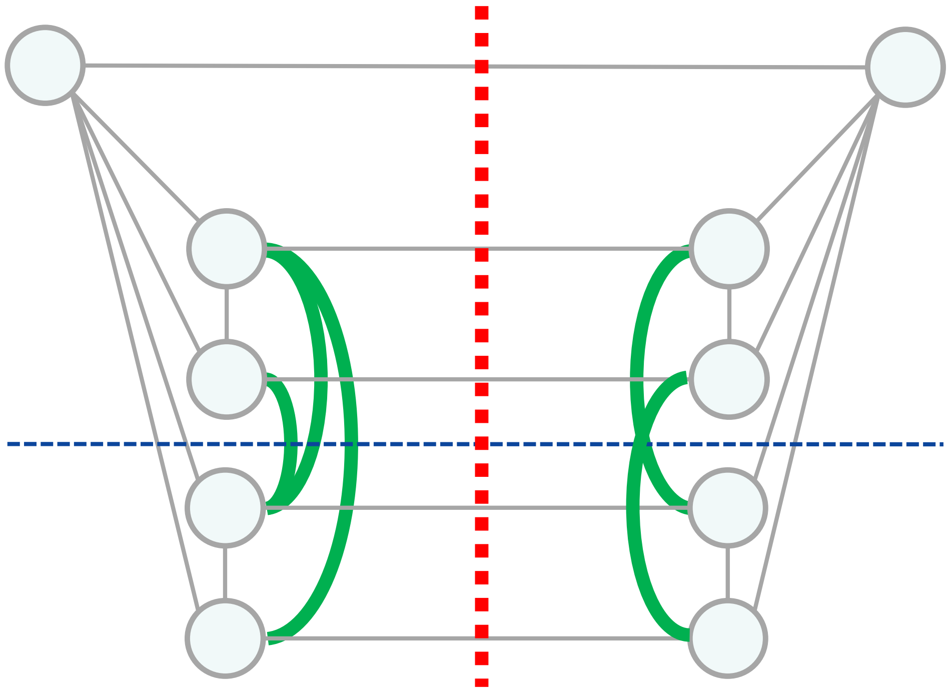

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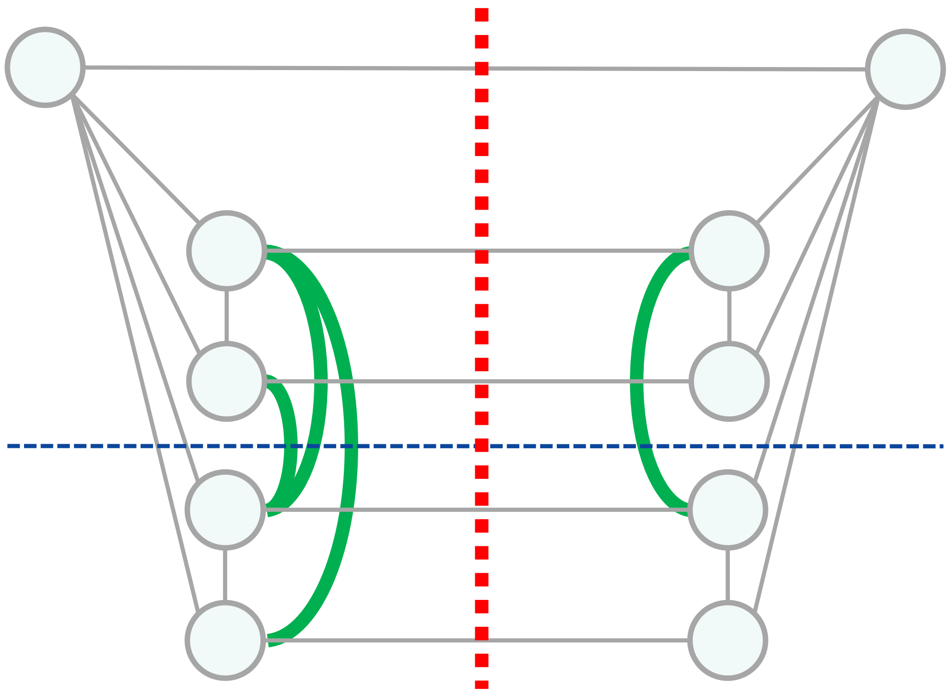
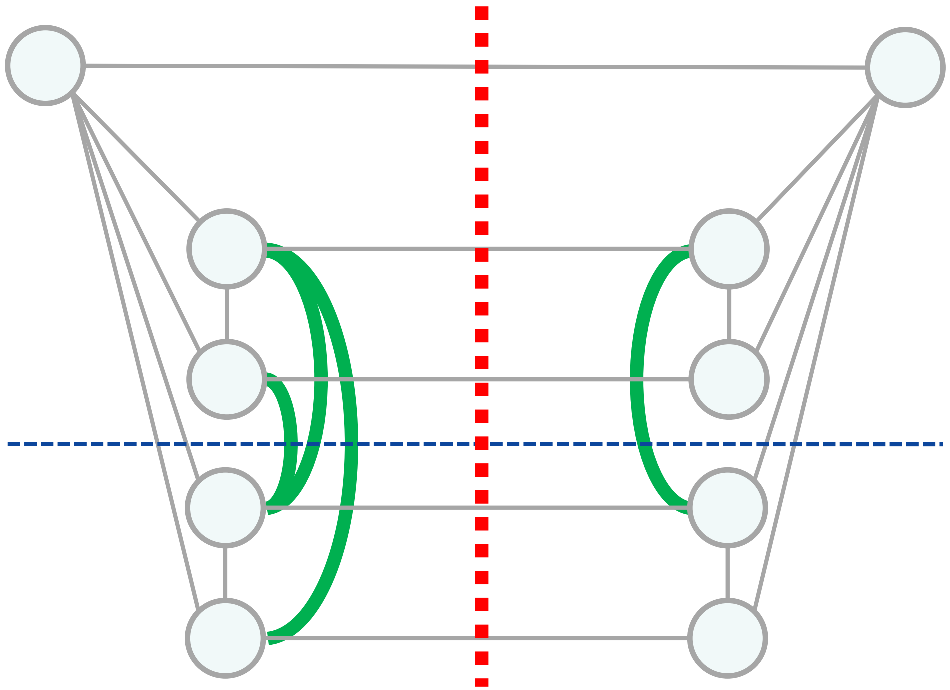


Networks Cannot Compute Their Diameter in Sublinear Time!

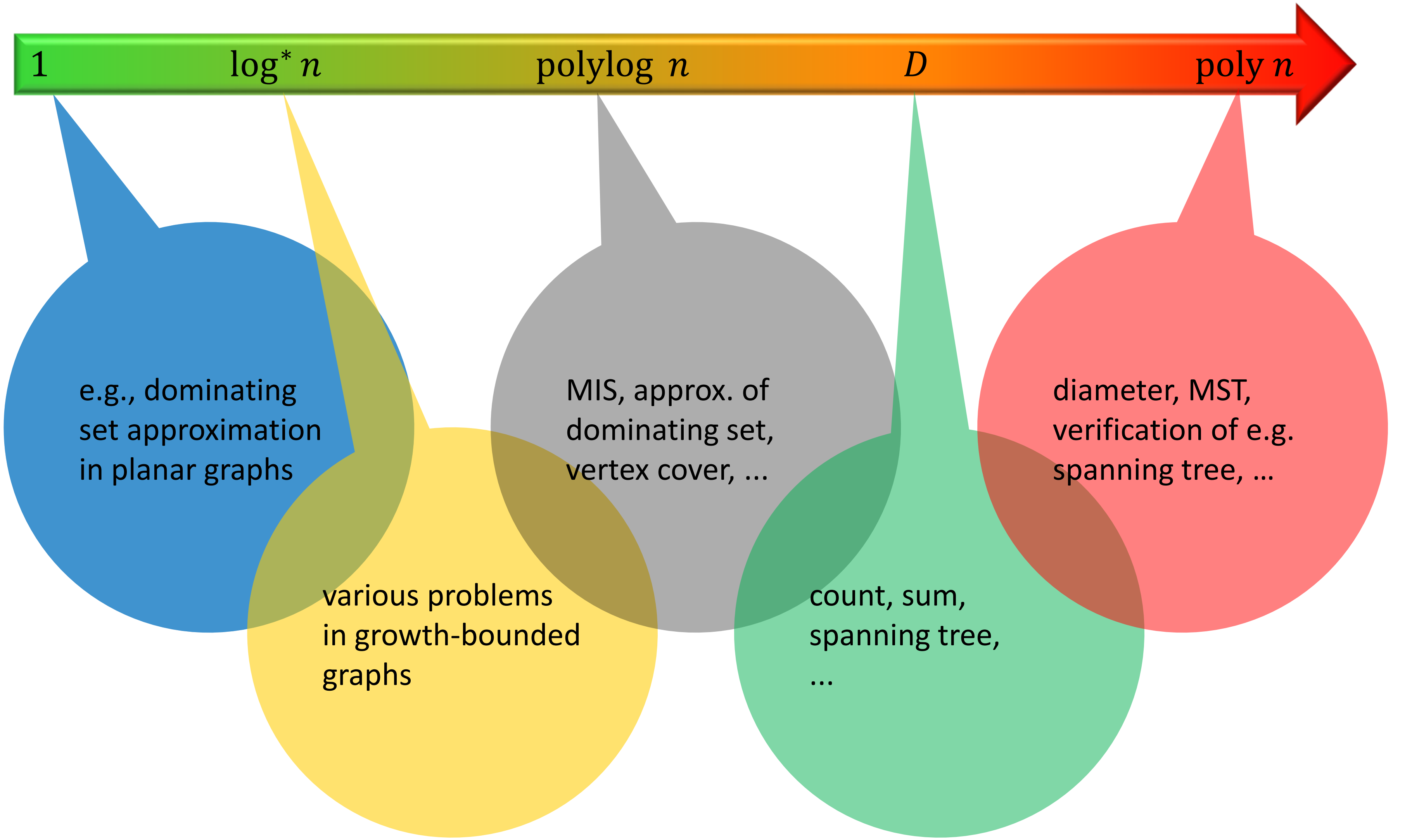
(even if diameter is just a small constant)



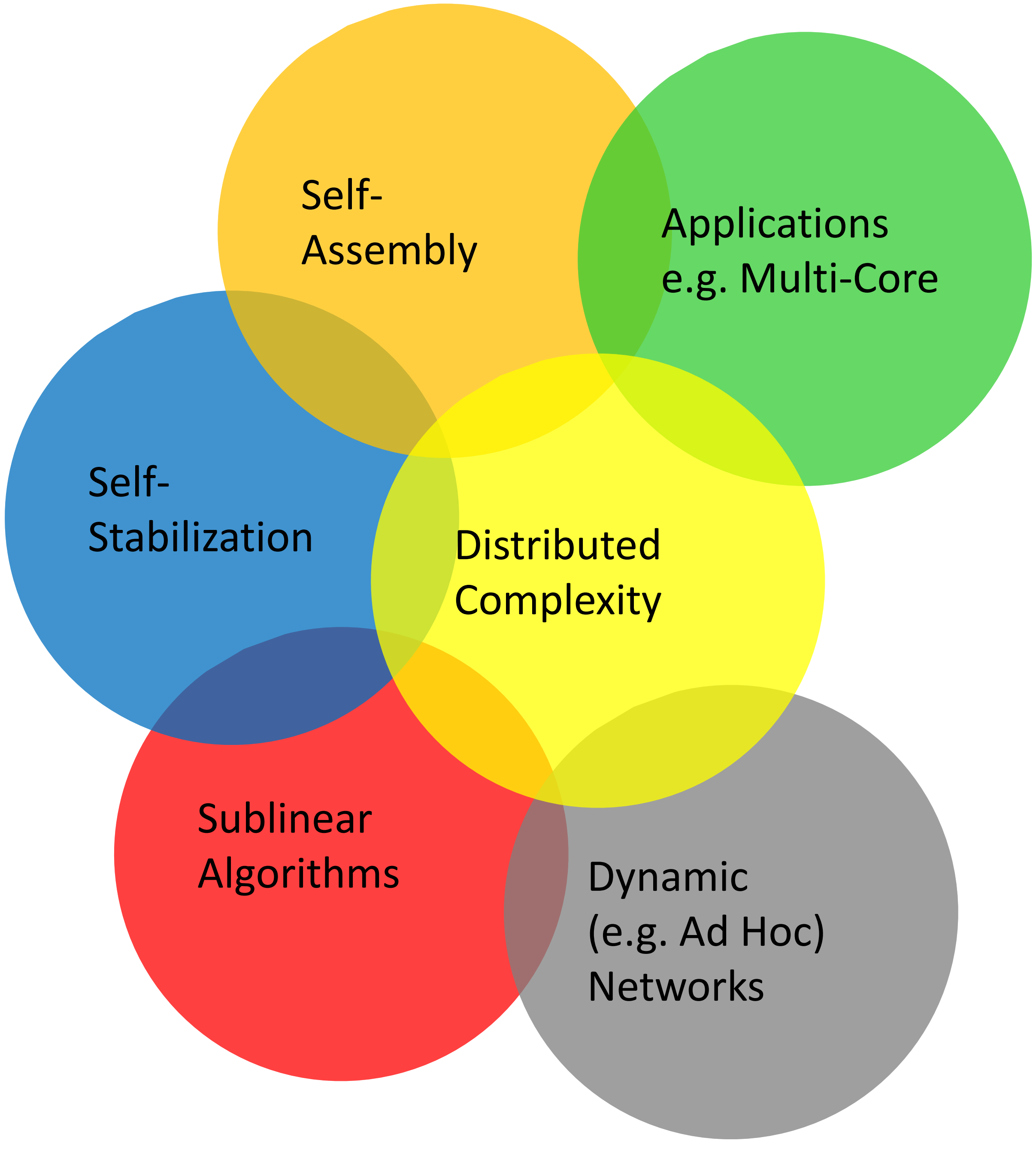
Pair of rows connected neither left nor right? Communication complexity:
Transmit $\Theta(n^2)$ information over $O(n)$ edges → $\Omega(n)$ time!

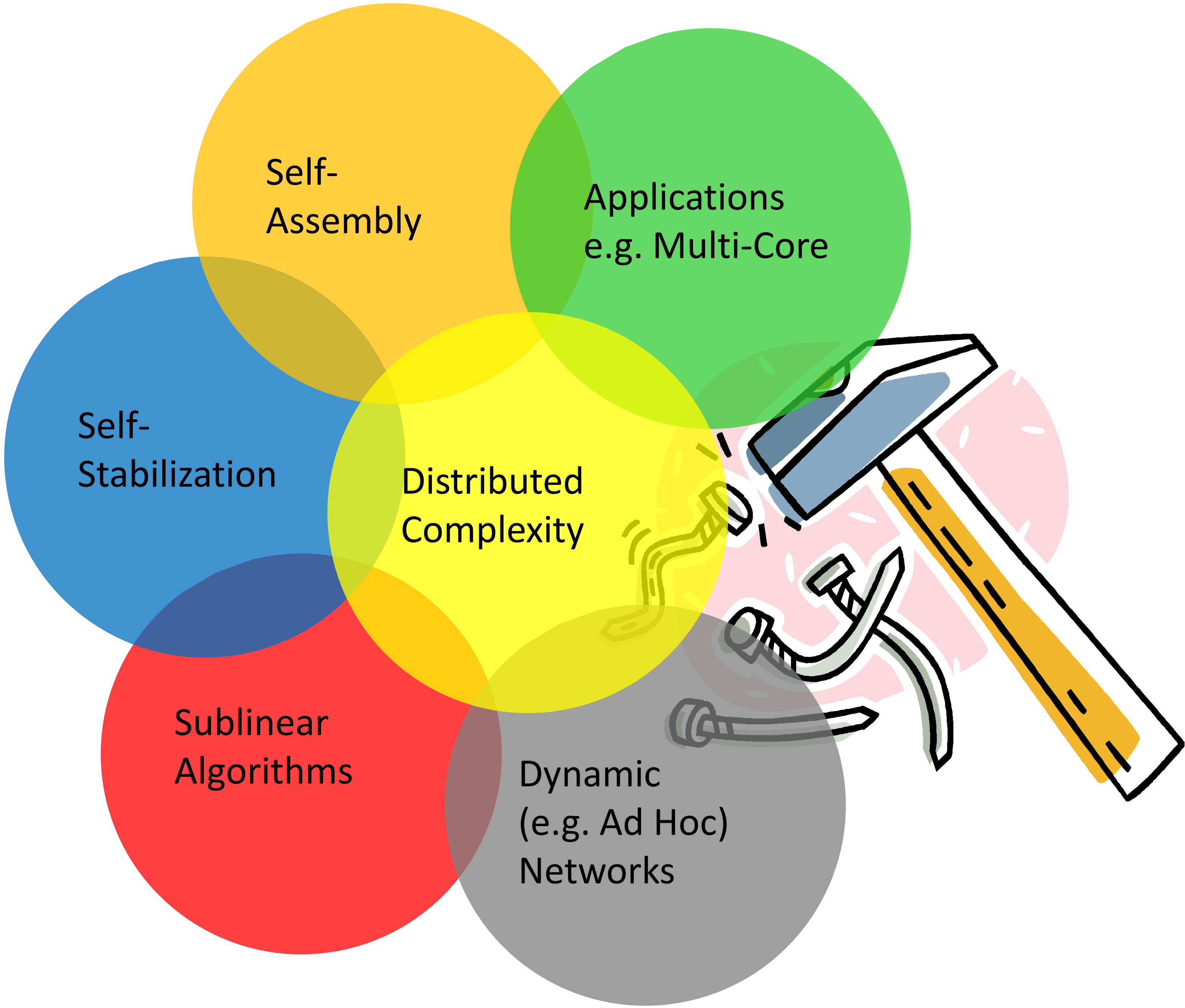
[Frischknecht, Holzer, W, 2012]

Distributed Complexity Classification



e.g., [Kuhn, Moscibroda, W, 2016]


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



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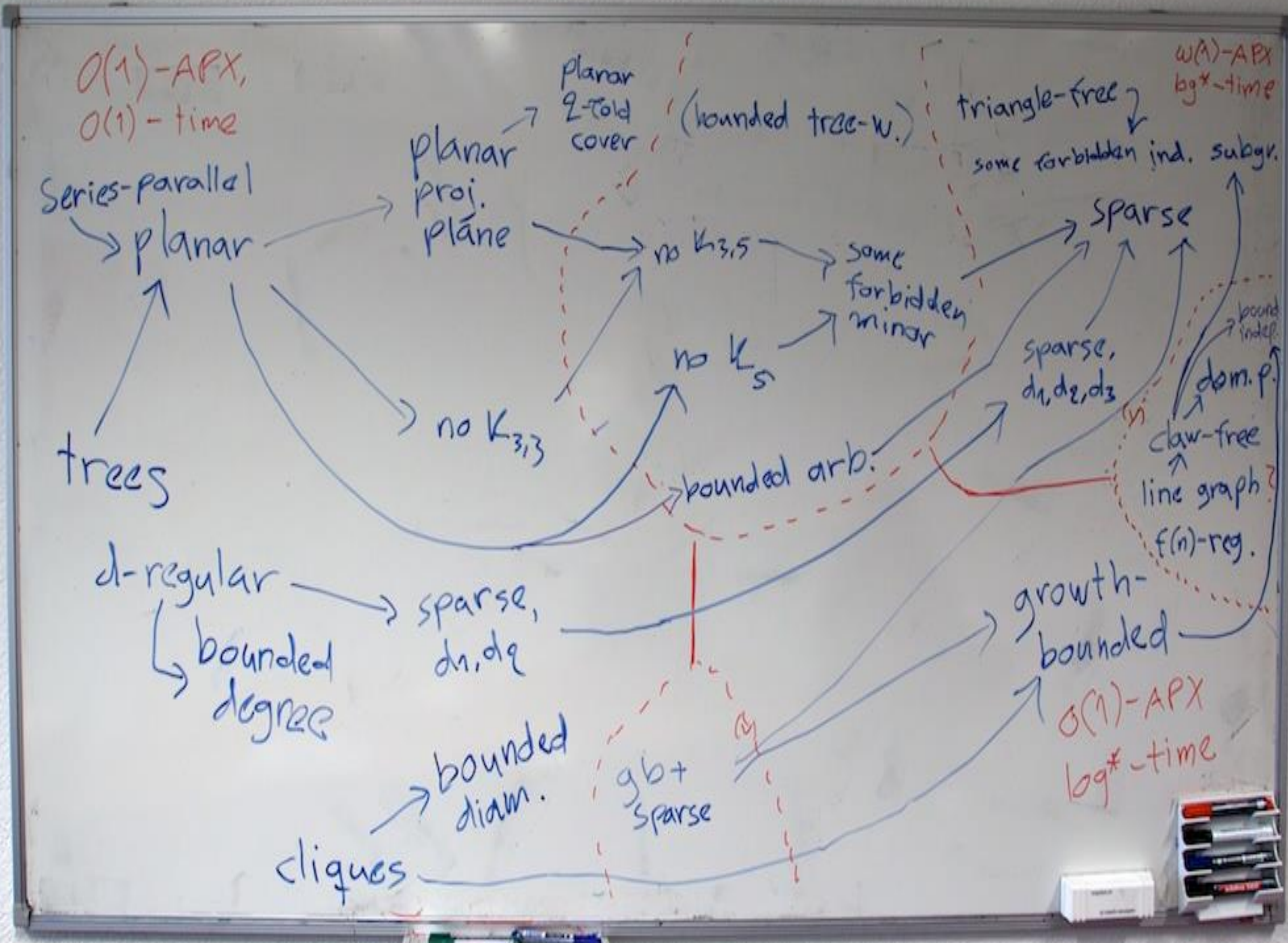
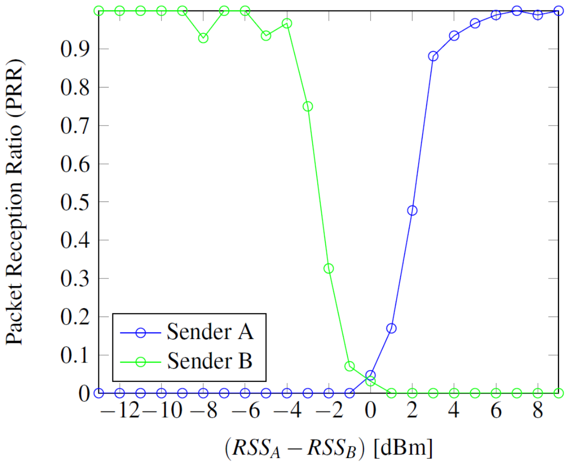
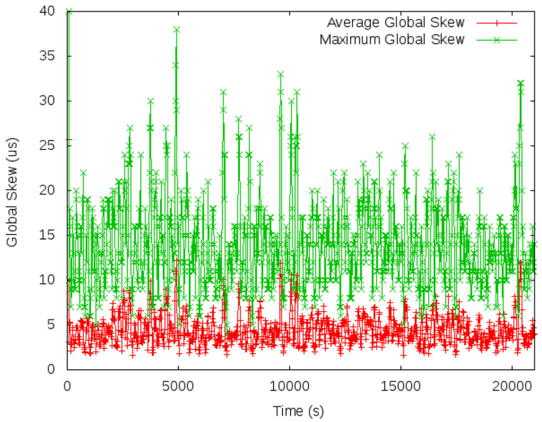
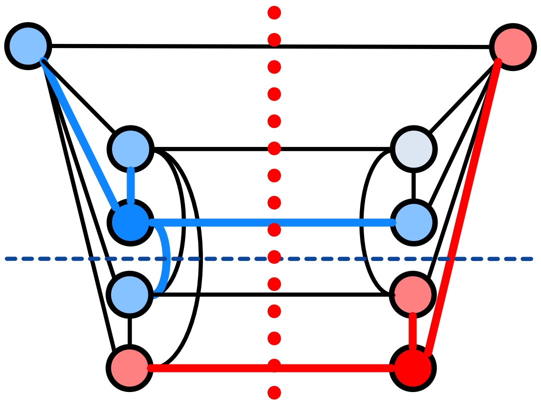


O(1)-APX,
O(1)-time
planar
2-fold
cover
(bounded tree-w.)
triangle-free
ω(1)-APX
log*-time
some forbidden ind. subgr.
series-parallel
planar
planar
proj.
plane
no $K_{3,5}$
some
forbidden
minor
sparse
no K_5
sparse,
d_1, d_2, d_3
bound
indep.
dom. p.
trees
no $K_{3,3}$
claw-free
bounded arb.
line graph?
f(n)-reg.
d-regular
sparse,
d_1, d_2
growth-
bounded
bounded
degree
O(1)-APX
log*-time
bounded
diam.
gb+
sparse
cliques

Summary


Packet Reception Ratio (PRR)
Sender A
Sender B
$(RSS_A - RSS_B)$ [dBm]


Average Global Skew
Maximum Global Skew
Global Skew (us)
Time (s)



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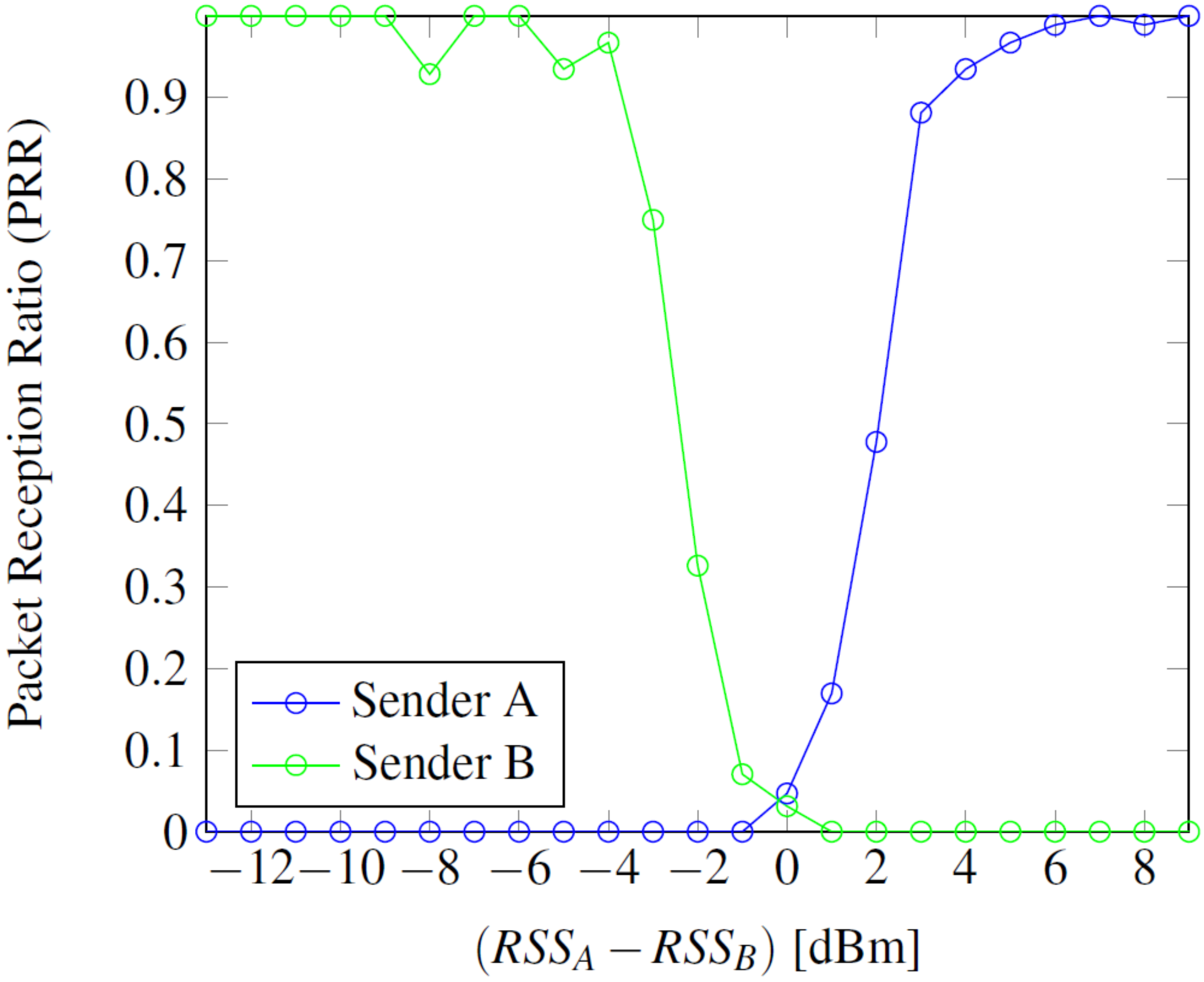

Theory for sensor networks, what is it good for?!

How many lines of pseudo code
Can you implement on a sensor node?

The best algorithm is often complex
And will not do what one expects.

Theory models made lots of progress
Reality, however, they still don't address.

My advice: invest your research £££s
in ... impossibility results and lower bounds!

Thank You!

Questions & Comments?

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