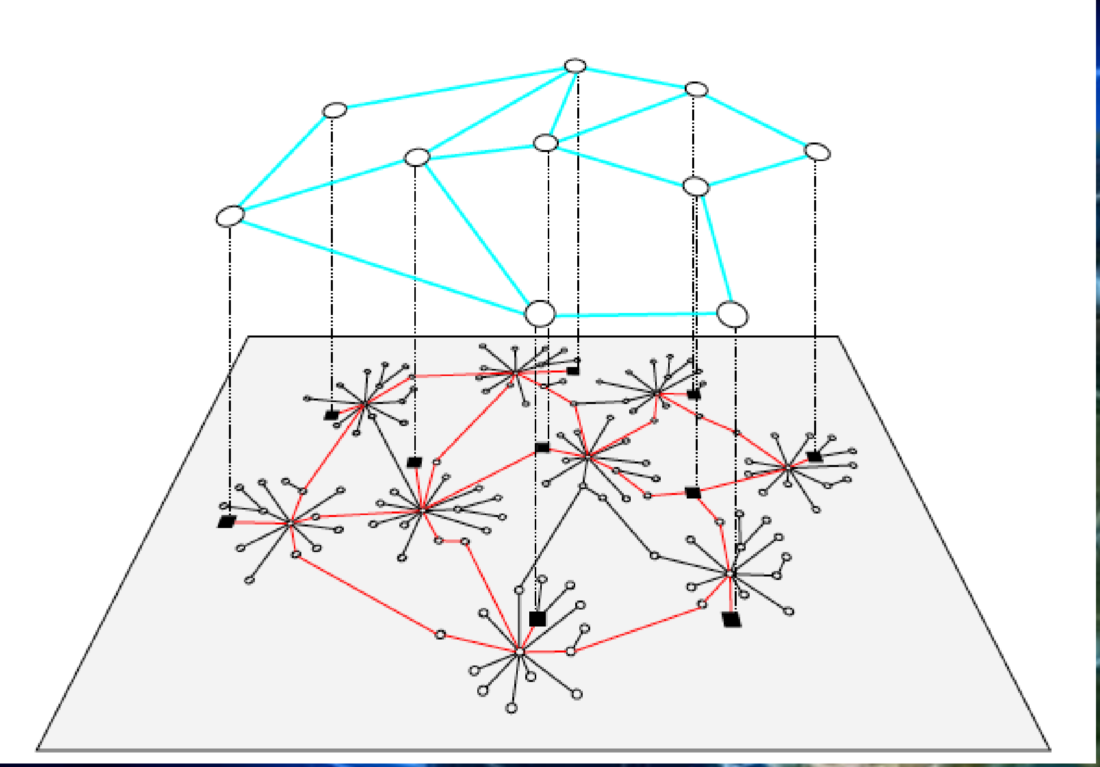
Distributed Graph Algorithms and Very Large Scale Integrated Circuits

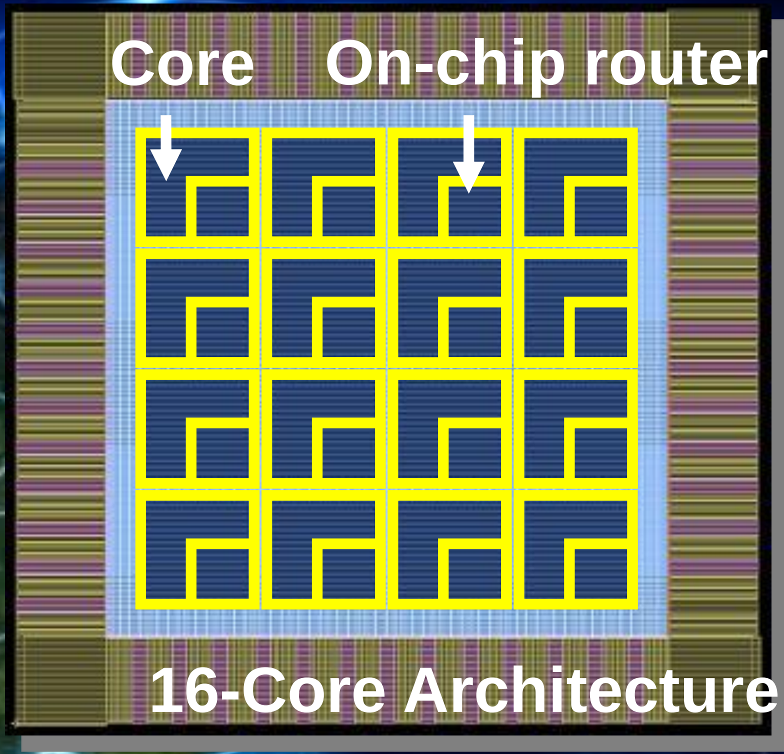
Danny Dolev

Specific work jointly with Matthias Függer, Christoph Lenzen, Martin Perner, Ulrich Schmid and Noam Teomim

Distributed Systems

In this talk we focus on fault tolerance of distributed functionalities -- to be implemented in hardware





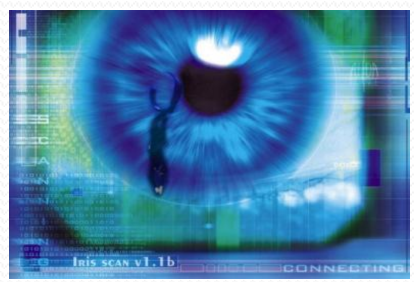
Some Systems Must Not Fail

space

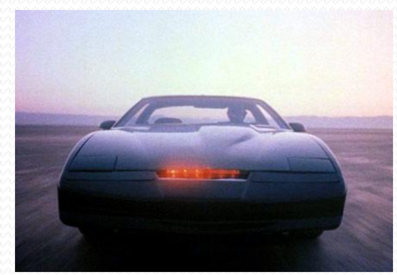
military

power grid

medical science

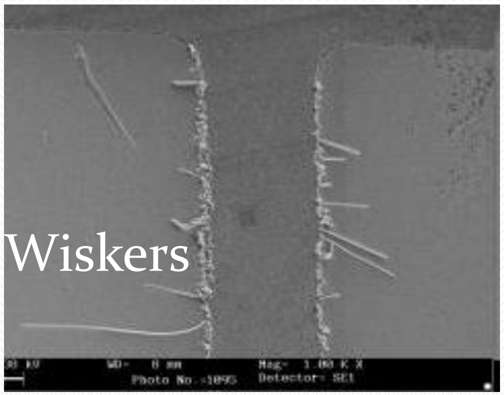


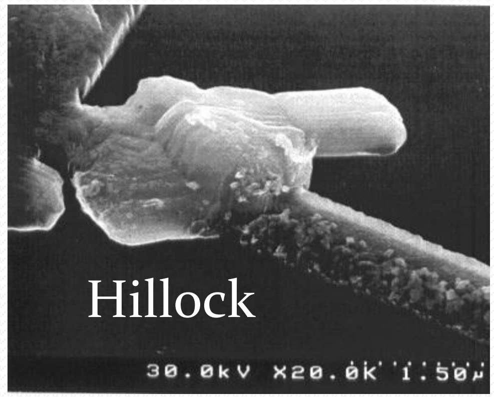
security



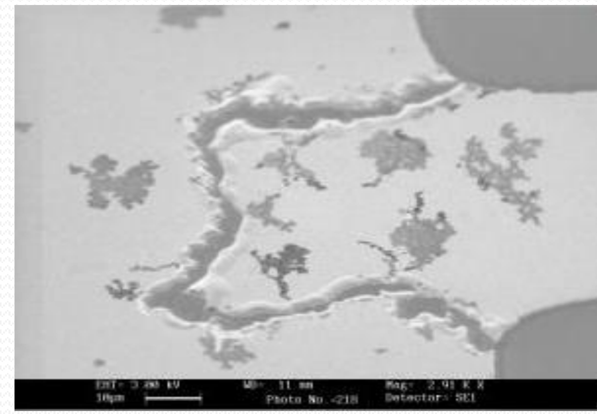
vehicles

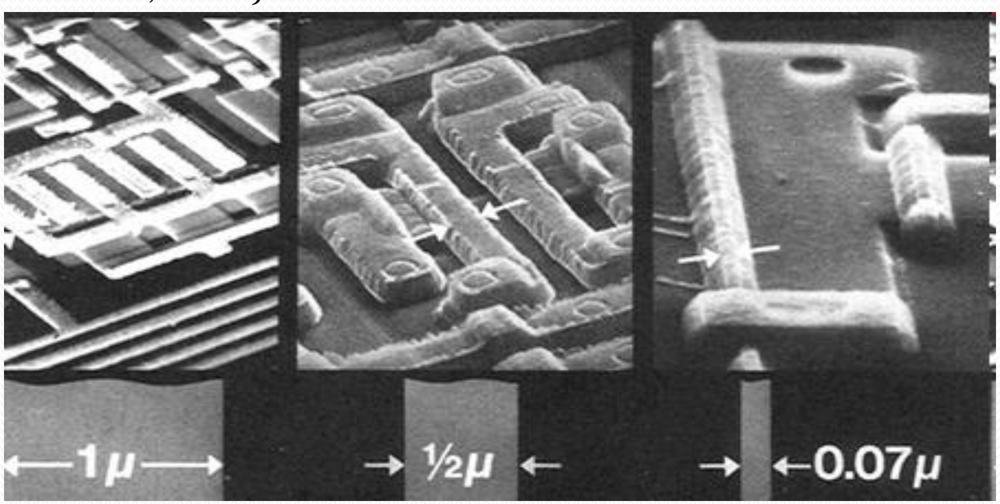
Defects (Electromigration)



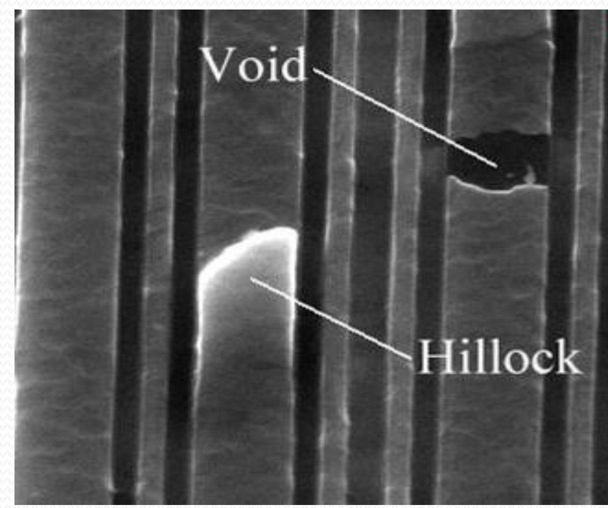


P. Gutman, IBM T.J.Watson Research Center



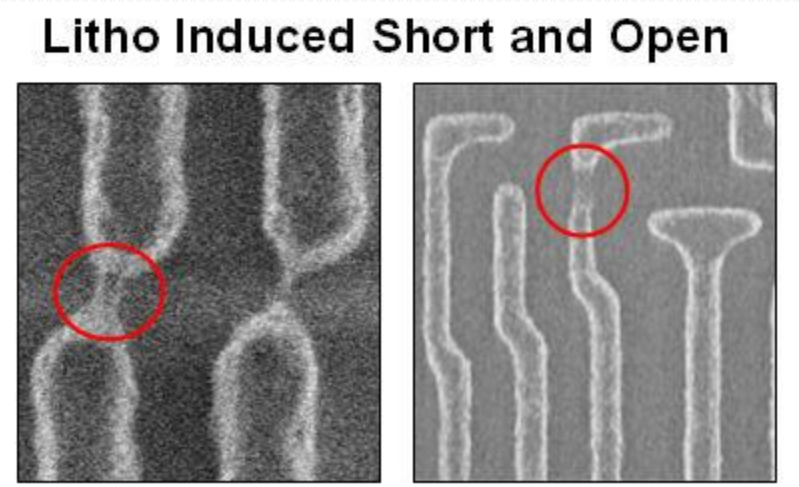


M. Ohring, Reliability and Failure of Electronic Materials and Devices,1998

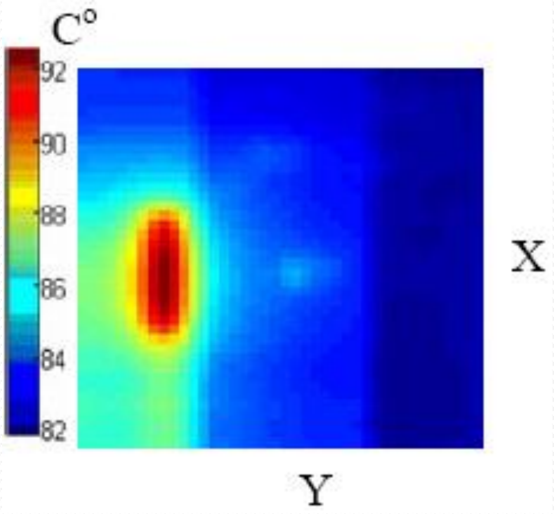


ASM Corp. Shanghai

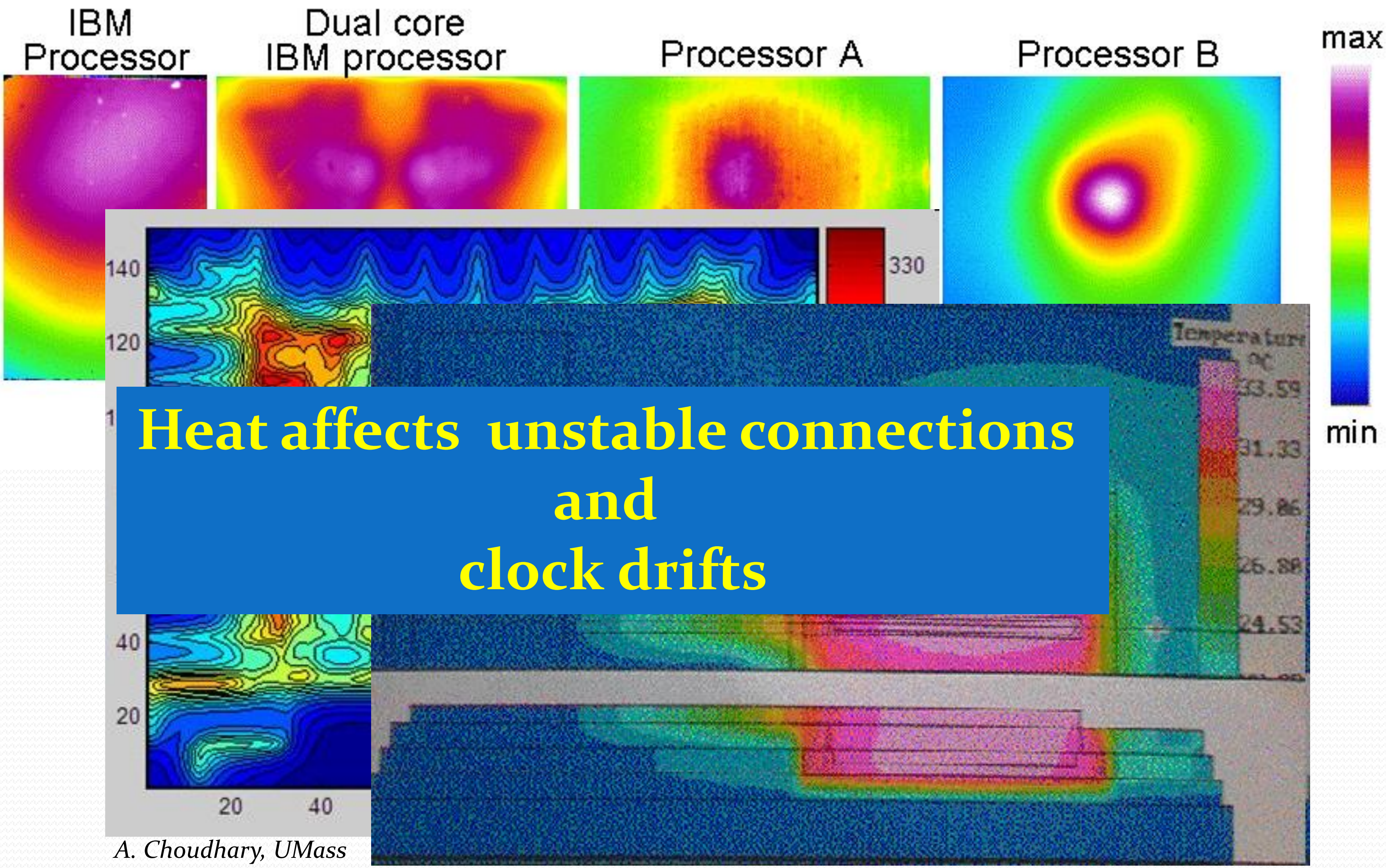
Process and Operational Variations



Even if there isn't a complete short or open, resistance and capacitance variations can lead to trouble



Chip temperature map



Heat affects unstable connections and clock drifts

A. Choudhary, UMass

Small transistor dissipating 5mW in an SOI wafer; University of Bolton

Decades of Fault Tolerance

- Nasa initiated these lines of research
  - Byzantine Faults
  - Self-stabilized systems (transient faults)
- Utopia
  - Efficient protocols that overcome both types of faults

  - DARTS project of Austrian Aerospace implemented Byzantine tolerant protocols in hardware

RUAG Aerospace Austria

Model

- Local clocks with bounded drifts
- A bound "d" on the time it takes two correct nodes to communicate
- Message passing
- FIFO and authenticated channels
- Transient faults
- A fraction of the nodes may be permanently faulty
  - Omission
  - Byzantine
- The number of nodes and their IDs are common knowledge

Typical Objectives

- Simulate synchronous rounds
  - Common numbering of rounds is another objective
- Produce “coordinated” pulsing
- Run consensus protocols
- Synchronize clocks
- Fault tolerant routing

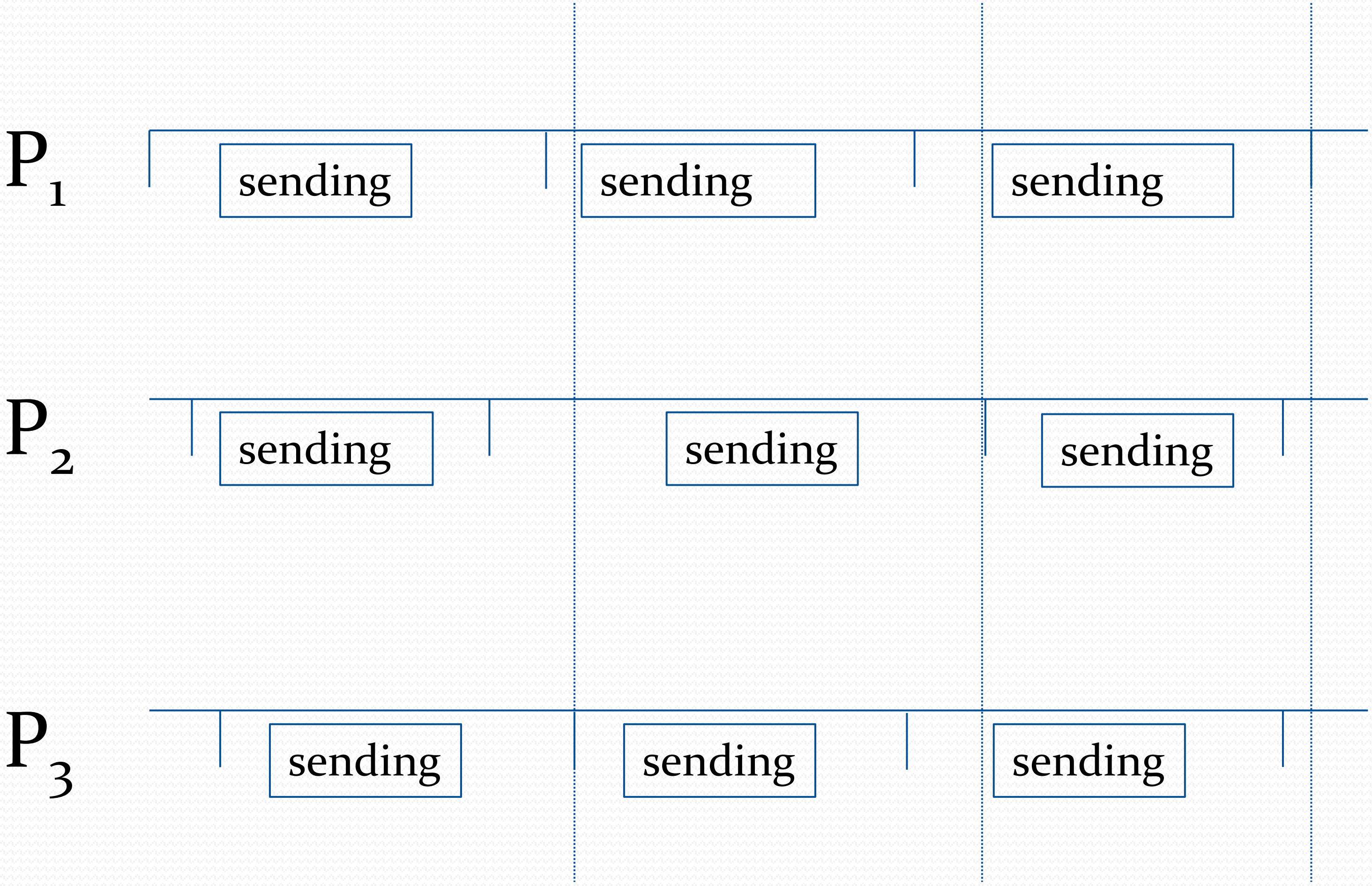
- We discuss such protocols in a fully connected system and on various communication graphs

Fully connected network

- Vast majority of previous research was in this model.
- Aim: "round separation"
  - Synchronize the nodes such that:
    - All messages sent by correct nodes in a given round is received by all correct nodes within that round.

  Thus, no correct node sends a message of the new round if any correct node is still willing to accept messages of the previous round.

Round Separation



The challedge

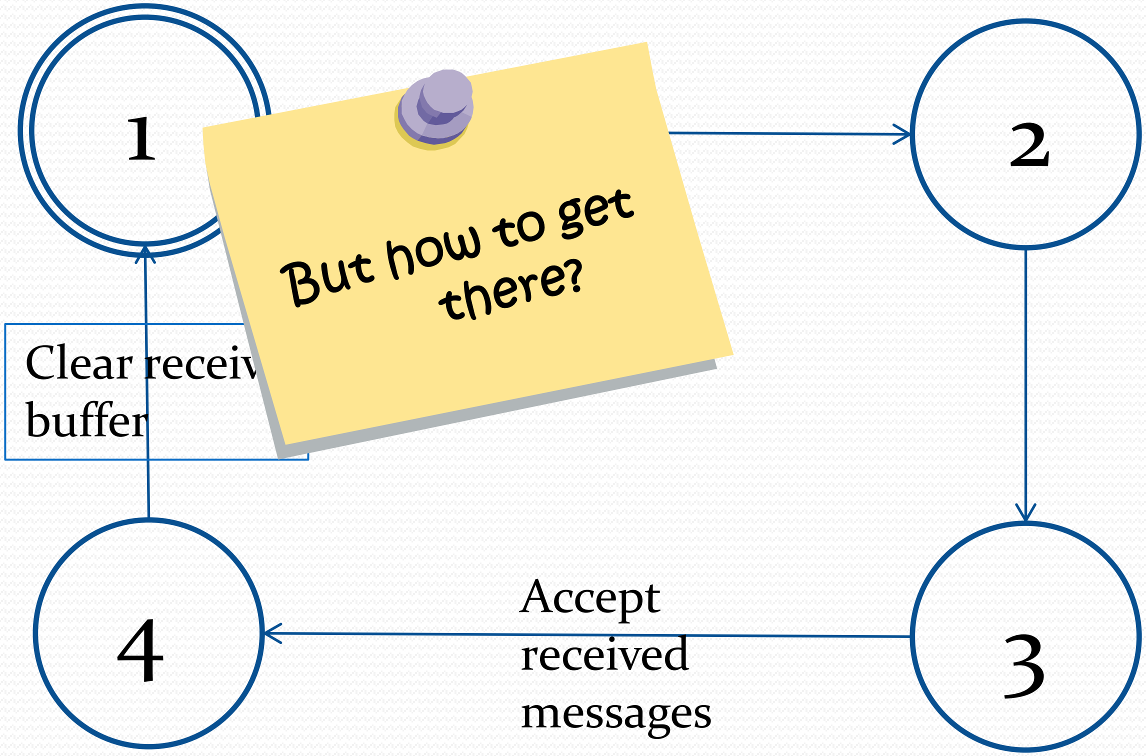
- Nodes start out “of the blue”
  - No common clock
  - No sense of round numbering or any other consistent relative states

  - The only means nodes have is to -
    - send and receive messages
    - measure duration of time passed

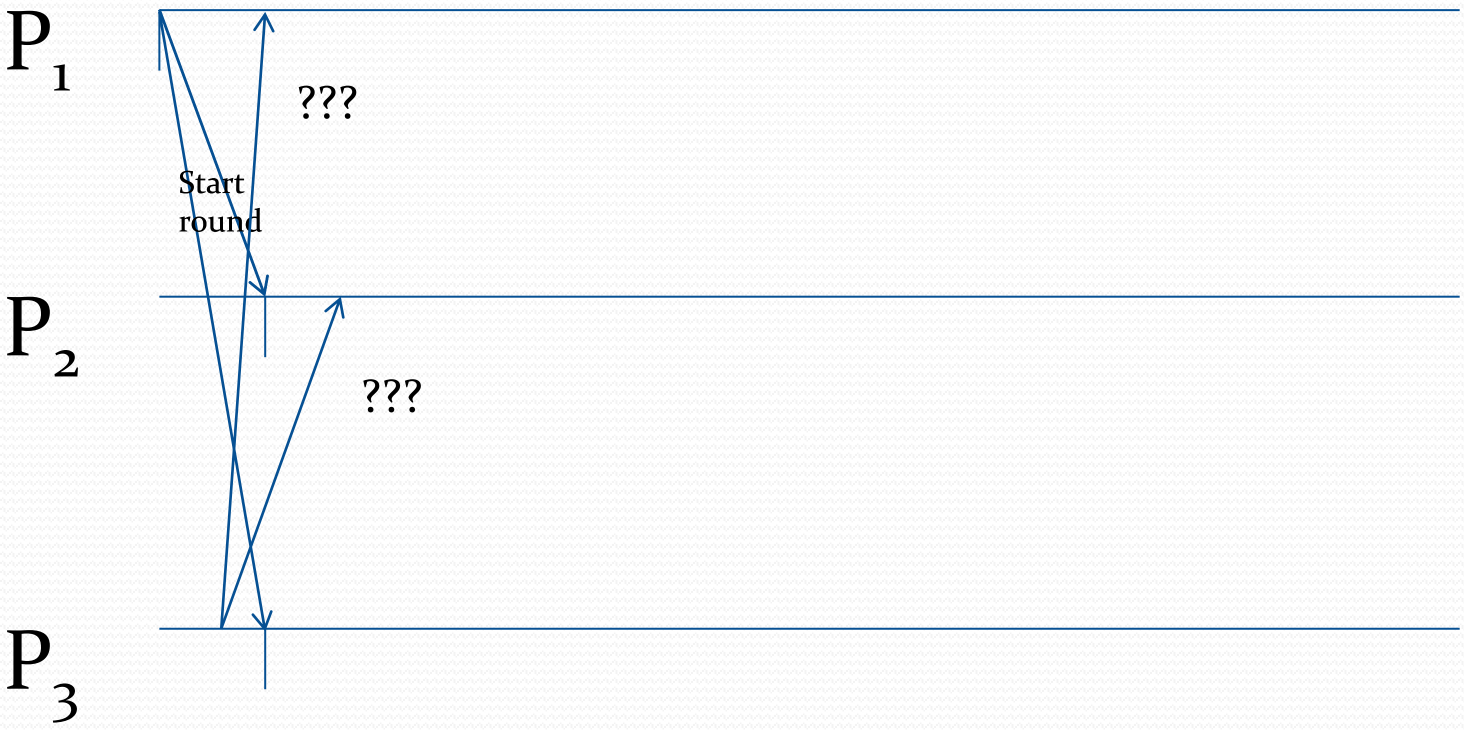
- Assume first transient faults and permanent omission faults

Node's State Machine

Rule: Every d switch states

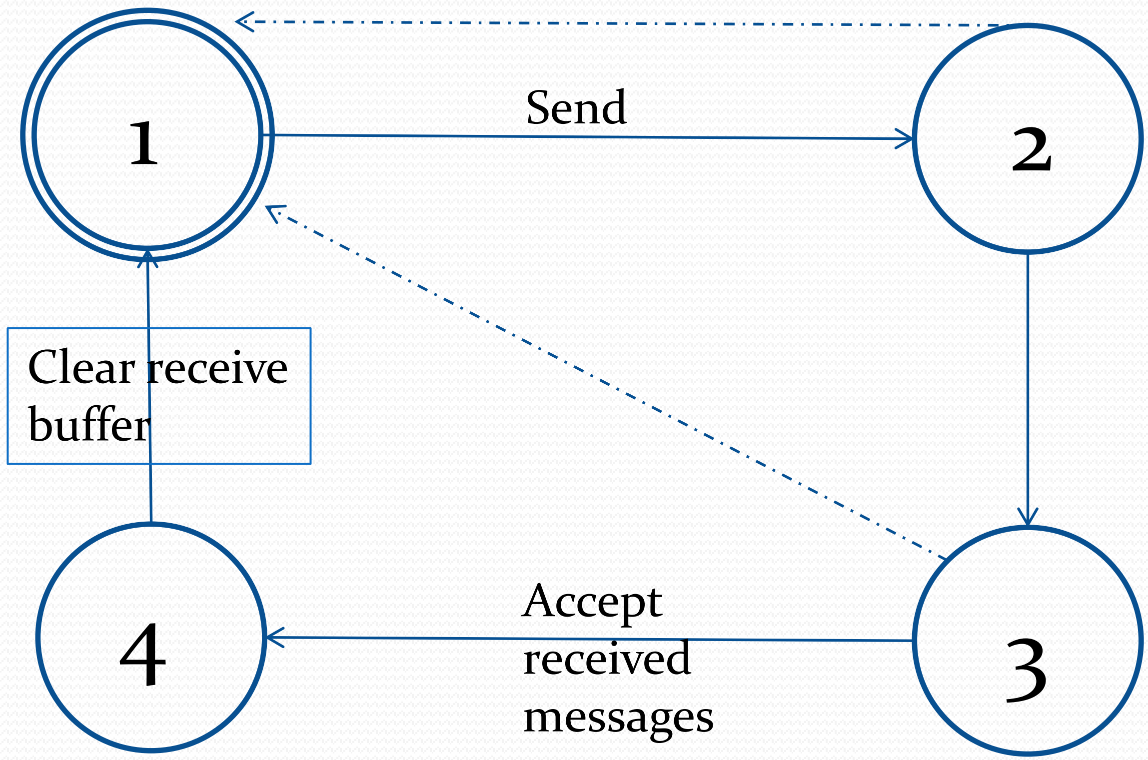


Dry Run



Node's State Machine

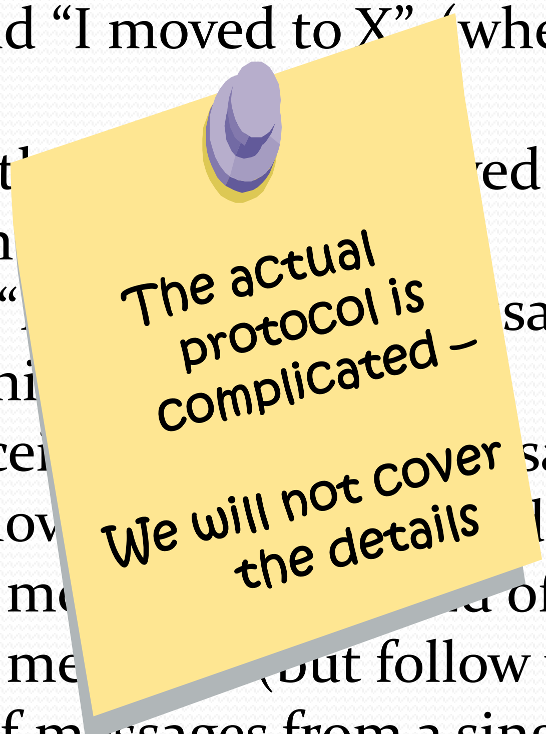
Rule: if within d there are n-f in your state – switch states



Lower Layer Protocol

1) If you see (n-f) messages of the same state in the last d:
   a) If it's your state move one state ahead.
   b) Otherwise, move to that state

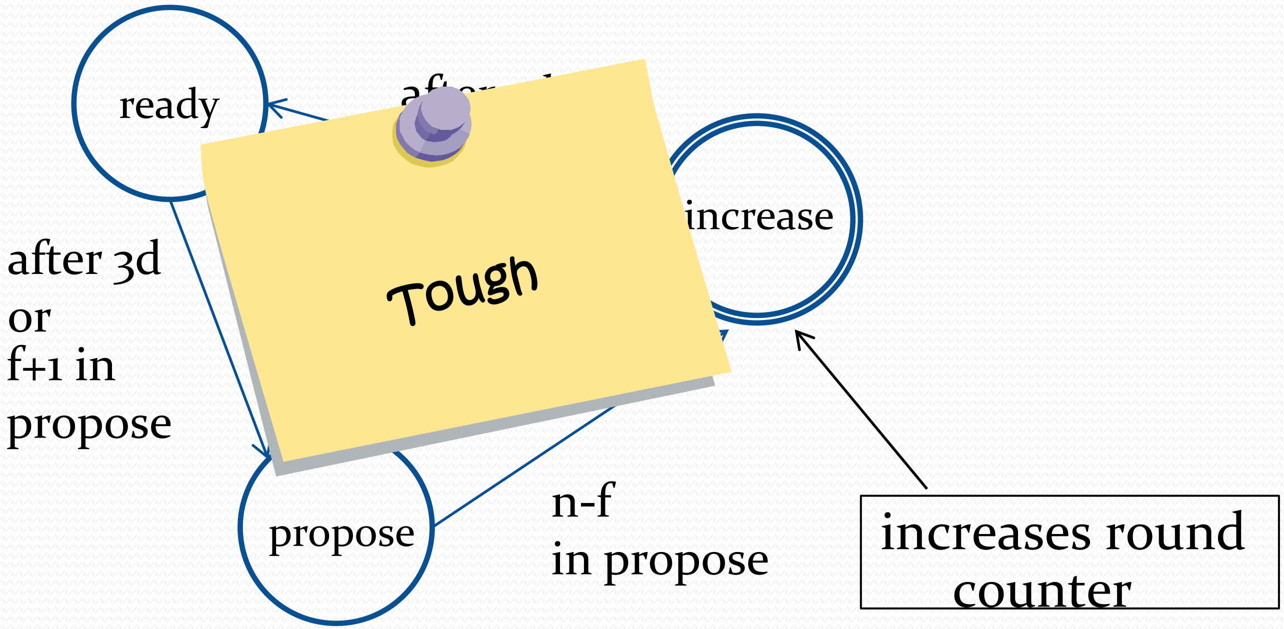
   Either way send "I moved to X" (where X is the state you moved to).
2) If you received t… …ved to X", move to X and send "I jumped to X" m…
3) If you received "… …sage, move to X (and don't announce anythi…
4) If you didn't recei… …sage within 2d move to state 1.
5) If you sent a "mov… …n't receive (n-f) "move"/"jump" me… …of the sending, stop sending "move"/"jump" me… (but follow the protocol) until you see a steady state (n-f messages from a single state within 4d).
6) Every d announce your state.



Dealing with Byzantine nodes

- Aim: "round counting"
  - Synchronize the nodes such that:
    - All nodes periodically increase their round count by 1 within a small time window of each other

Why is this difficult?



...Byzantine tolerant, but not self-stabilizing

Main Result (complete graph)

- There exists a "wrapper" protocol A(.):

Theorem

Given: synchronous consensus protocol P

- resilient to rushing
- terminates in R rounds (w.h.p.)
- sends B bits per node

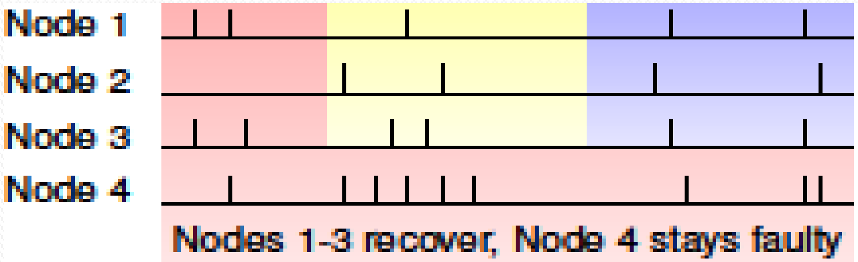
Then: A(P) simulating synchronous rounds

- global round counter modulo M
- stabilizes in O(R) time (w.h.p.)
- sends $O(nB+n^2+n \log M)$ bits per node (for stabilization)
- O(1) broadcasted bits overhead per node when stabilized

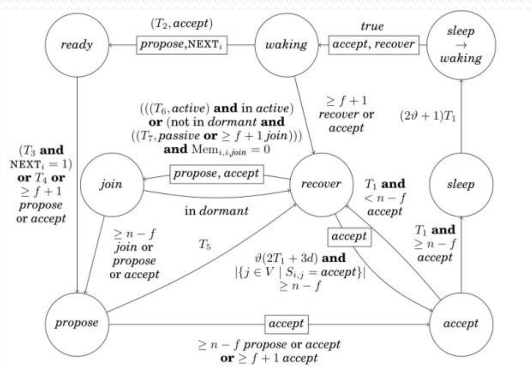
Result by D. Dolev and C. Lenzen

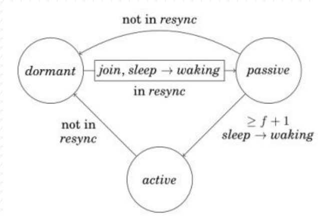
Hardware synchronization:

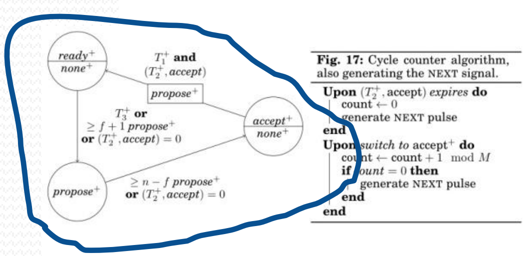
recovery from arbitrary transient faults despite f<n/3 permanent faults

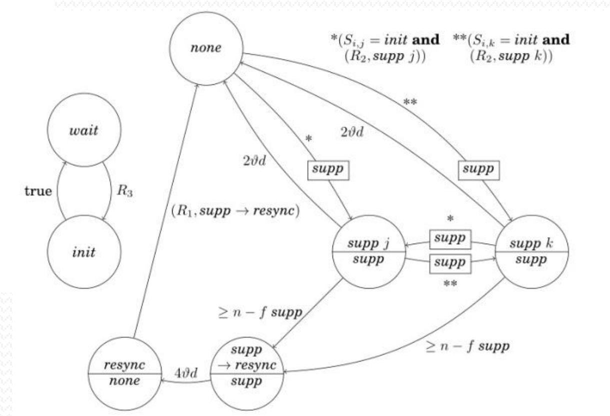


FATAL⁺: Robust Pulse Generation. Dolev, Fuegger, Lenzen, and Schmid. Under submission to JACM

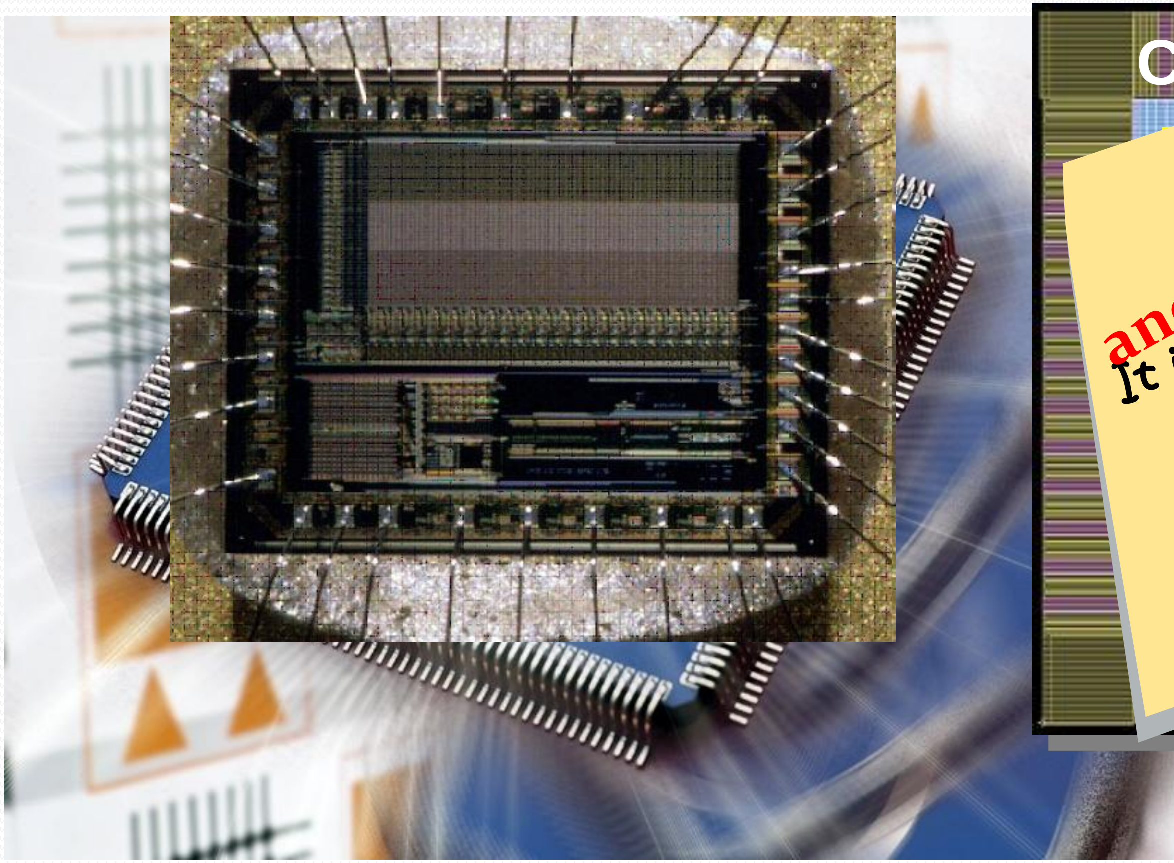


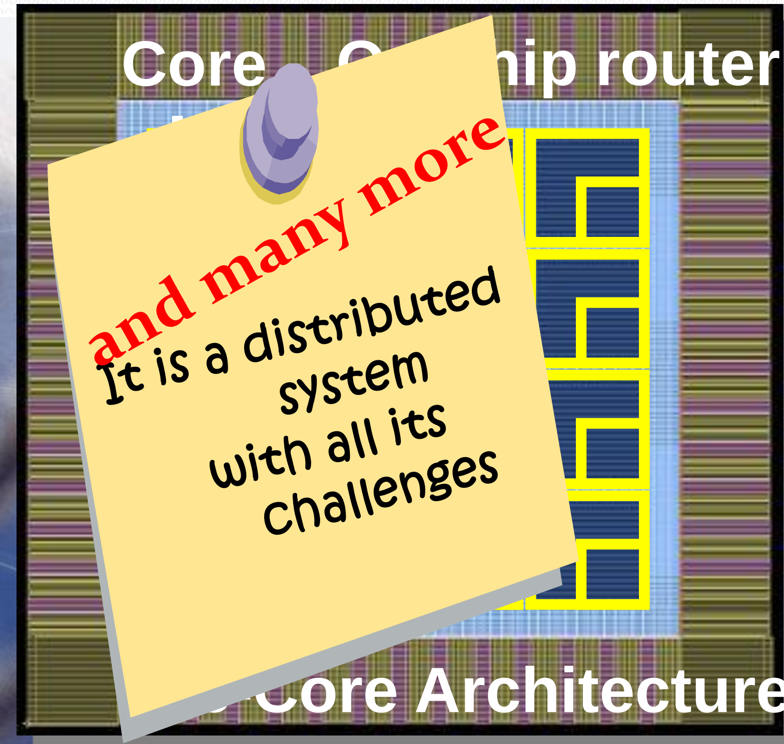




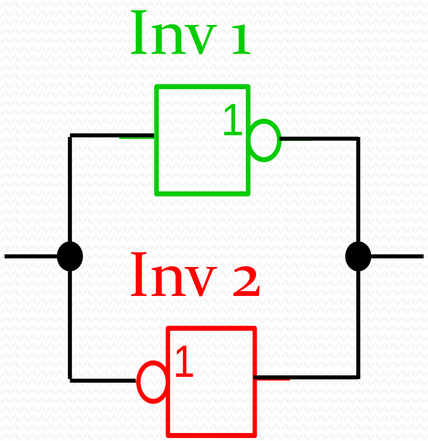


VLSI Circuits

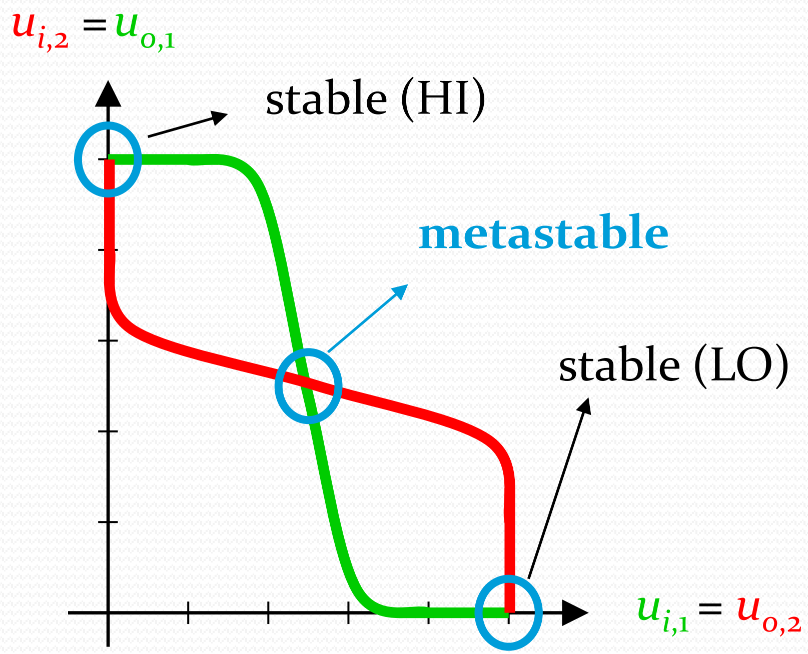




Metastability



Bistable element (memory cell) with positive feedback



Further challenges

- Uncertainty regarding signals spreading around the chip
- Time difference between local and distant events
- Identifying node's internal events

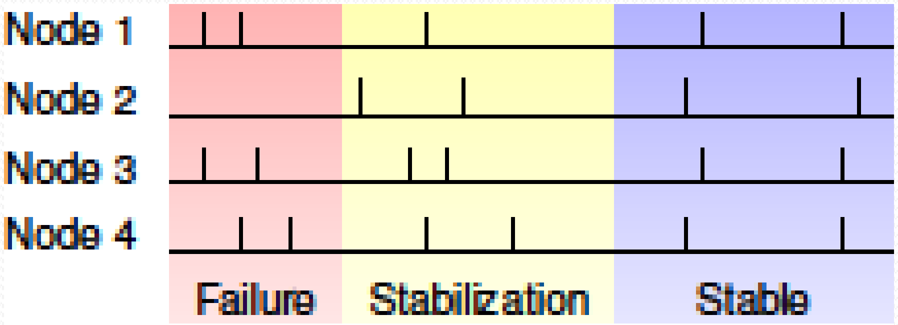
- Tight synchronization
- Simple state machines = less logic
- Tolerance to significant clock drifts

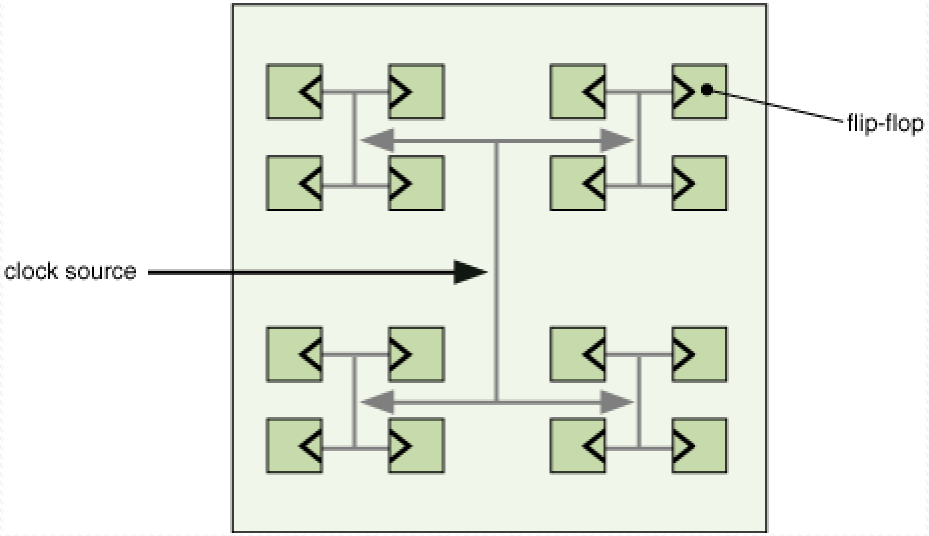
Resulting implementation (FATAL$^+$)

- Complexity bounds:
  - optimal resilience (n=3f+1 nodes for f faults)
  - full connectivity (linear in n necessary)
  - few 1-bit channels per link
  - O(n) worst-case stabilization time (~10^{-3}s)
  - O(1) stabilization time for most cases (~10^{-5}s)
  - gate complexity O(n log n) per node
- Clock distribution local for each node
  - no fault-tolerance required
  - clock *generation* network covers less area

Scalability – clock trees?

recovery from arbitrary transient faults
⇔
"correct" state reached from arbitrary initial state

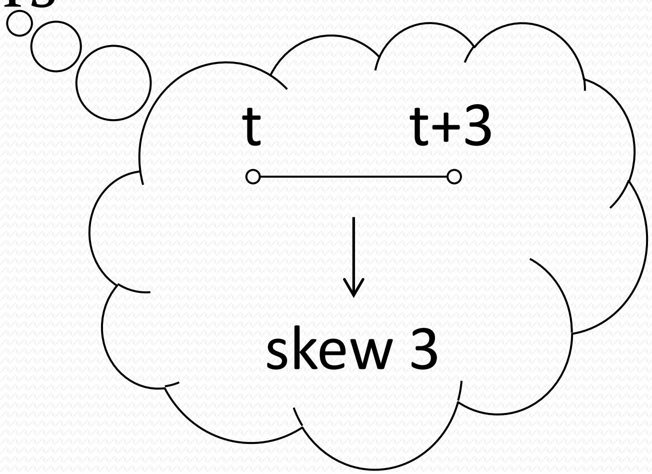




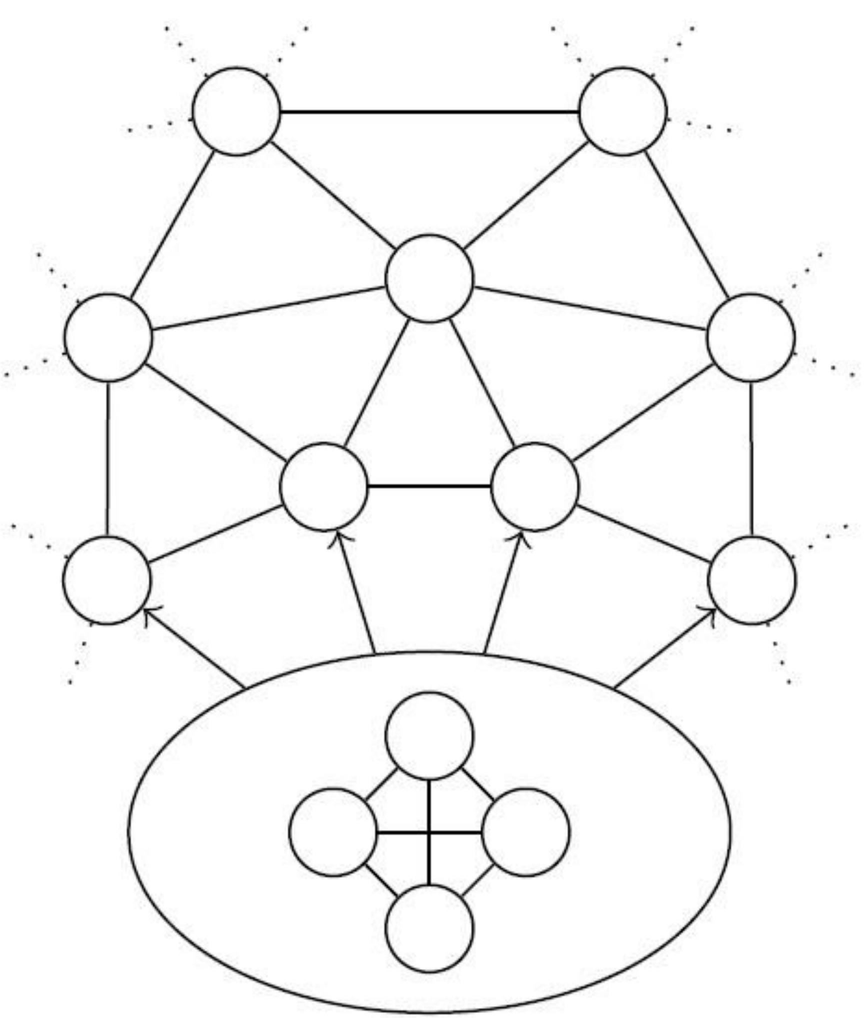
Clock trees are self-stabilizing!
(But they cannot mask faults)

Scalability Goals

- Distribute clock signal (from multiple sources)
- Small connectivity
- Uniform edge length
- Small clock skew between neighbors
- Byzantine fault-tolerance
- Self-stabilization



Use Robust Generation + Distribute



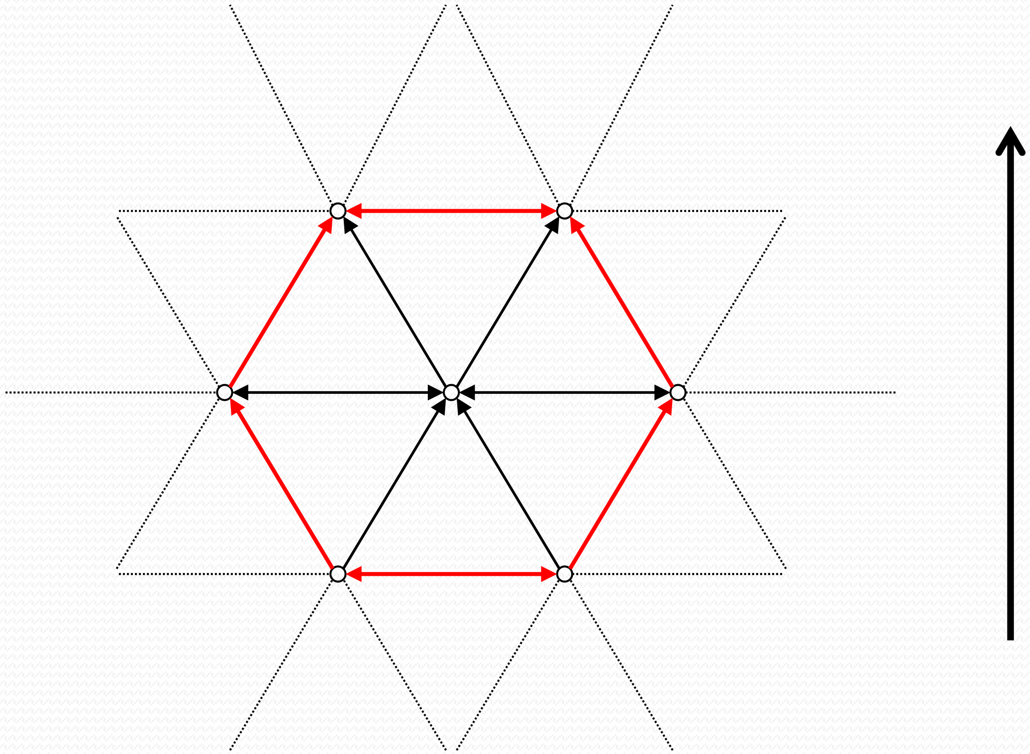
Dolev, Fuegger, L., Perner, and Schmid, SPAA '13.

HEX

↑

FATAL$^+$

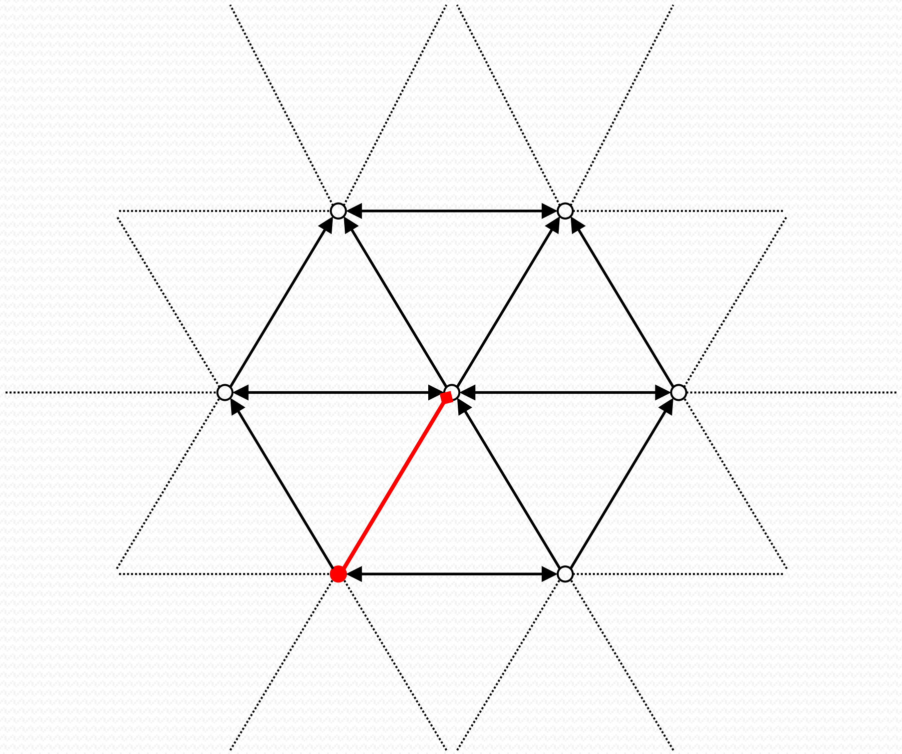
The HEX Grid



direction
of clock
propagation

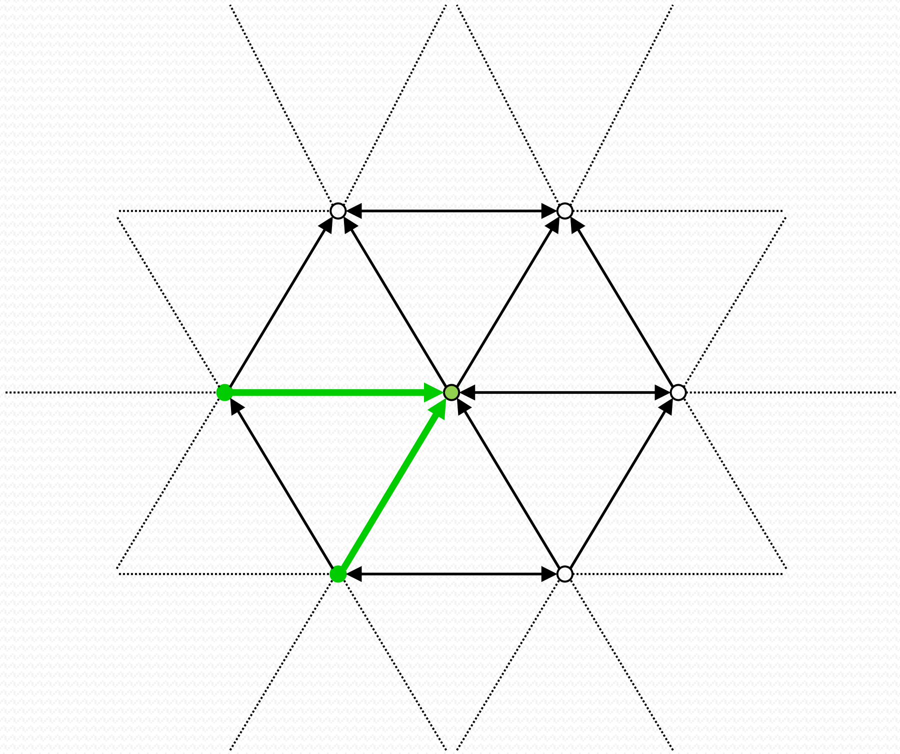
- ✓ small connectivity
- ✓ uniform edge length

Fault-Tolerance



- one Byzantine fault per neighborhood
- must wait for pulse from two neighbors

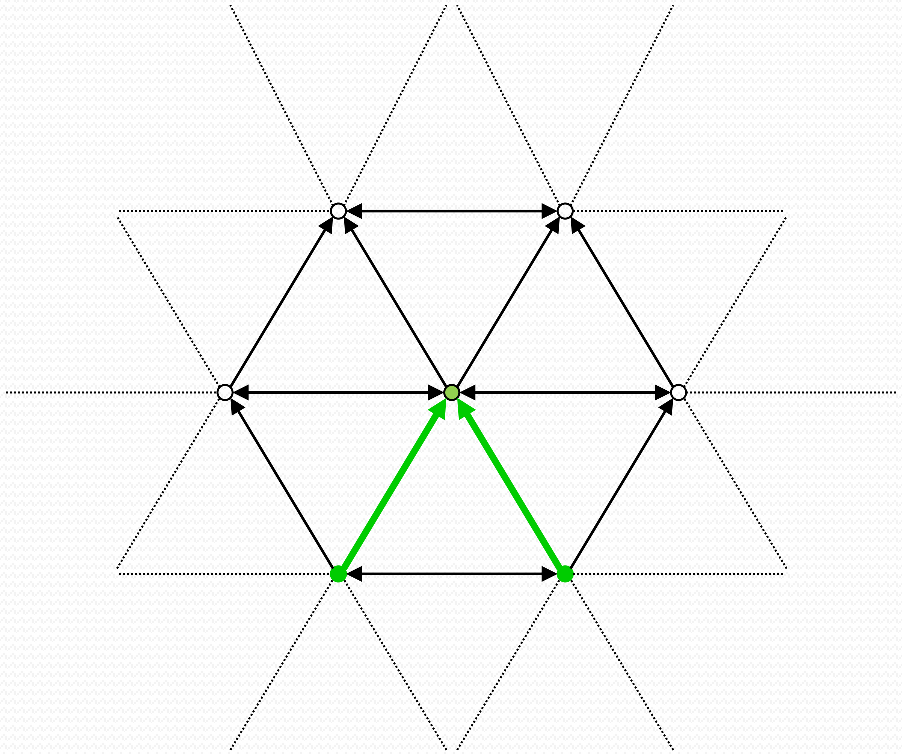
Fault-Tolerance



left-triggered

- one Byzantine fault per neighborhood
- must wait for pulse from two neighbors

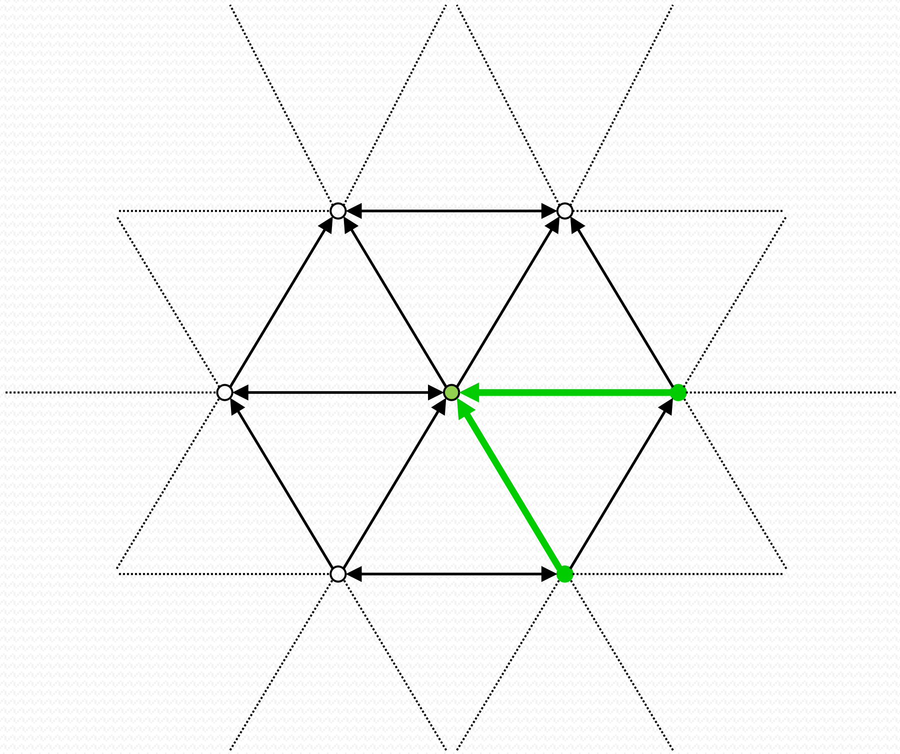
Fault-Tolerance



centrally triggered

- one Byzantine fault per neighborhood
- must wait for pulse from two neighbors

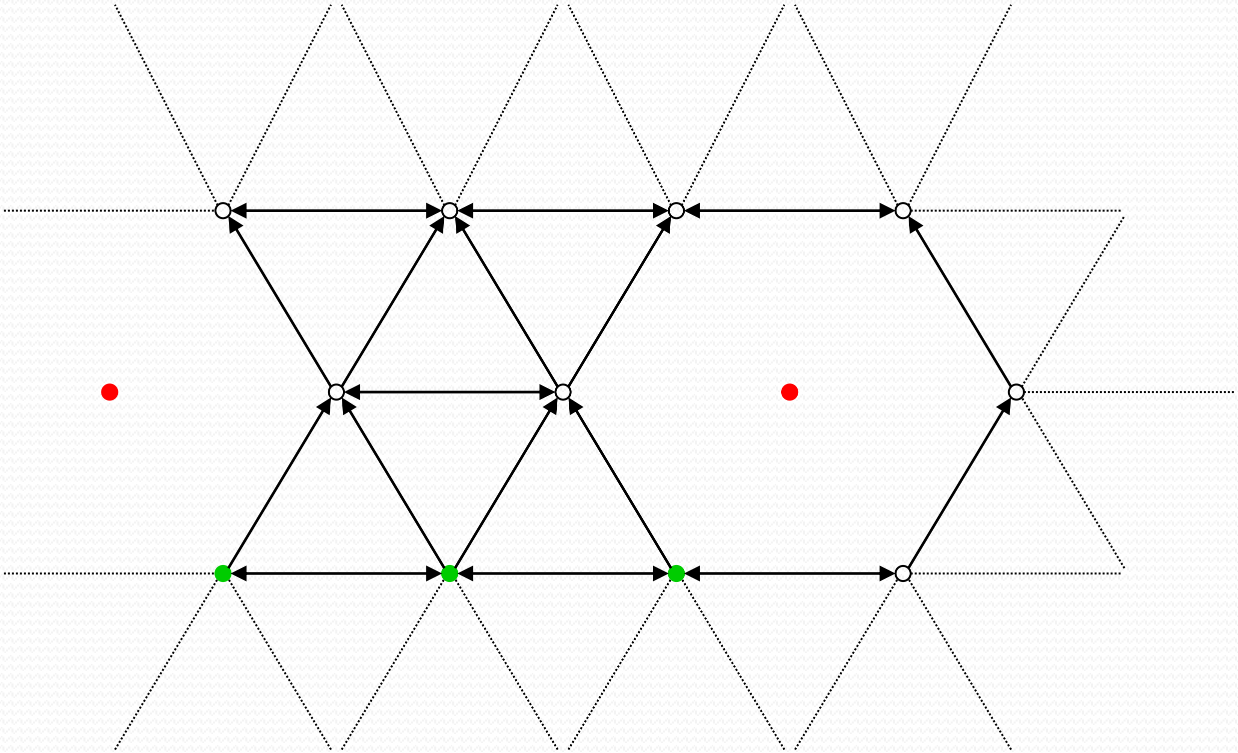
Fault-Tolerance



right-triggered

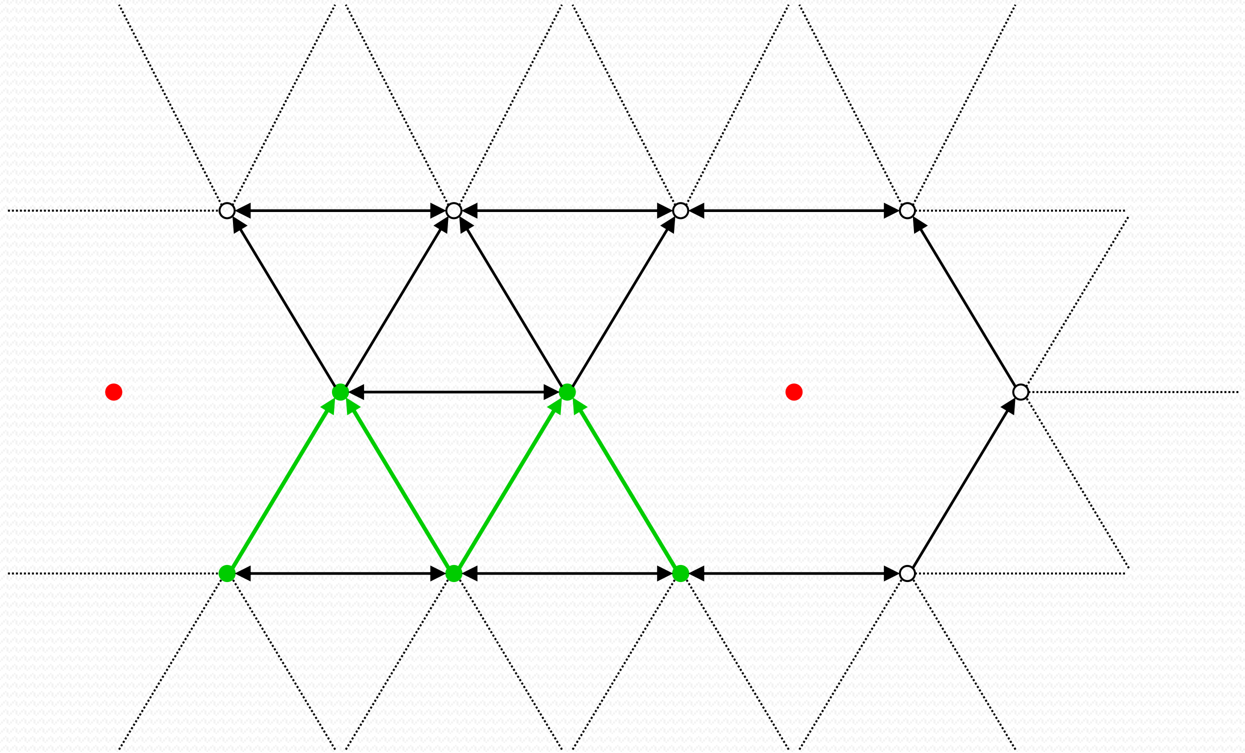
- one Byzantine fault per neighborhood
- must wait for pulse from two neighbors

Fault-Tolerance



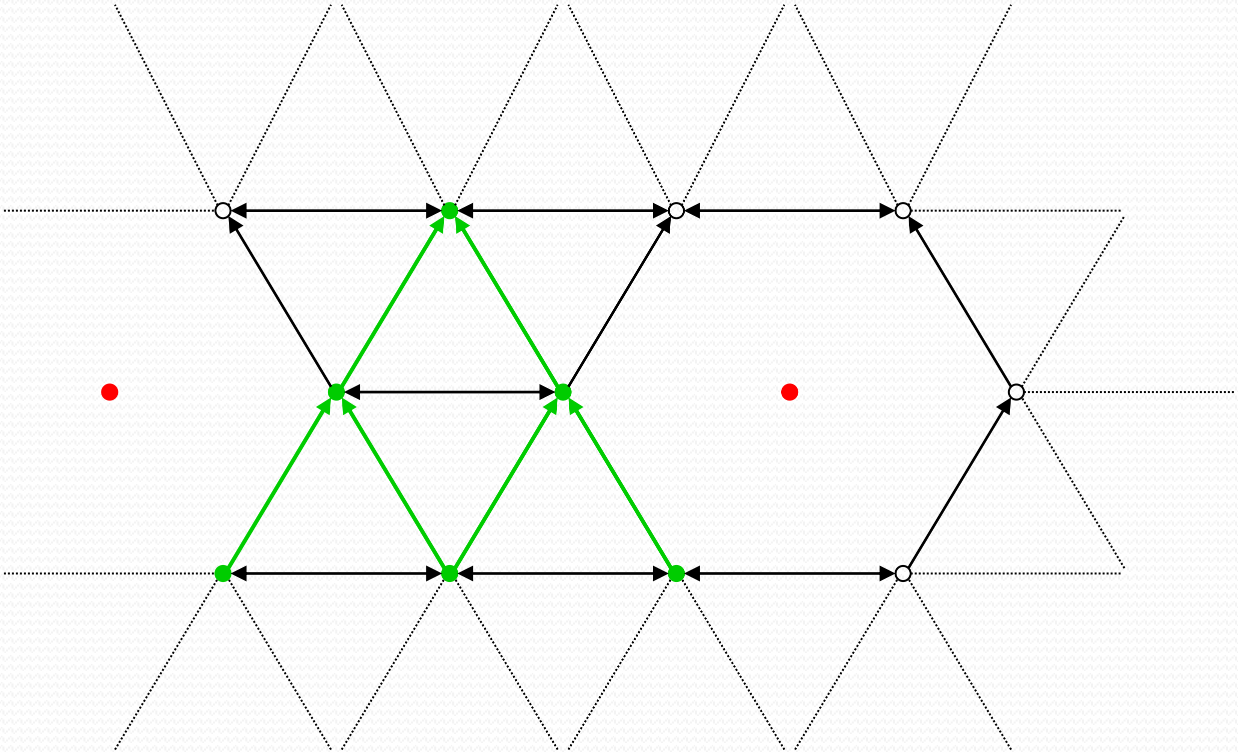
- wave propgates around faults

Fault-Tolerance



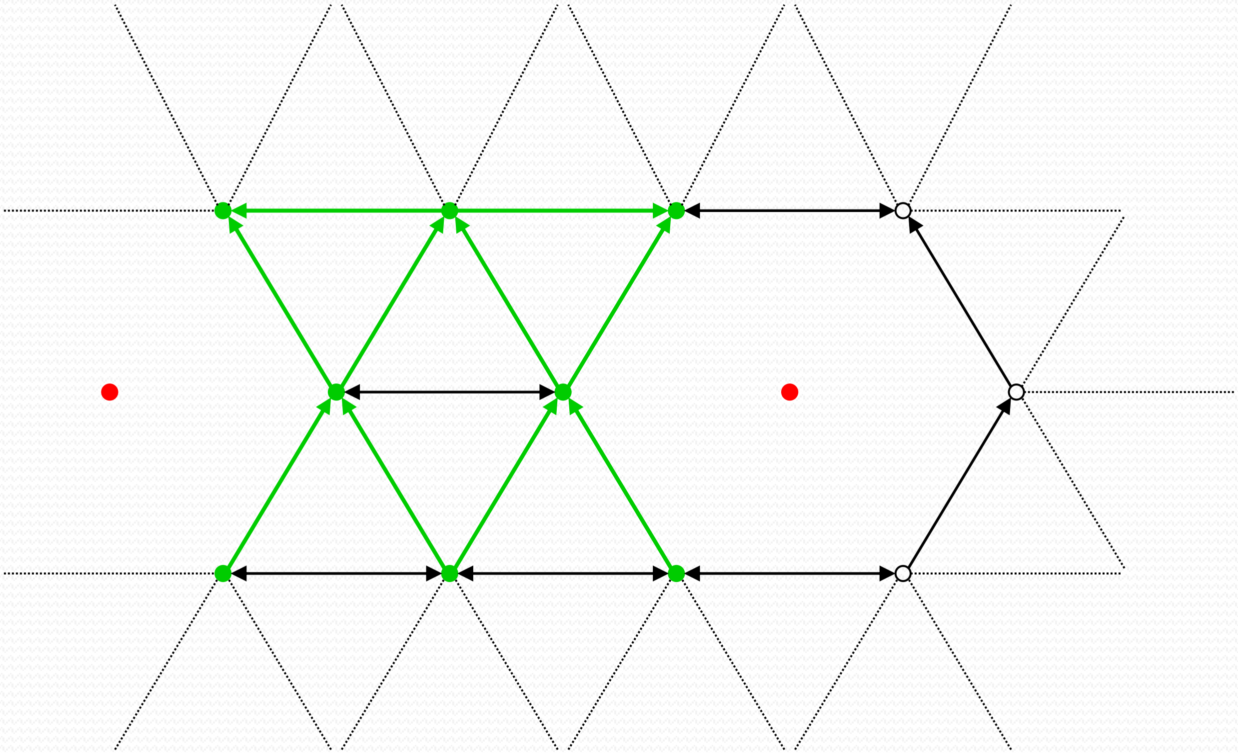
- wave propgates around faults

Fault-Tolerance



- wave propgates around faults

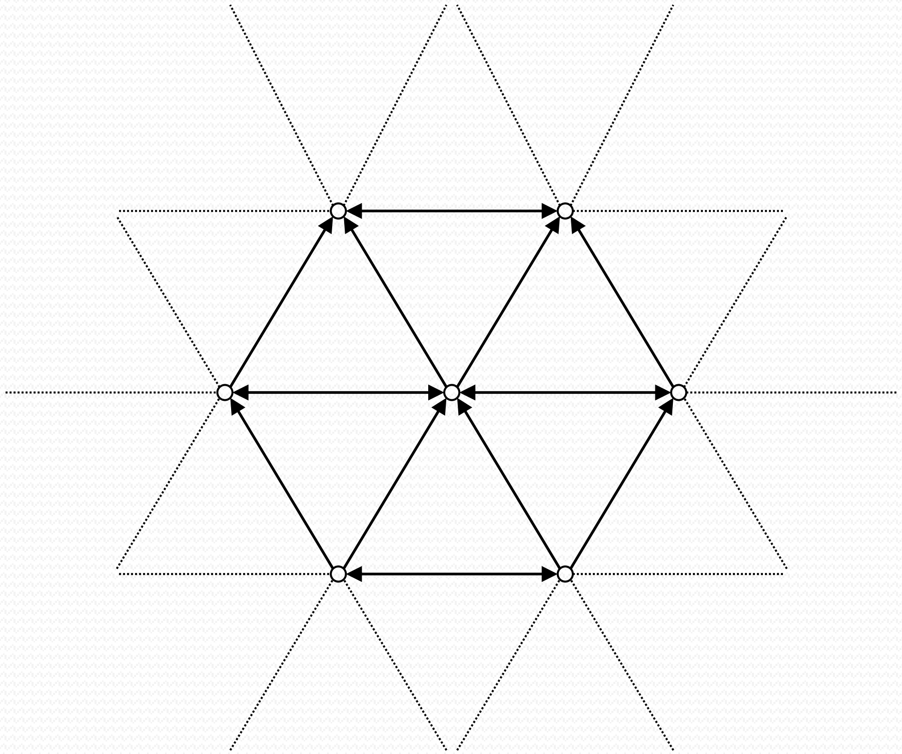
Fault-Tolerance



- wave propgates around faults

Nature deals with local Byzantines

Fault-Tolerance

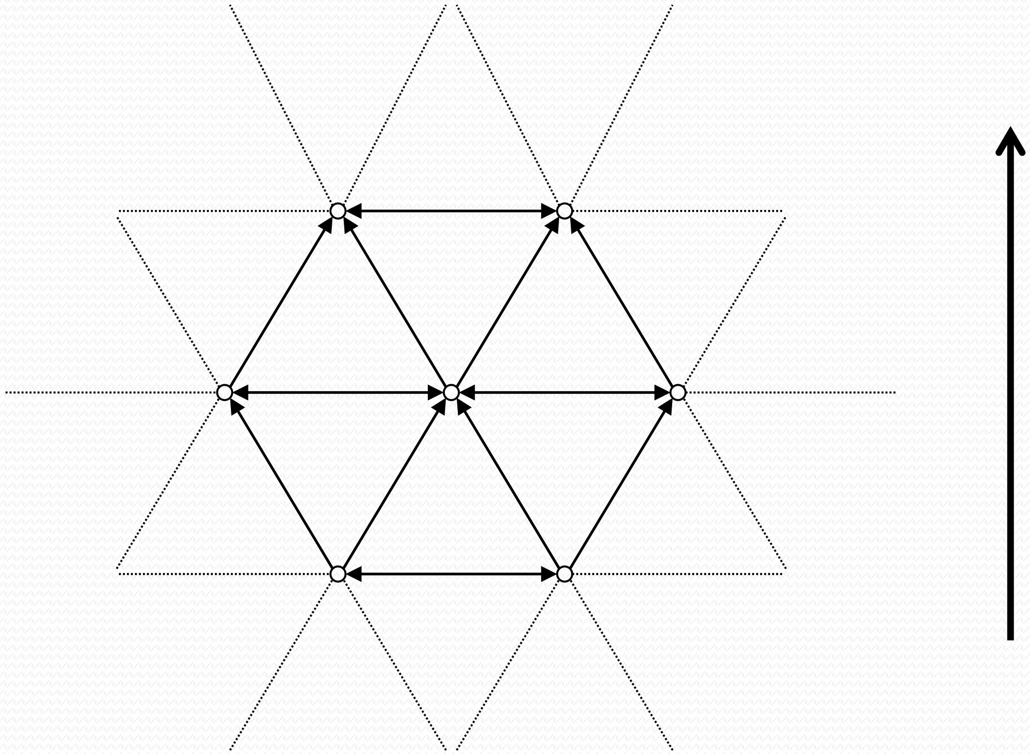


✓ small connectivity

✓ uniform edge length

✓ Byzantine Tolerance

Skew: Fault-Free Case



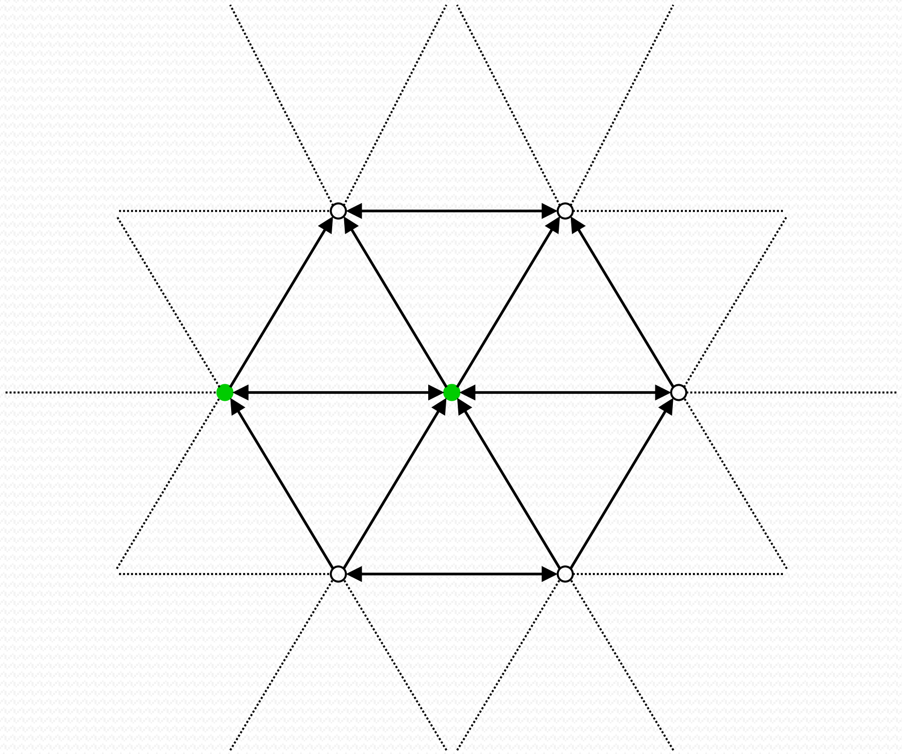
between

1 and 1+ε

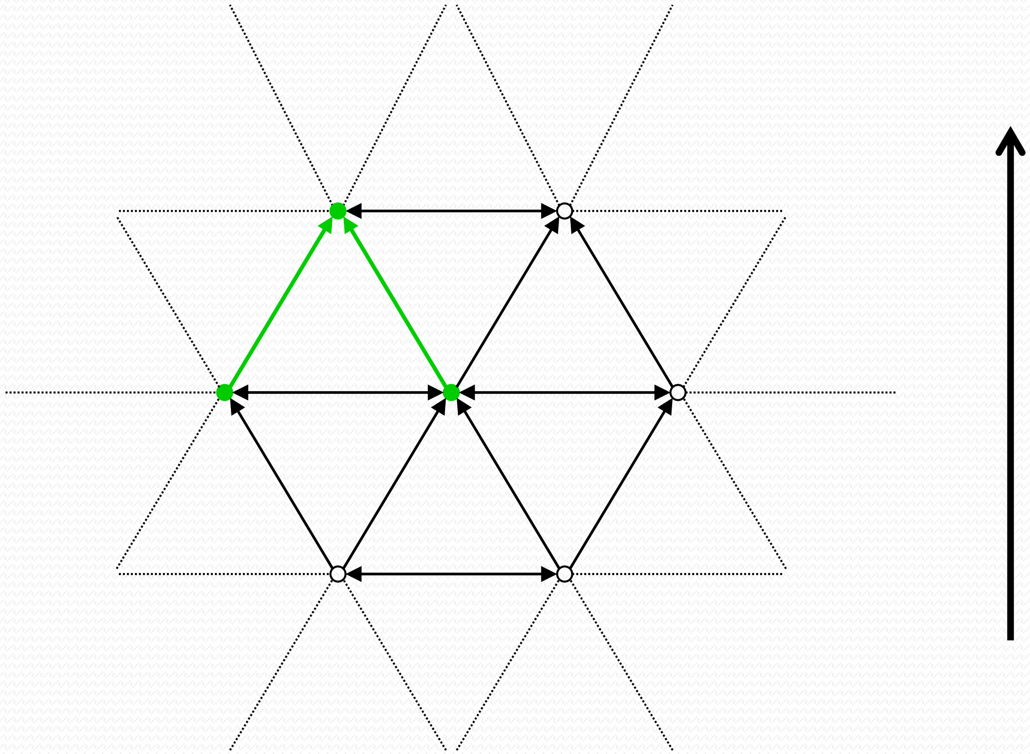
time per layer

- assume that link delays are from [1,1+ε]
- neighbors in layer ℓ trigger at most εℓ time apart

Skew: Fault-Free Case



Skew: Fault-Free Case



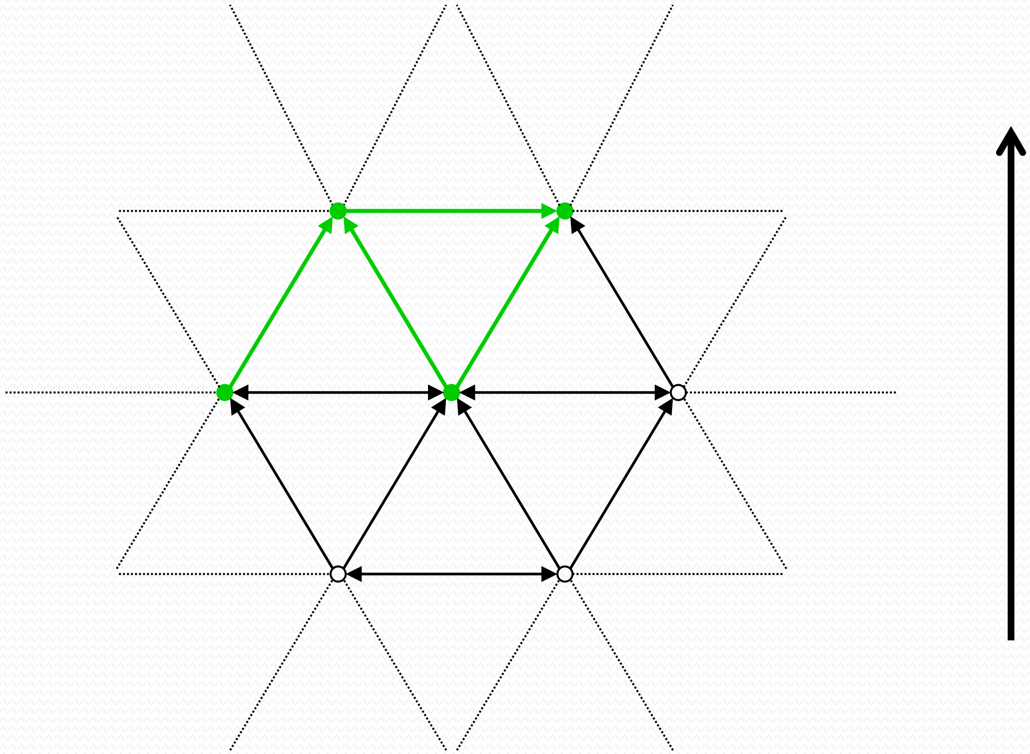
between

1 and 1+ε

time per layer

- but: links within layers keep skew in check

Skew: Fault-Free Case



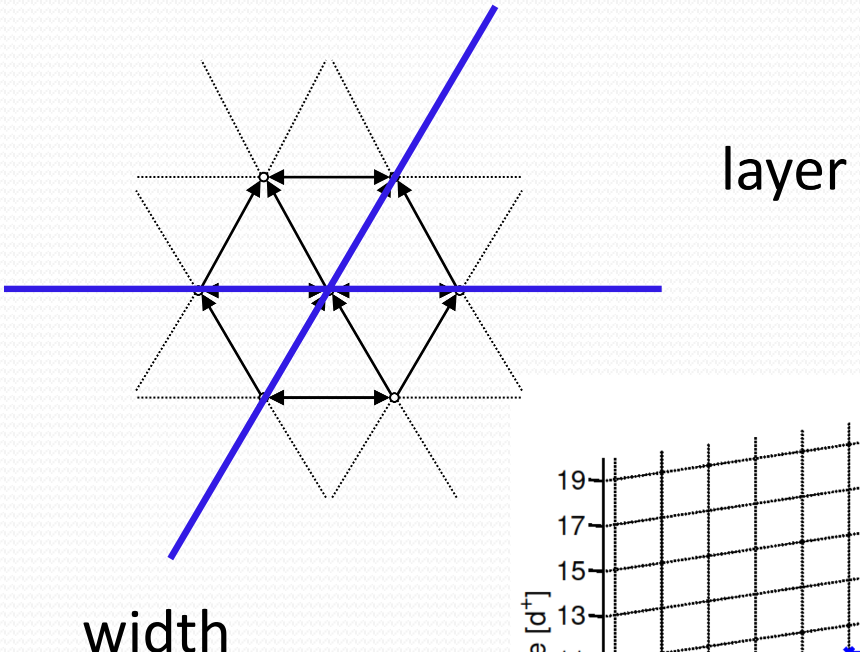
between

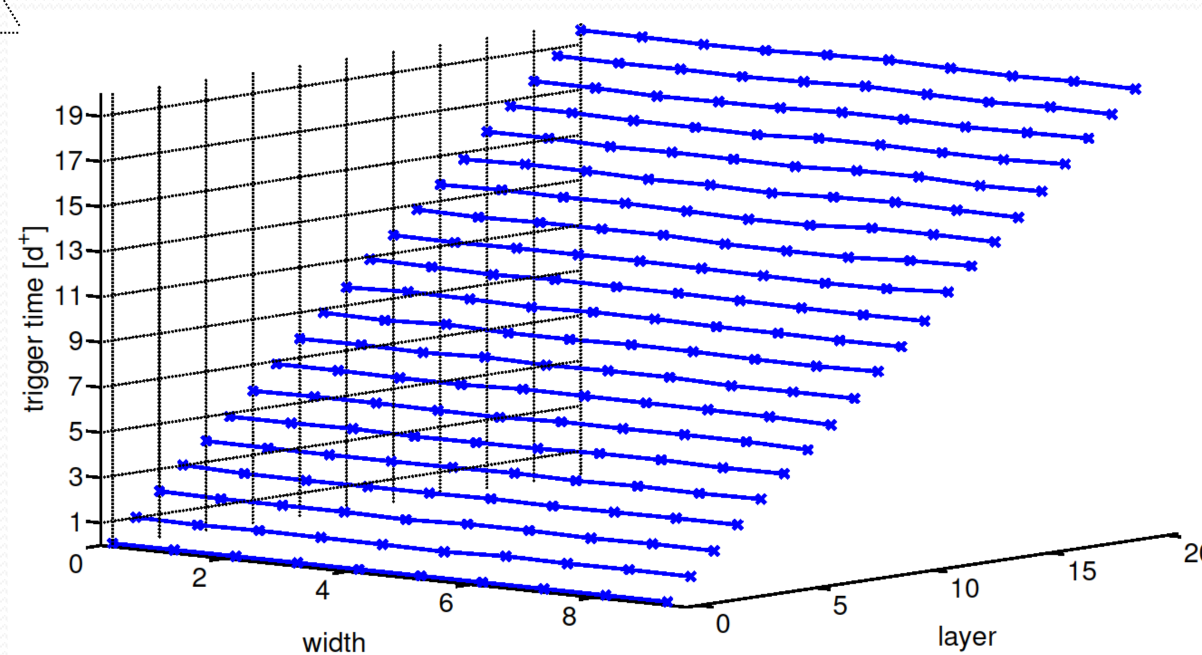
1 and 1+ε

time per layer

- but: links within layers keep skew in check
- we show a worst-case bound of $1+O(\varepsilon^2\ell)$

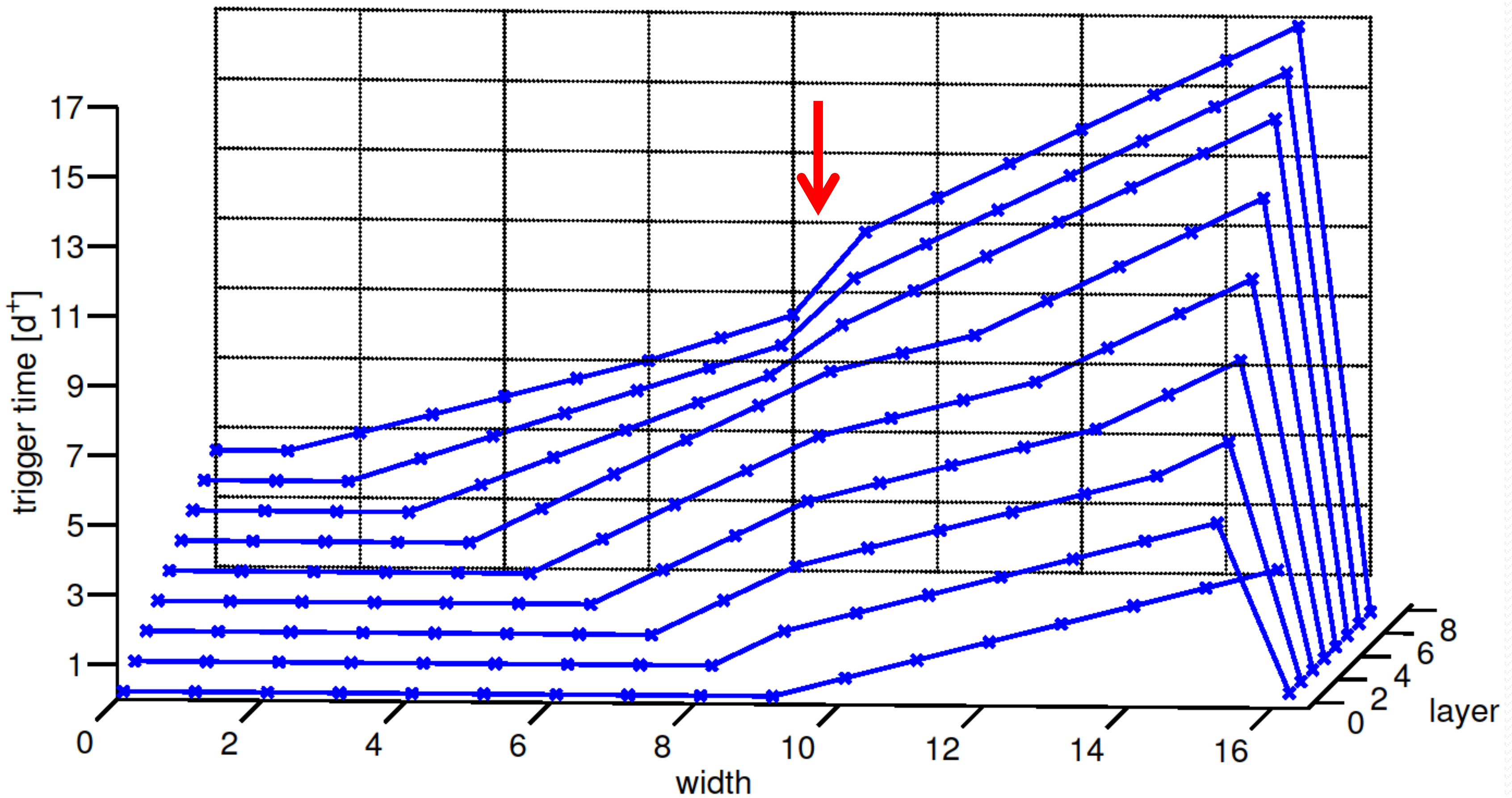
Some Plotting





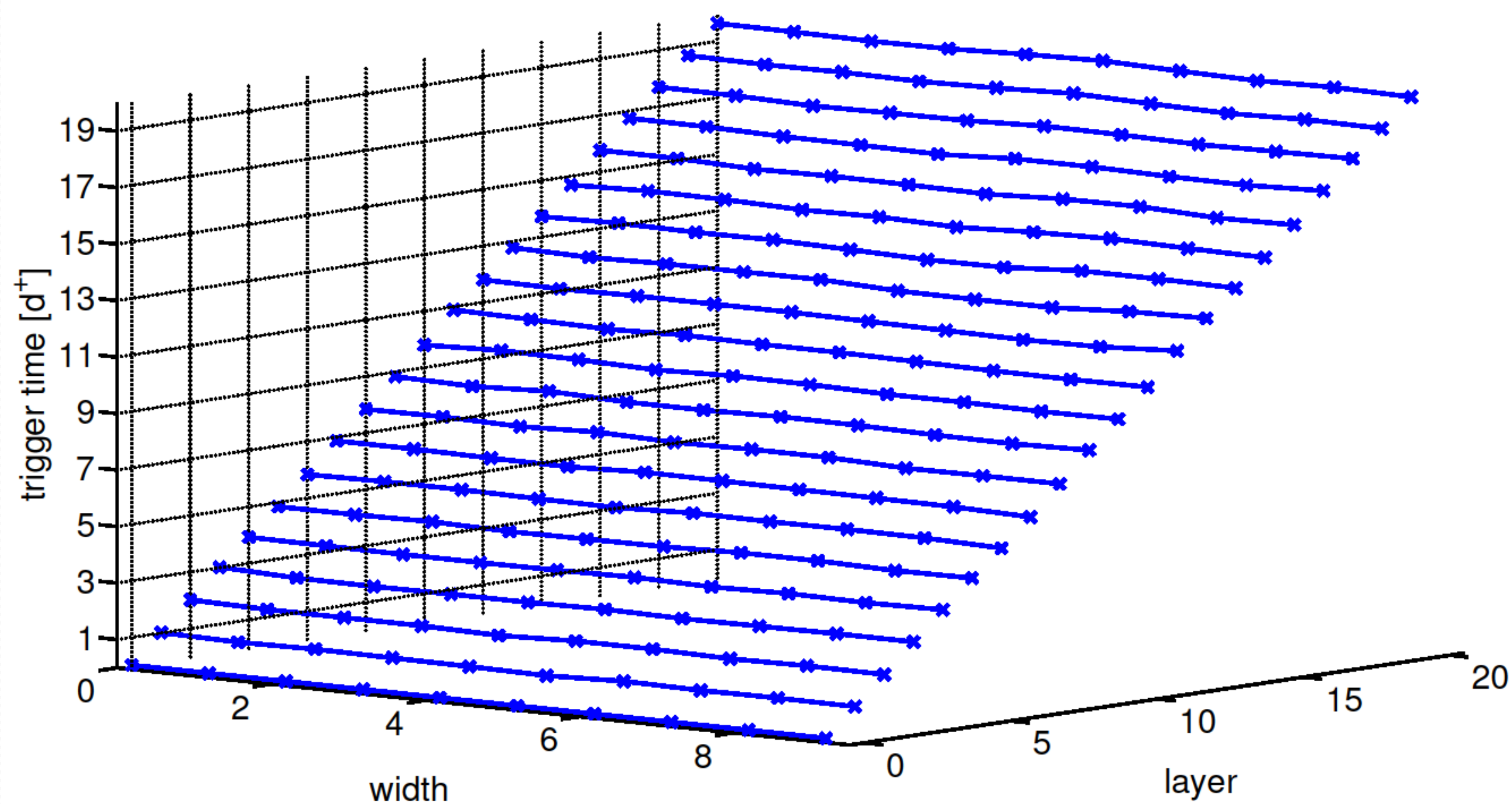
Skew: Fault-Free Case

worst-case execution

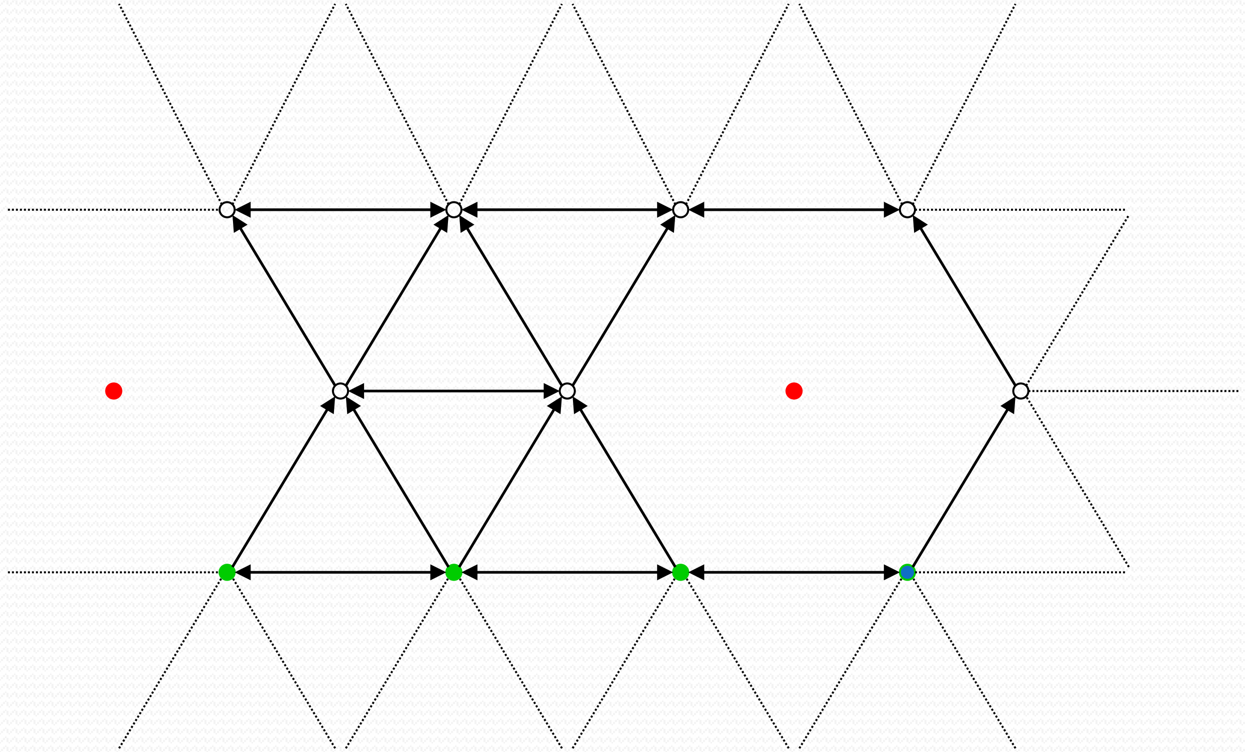


Skew: Fault-Free Case

random delays

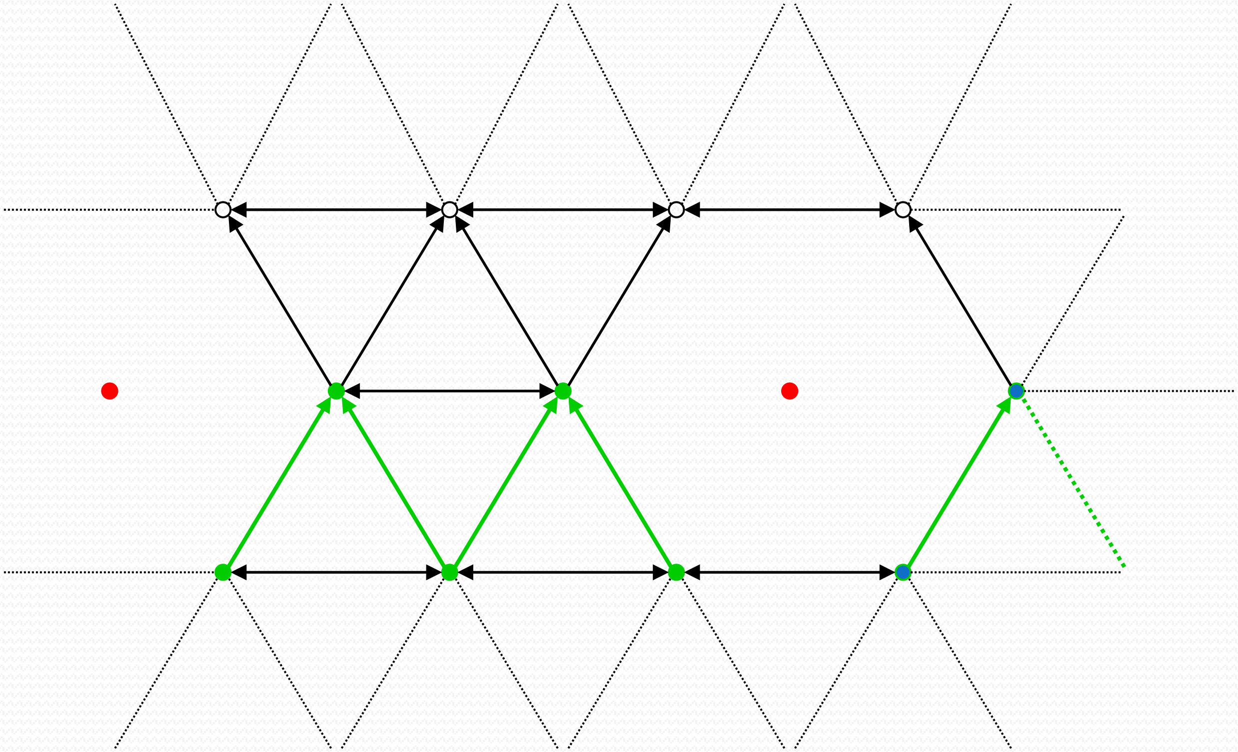


Skew and Faults



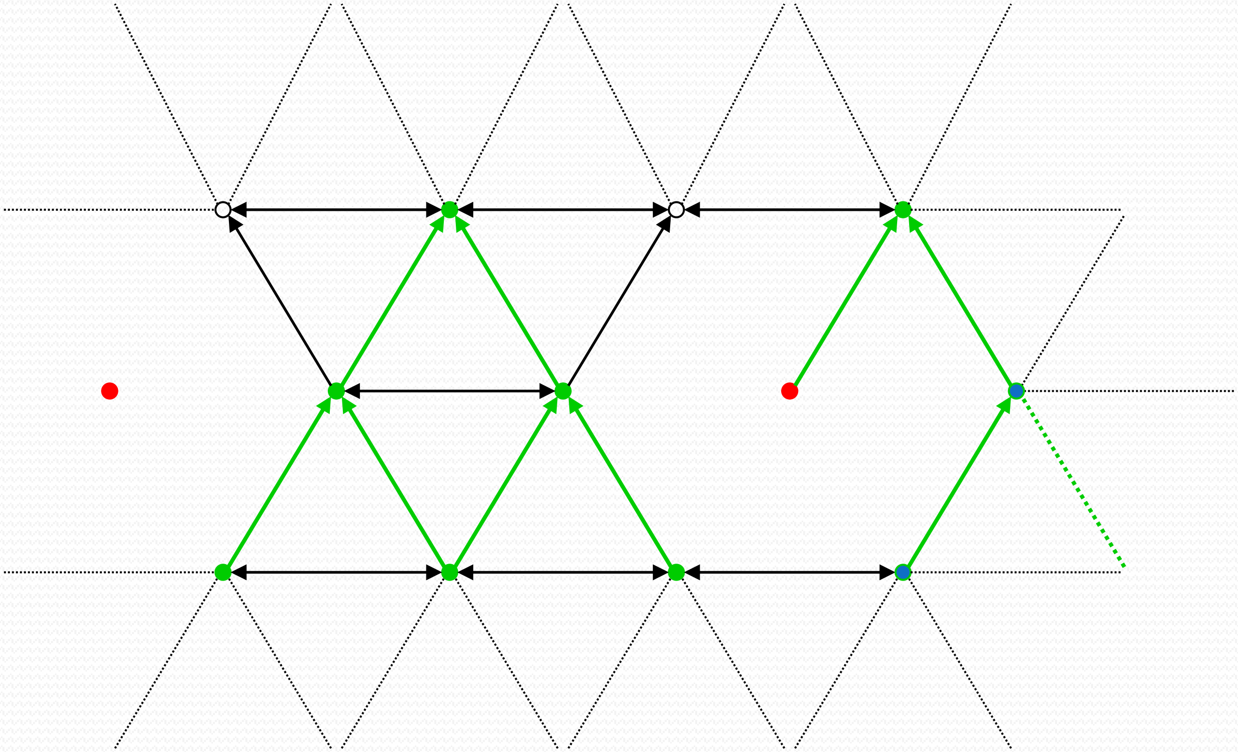
- faulty nodes can influence propagation by O(1)

Skew and Faults



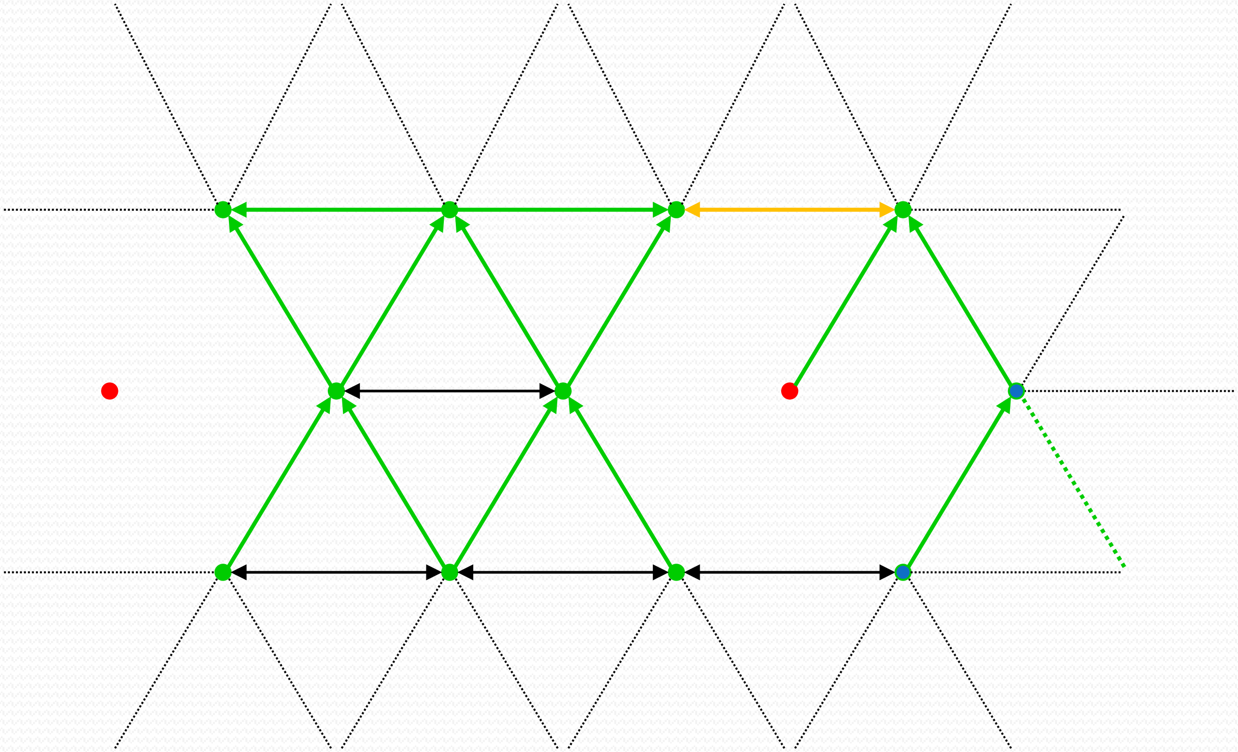
- faulty nodes can influence propagation by O(1)

Skew and Faults



- faulty nodes can influence propagation by O(1)

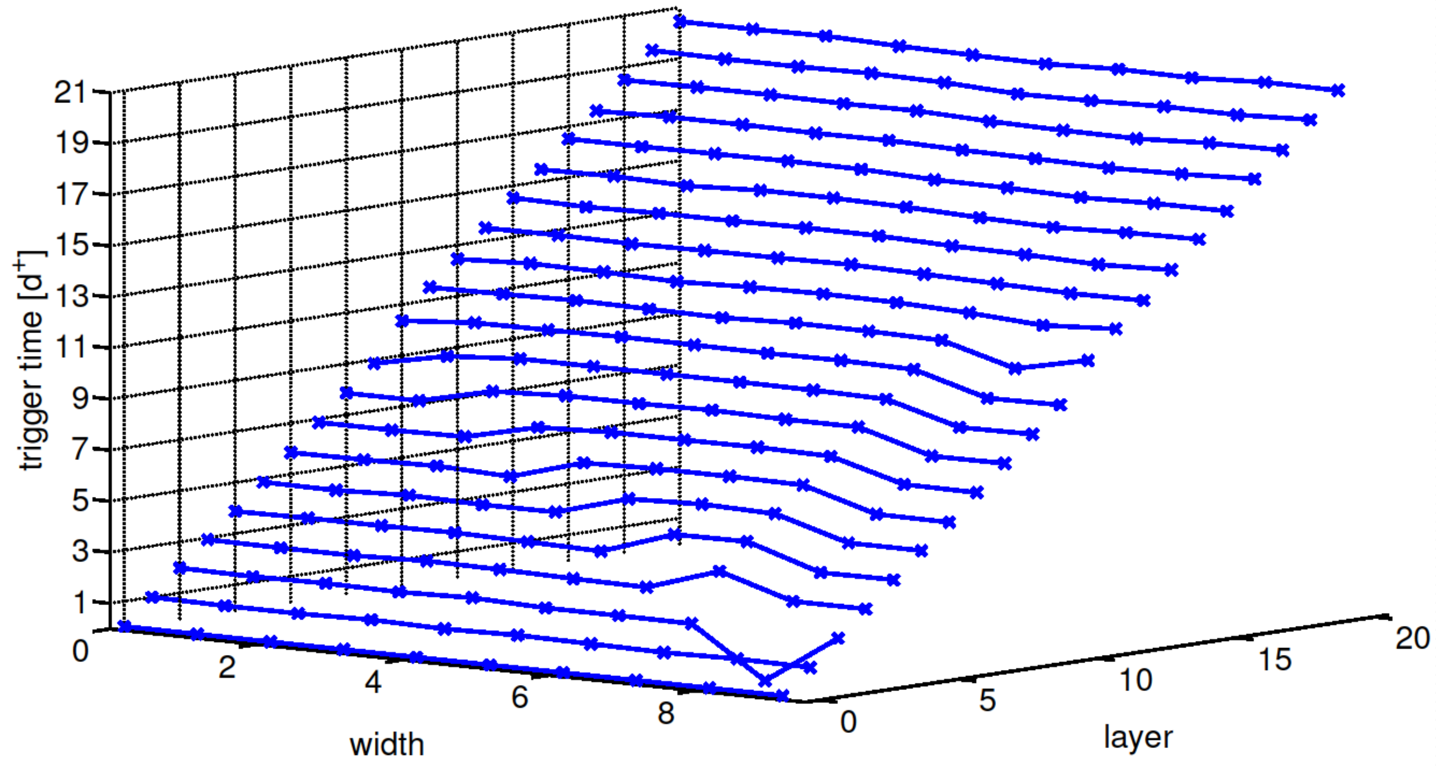
Skew and Faults



- faulty nodes can influence propagation by O(1)
- worst-case skew of $O(f+\varepsilon^2\ell)$ with f faults

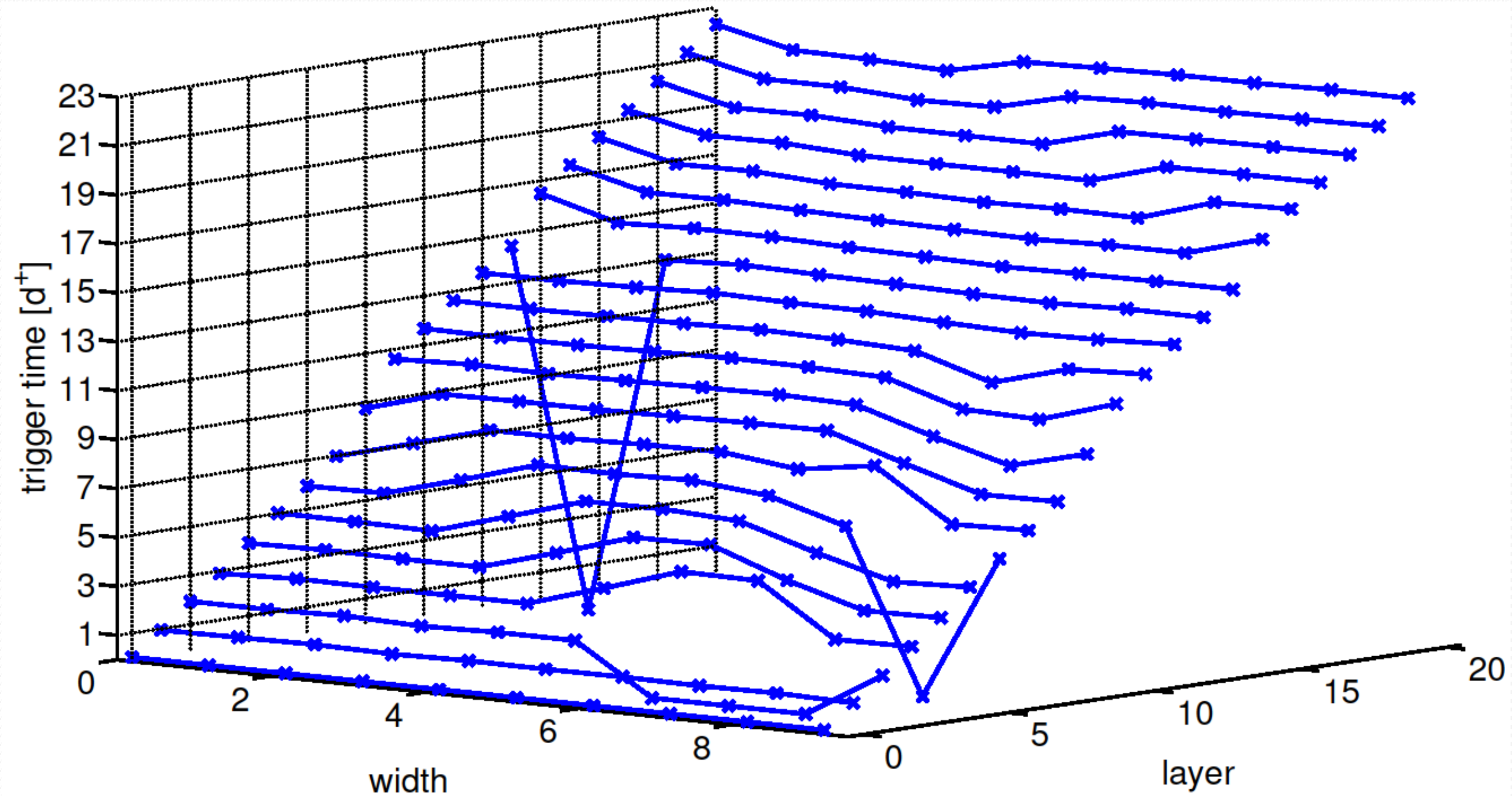
Skew and Faults

wave propagation with one fault

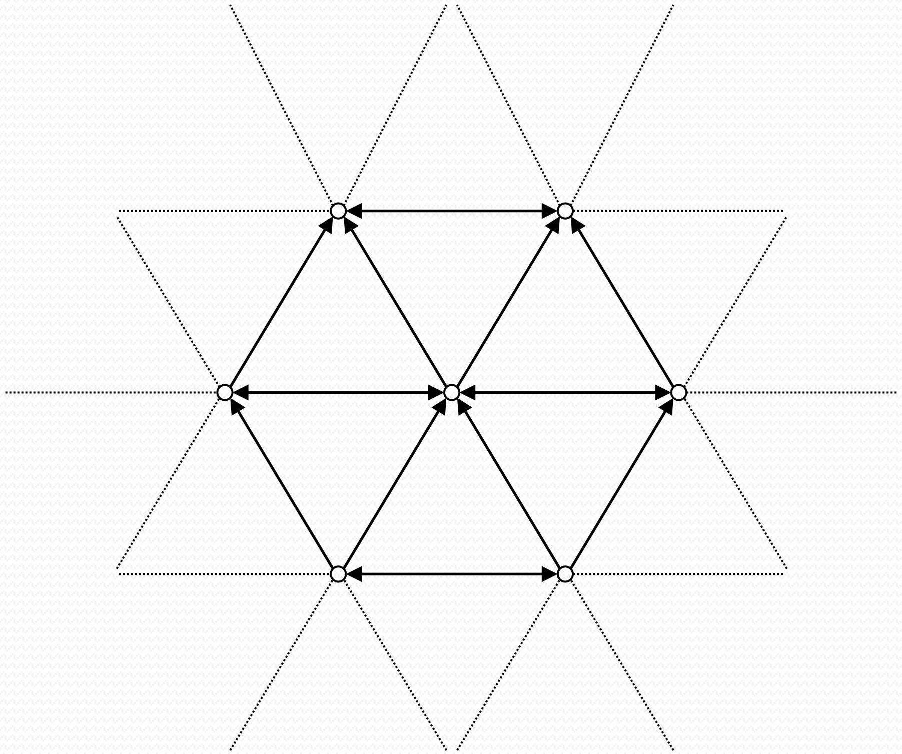


Skew and Faults

wave propagation with multiple faults



Skew and Faults



✓ small connectivity

✓ uniform edge length

✓ Byzantine tolerance

✓ small clock skew

Multiple Pulses

Algorithm 1: Pulse forwarding algorithm for nodes in layer $\ell > 0$.

once *received trigger messages from (left and lower left) or (lower left and lower right) or (lower right and right) neighbors* **do**
  broadcast trigger message; // local clock pulse
  sleep for some time within $[T^-, T^+]$;
  forget previously received trigger messages

- go to sleep once triggered pulse
- wake up & clear memory once wave has passed

Self-Stabilization (assuming no permanent fault)

If nodes in a layer are awake when a wave arrives:

- they are triggered

- they will go to sleep

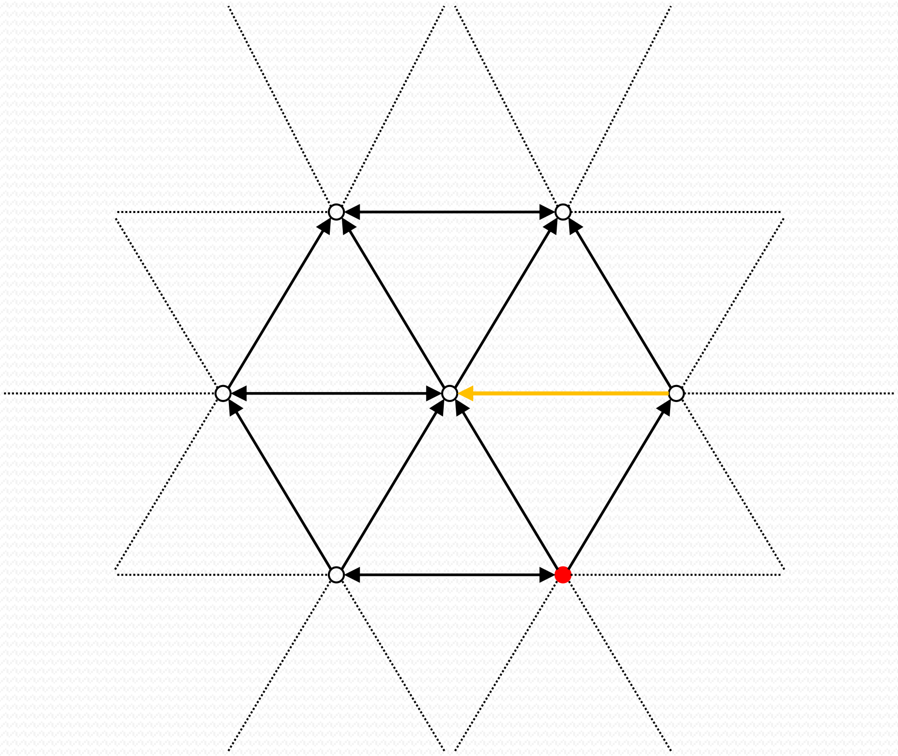
- they will clear memory upon waking up

- they will be awake when the next pulse arrives

=> self-stabilization (by induction on layers)

Self-Stabilization Despite Faults

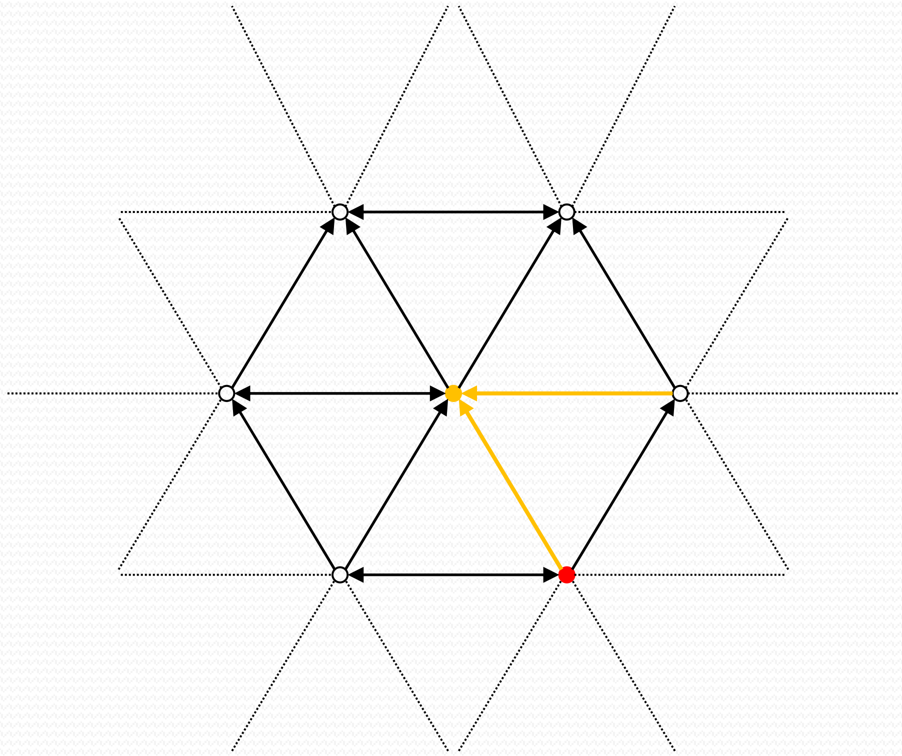
Does not work with worst-case faults:



- pulse memorized

Self-Stabilization Despite Faults

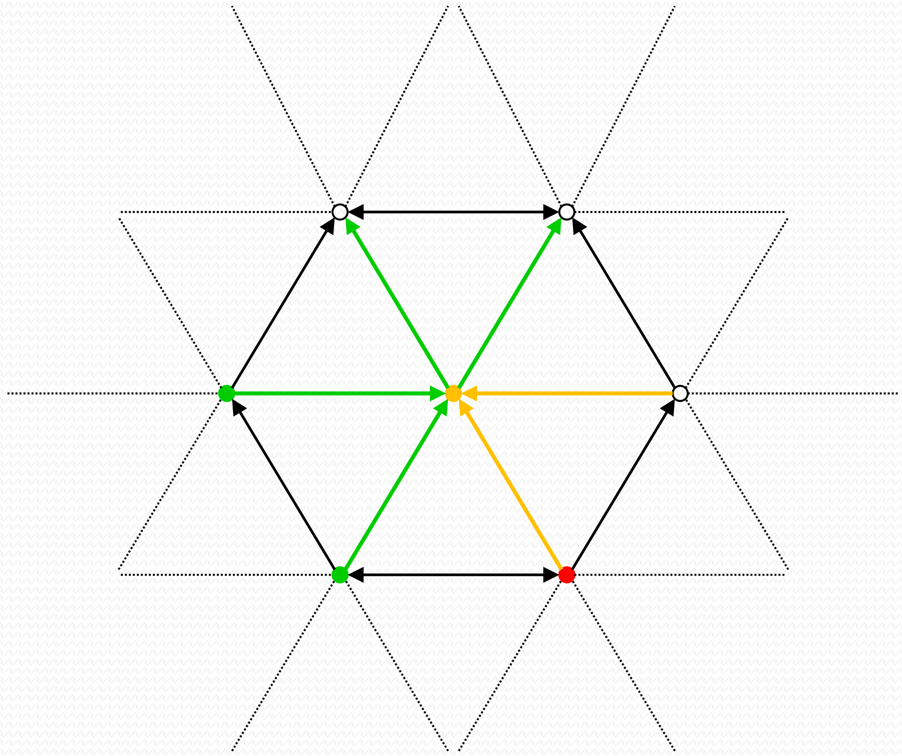
Does not work with worst-case faults:



- pulse memorized
- faulty node triggers

Self-Stabilization Despite Faults

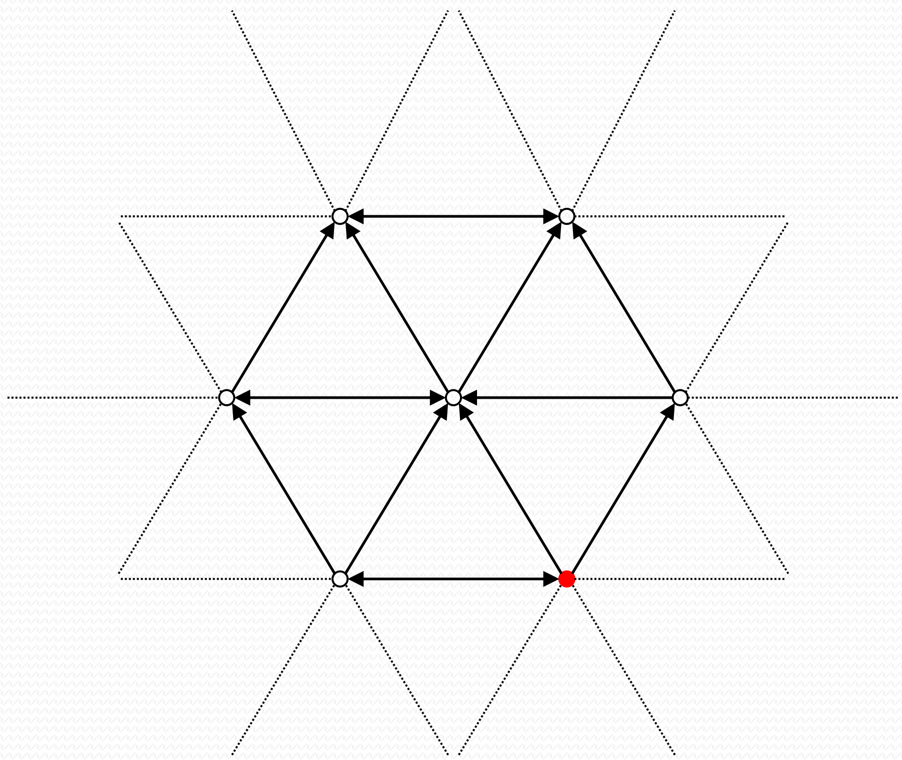
Does not work with worst-case faults:



- pulse memorized
- faulty node triggers
- pulse arrives on left

Self-Stabilization Despite Faults

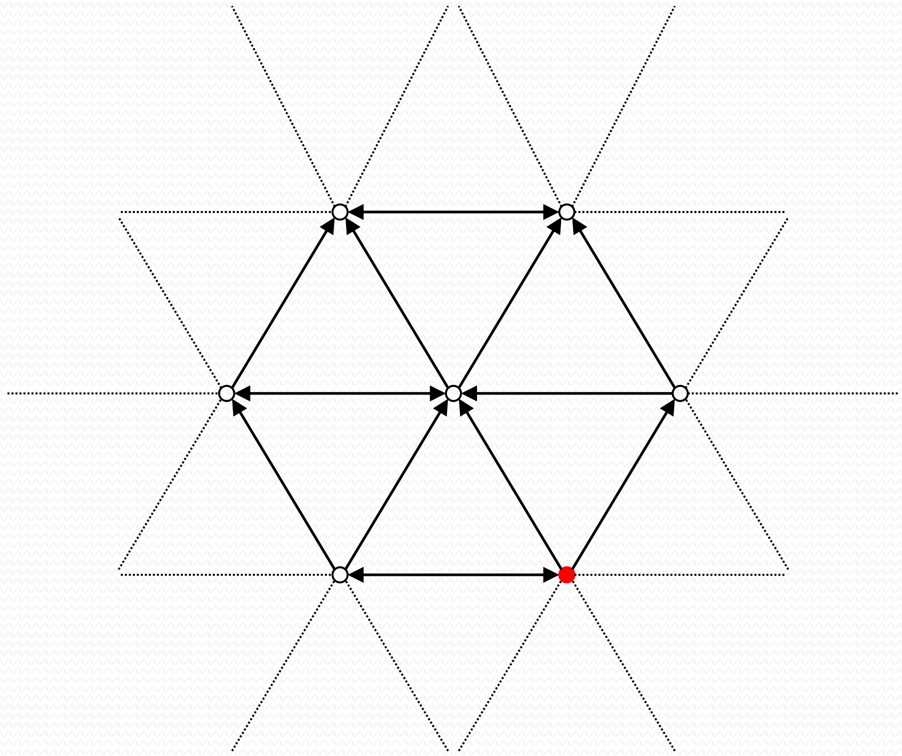
Does not work with worst-case faults:



- pulse memorized
- faulty node triggers
- pulse arrives on left
- node goes to sleep

Self-Stabilization Despite Faults

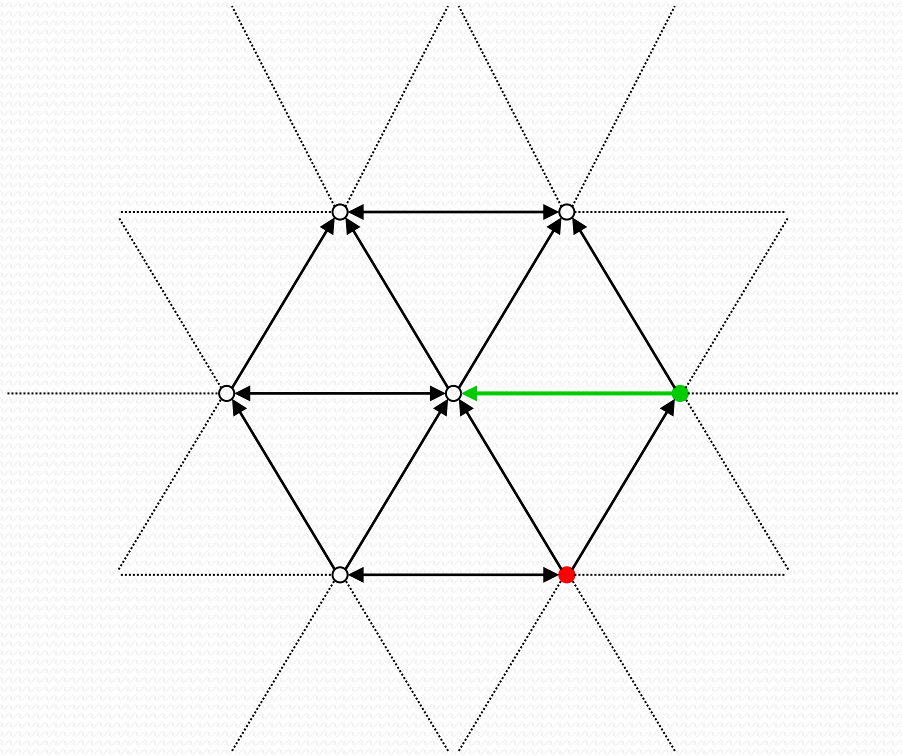
Does not work with worst-case faults:



- pulse memorized
- faulty node triggers
- pulse arrives on left
- node goes to sleep
- node wakes up

Self-Stabilization Despite Faults

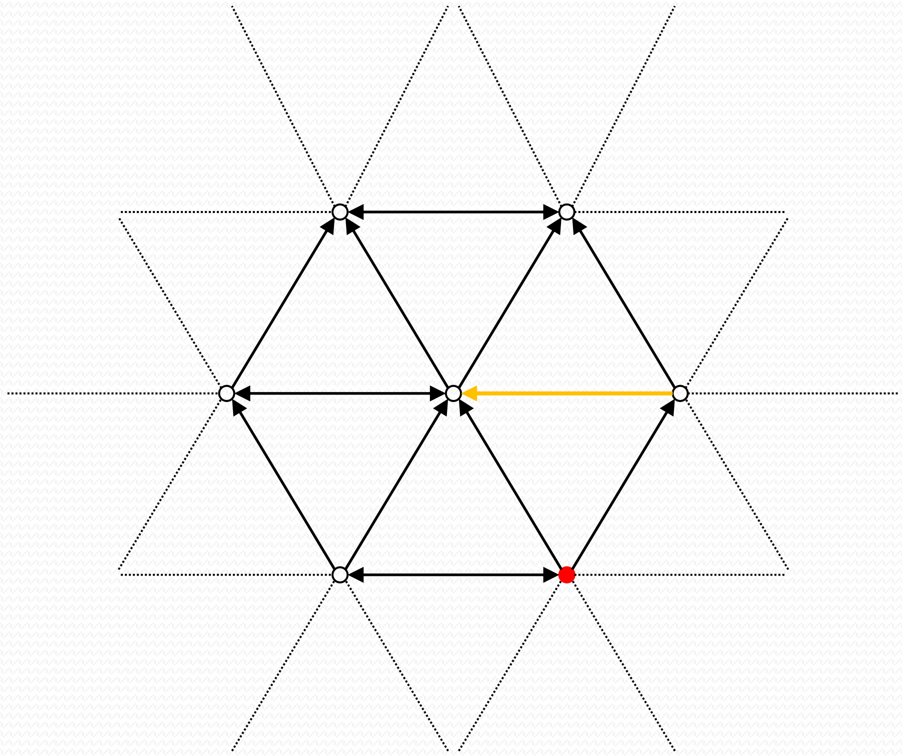
Does not work with worst-case faults:



- pulse memorized
- faulty node triggers
- pulse arrives on left
- node goes to sleep
- node wakes up
- pulse arrives on right

Self-Stabilization Despite Faults

Does not work with worst-case faults:



- pulse memorized
- faulty node triggers
- pulse arrives on left
- node goes to sleep
- node wakes up
- pulse arrives on right
- repeat

Self-Stabilization Despite Faults

Fix: "forget" pulse signals after a while

=> self-stabilization with faults

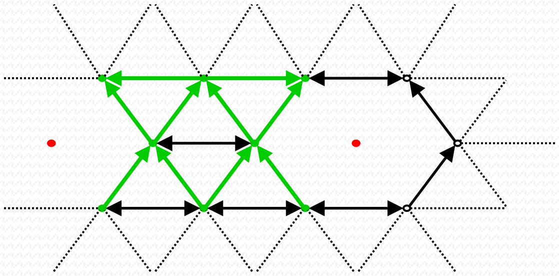
also: improves stabilization time

Algorithm 1: Pulse forwarding algorithm for nodes in layer $\ell > 0$.

upon *receiving trigger message from neighbor* **do**
  memorize message for $\tau \in [T^{-}_{\mathbf{link}}, T^{+}_{\mathbf{link}}]$ time;
upon *having memorized trigger messages from (left and lower left) or (lower left and lower right) or (lower right and right) neighbors* **do**
  broadcast trigger message; // local clock pulse
  sleep for $\tau \in [T^{-}_{\mathbf{sleep}}, T^{+}_{\mathbf{sleep}}]$ time;
  forget previously received trigger messages;

HEX Summary

- HEX has many promising features:
  - few edges of similar length
  - fault containment
  - self-stabilization
  - $O(f+\varepsilon^2\ell)$ worst-case skew, better on average



HEX Summary

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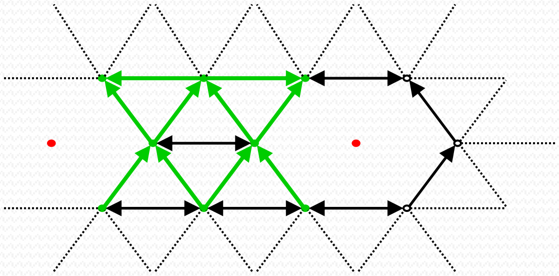

- Future work:
  - implementation in state-of-the-art hardware
  - reduce skews further
  - formal verification of HEX and FATAL⁺

“Wild” Synchronization…

“The benefit of being synchronized…”

Questions?