

Distributed Computing over
Communication Networks:

Leader Election

Motivation

Reasons for electing a leader?

Reasons for *not* electing a leader?



Motivation

Reasons for electing a leader?

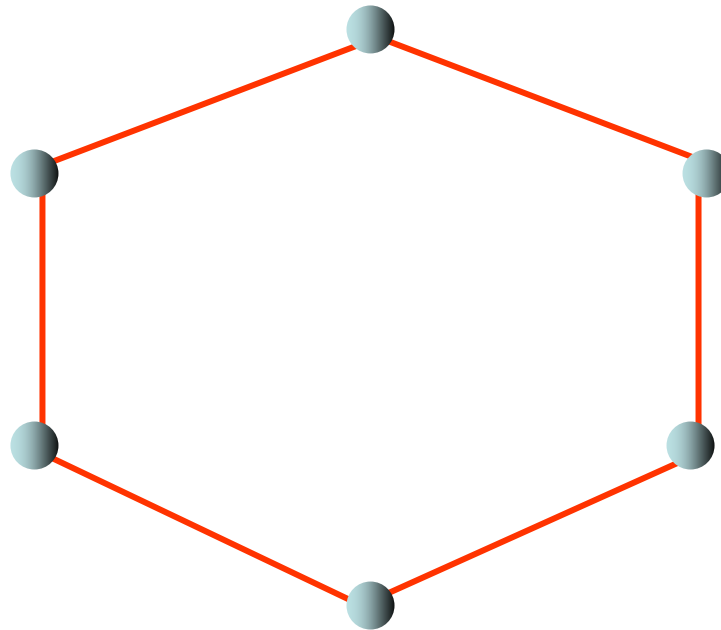
- Once elected, **coordination** tasks may become simpler
- For example: wireless medium access
(break symmetry)

Reasons for *not* electing a leader?

- Reduced parallelism?
- Self-stabilization needed: re-election when leader „dies“
- Leader **bottleneck** / single point of failure?

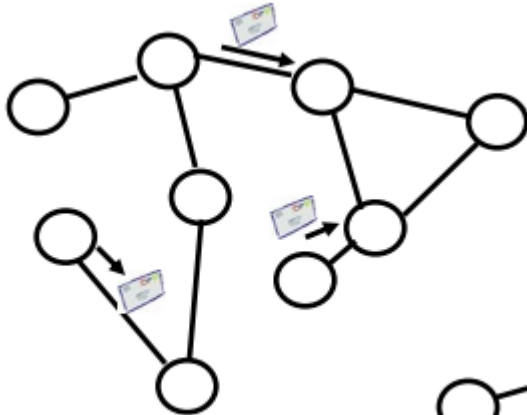


How to elect a leader in a ring?

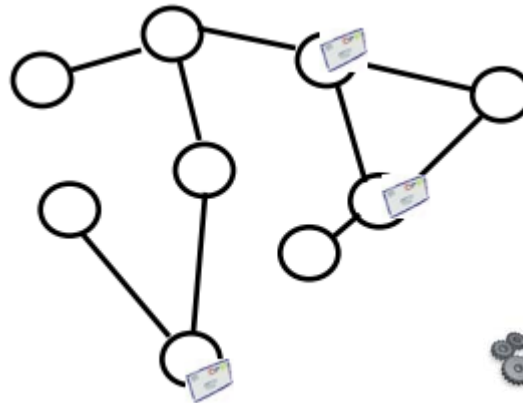


Model „Synchronous Local Algorithm“: Round

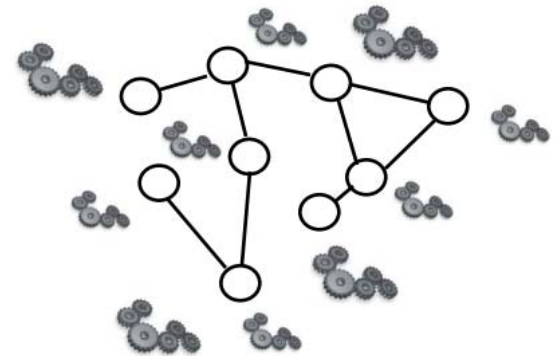
Send...



... receive...



... compute.



Anonymous System

Anonymous nodes do not have **identifiers**.

Theorem

In an anonymous ring, leader election is impossible!

Why?

Impossibility in Synchronous Ring

Theorem

In an anonymous ring, leader election is impossible!

First, note the following lemma:

Lemma

After round k of any **deterministic algorithm** on an anonymous ring, each node is in the **same state** s_k .

Proof idea?!

By **induction**: all nodes start in same state, and each round consists of sending, receiving and performing local computations. All nodes send the **same messages**, receive the same messages, and do the **same computations**. So they **always stay in same state**...

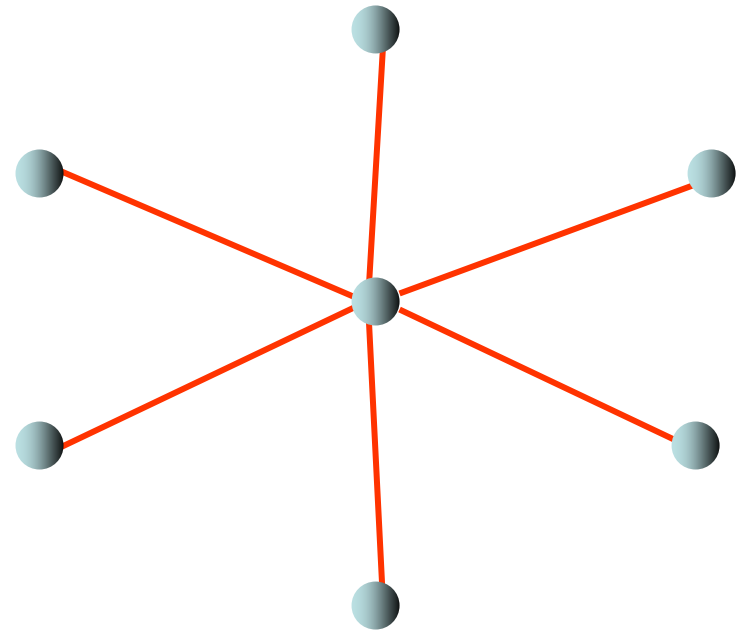
QED

So when a node decides to become a leader, then all others do too.

What is the basic problem?

Symmetry.... How could it be broken?

- How to elect a leader **in a star**?
- **Randomization**?
- What if nodes have **IDs**?



Asynchronous Ring

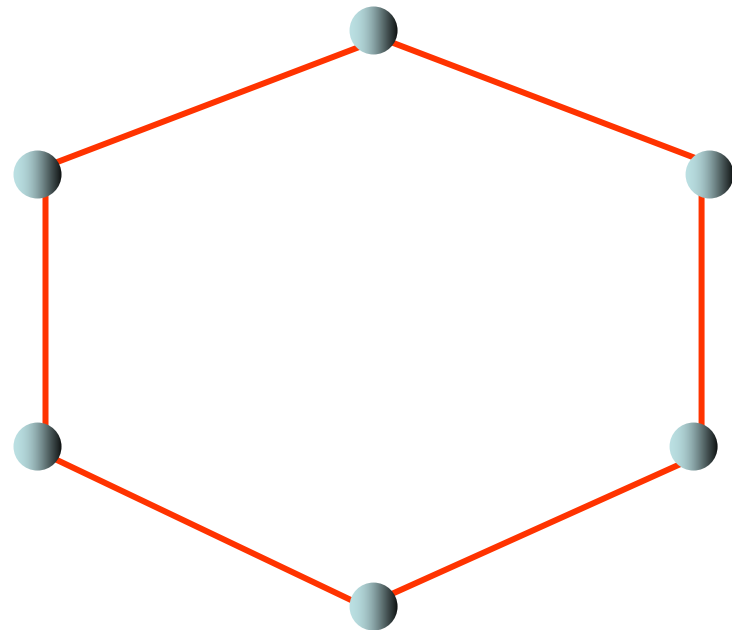
Let's assume:

- non-anonymous nodes with **unique IDs**
- **asynchronous** ring
- **uniform** ring: n unknown!
- no message losses etc.

How to elect a leader now?

Uniform System

Nodes do not know **n** .



Asynchronous Ring

Let's assume:

- non-anonymous nodes with unique IDs
- asynchronous ring

How to evaluate?

Criteria?

Asynchronous time?!

Algorithm Clockwise

each node v does the following:

- v sends a message with its ID v to **clockwise neighbor**
(unless v already received a message with **ID $w > v$**)
- if v receives message w with $w > v$ then
 - v forwards w to clockwise neighbor
 - v *decides* not to be the leader
- else if v receives its own ID v then
 - **v *decides* to be the leader**

Time Complexity

Number of rounds (for asynchronous, assume max delay of **one unit**).

Message Complexity

Number of messages sent.

„Local Complexity“

Local computations...

For our algorithm?!

Clockwise Algorithm

Theorem

Algo is correct, time complexity $O(n)$, message complexity $O(n^2)$.

Proof idea?

Correctness: Let z be **max ID**. No other node can swallow z 's ID, so z will get the message back. So z becomes leader. Every other node declares non-leader when forwarding z (the latest!).

Message complexity: Each node forwards at most n messages (n IDs in total).

Time complexity: Message circles around cycle (depending on model, at most twice: once to wake up z , and then until z becomes leader).

QED

**Can we do better?!
Time? Messages? ...**

Radius Growth

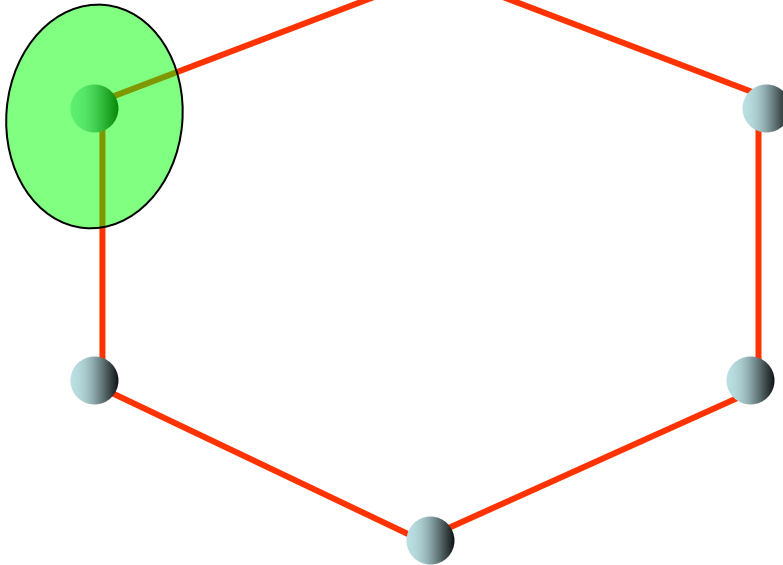
Algorithm Radius Growth

each node v does the following:

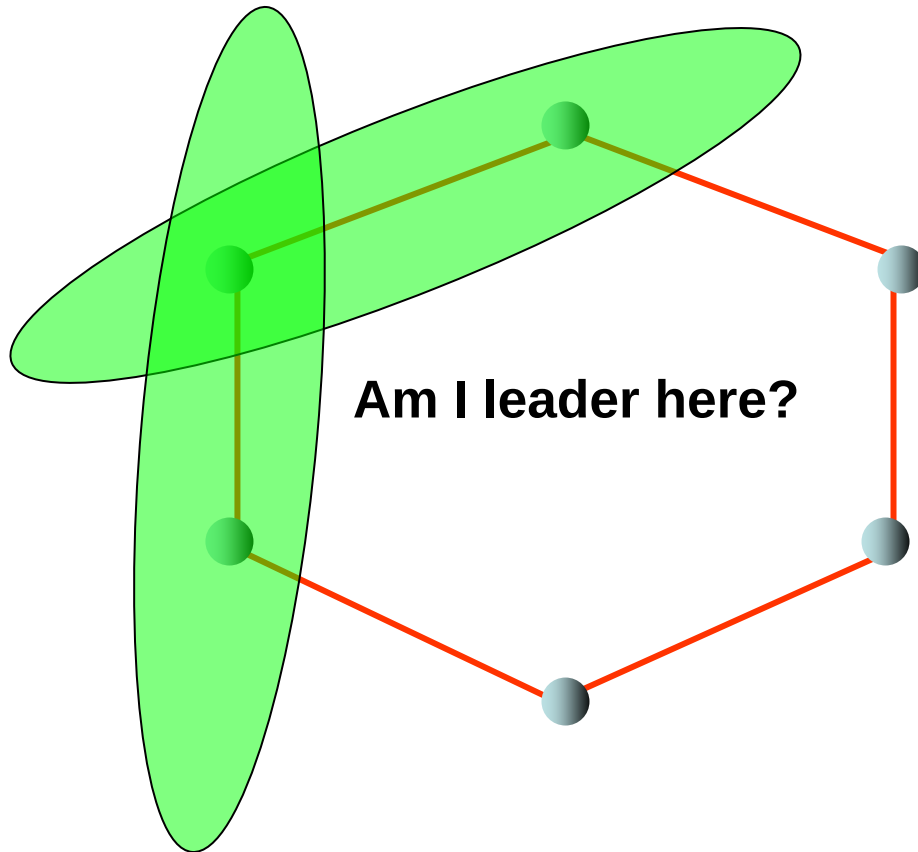
- Initially, all nodes are **active** (can still become leader)
- Whenever a node v sees a message with $w > v$, it *decides* **not to be a leader** and becomes **passive**
- Active nodes search in an **exponentially growing** neighborhood (clockwise and counterclockwise) for nodes with higher IDs by sending out **probe messages**: a probe includes sender's ID, a **leader bit** saying whether original sender can still become a leader, and TTL (initially =1).
- All nodes w receiving a probe **decrement TTL** and forward to next neighbor; if w 's ID is larger than original sender's ID, the **leader bit** is set to zero. If TTL=0, return message to sender (**reply msg**) including leader bit.
- If leader bit is still 1, double the TTL, and two new probes are sent (for both neighbors); otherwise node becomes **passive**.
- If v receives its own probe message (not the reply): it becomes **leader**.

Radius Growth

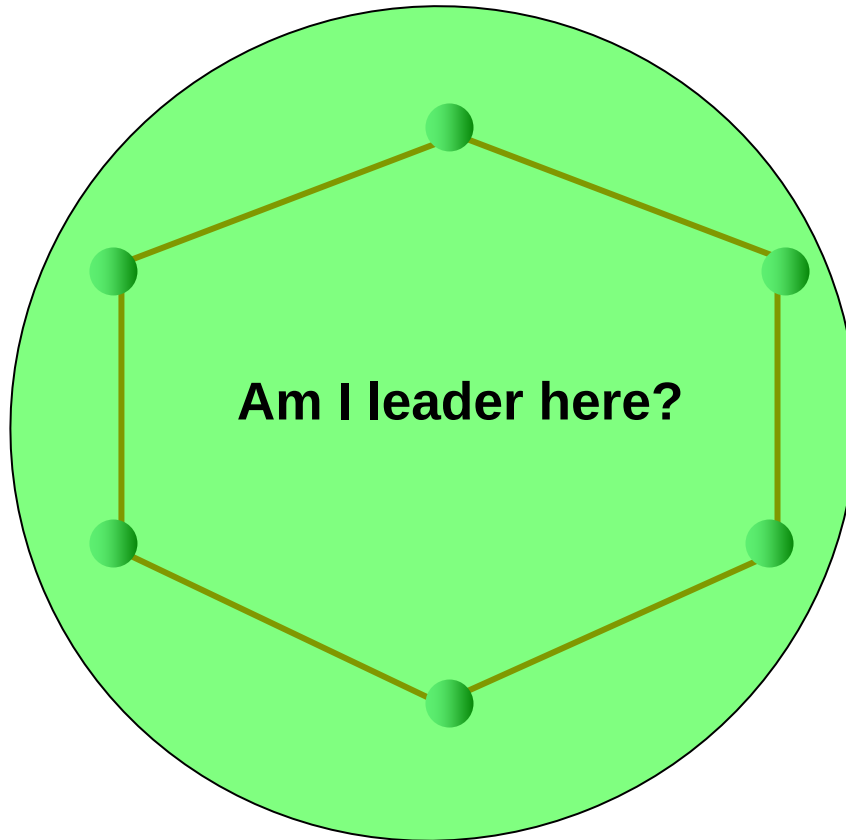
Am I leader here?



Radius Growth



Radius Growth



**How to analyze?
Complexities?**

Radius Growth

Theorem

Algo is correct, time complexity $O(n)$, message complexity $O(n \log n)$.

Proof idea?

Correctness: Like clockwise algo.

Time complexity: $O(n)$ since node with max identifier sends messages with round trip times 2, 4, 8, ..., 2^k with $k \in O(\log n)$. The sum constitutes a **geometric series** and is hence linear in n .

Message complexity: **Only one node** can survive phase p that covers a distance of 2^p . So **less than $n/2^p$ nodes are active in round $p+1$** . Being active in round p costs roughly 2^p messages, so it's around $O(n)$ per round over all active nodes. As we have a logarithmic number of phases, the claim follows.

QED

Can we do better?!

**Or how can we prove
that we cannot?**

Lower bounds!

Lower Bound (1)

Take-Away

In message passing systems, lower bounds can often be proved by arguing about messages that need to be exchanged!

Concepts:

1. Generally, we need some definitions to **characterize the class of algorithms** for which the lower bound holds.
2. Moreover, in distributed systems, a **(hypothetical) scheduler** determines sequence of events...

Execution

An execution of a distributed algorithm is a list of **events**, sorted by time. An event is a record **(time, node, type, message)** where type is „send“ or „receive“.

Lower Bound (2)

Assumptions:

- Asynchronous ring: nodes **wake up** at arbitrary times but always when receiving a packet
- nodes have IDs, and node with **max ID** should become leader
- **every node** must know ID of leader
- **uniform algorithm**: n is not known
- arbitrary scheduler but links are **FIFO**

For our lower bound proof, we define the concept of *open schedules*:

Open Schedule

Schedule chosen by scheduler. Open if there is an **open edge** in the ring. Edge is *open* if no message traversing edge has been received so far.

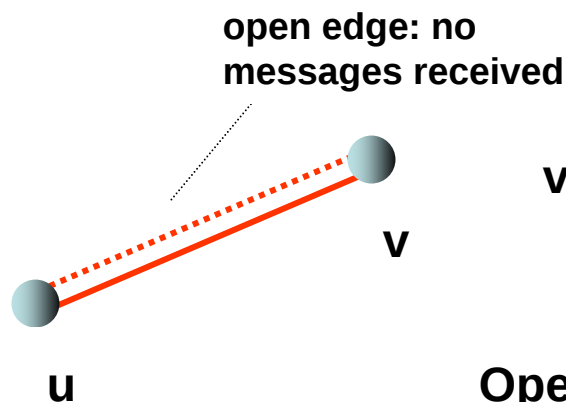
Lower Bound by Induction

Proof by induction:

2-node Ring

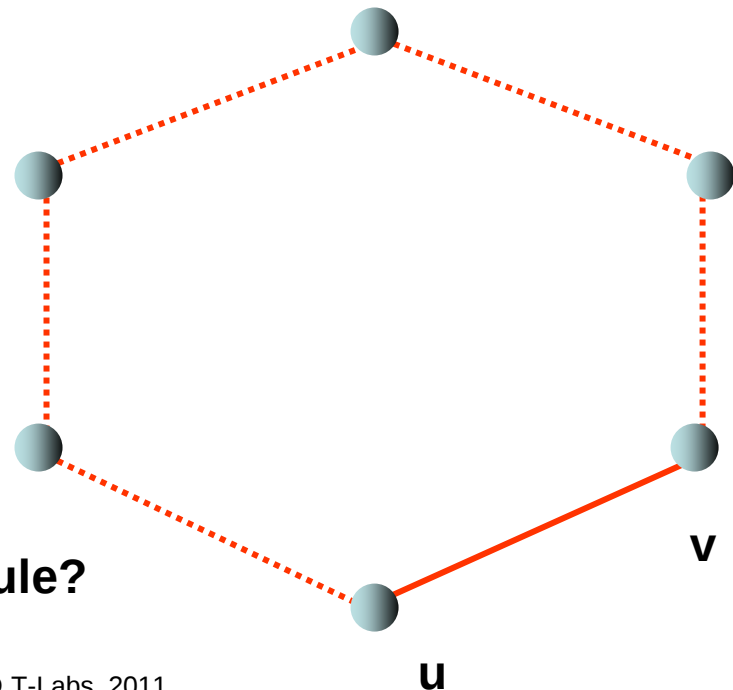
Given a ring R with two nodes, we can **construct an open schedule** in which **at least one message is received**. The nodes cannot distinguish this schedule from one on a larger ring with all other nodes being where the open edge is.

Proof of Lemma: u and v cannot distinguish between the two scenarios!



VS

Open schedule?



Proof of Lemma: Open Schedule

2-node Ring

Given a ring R with two nodes, we can construct an open schedule in which at least one message is received. The nodes cannot distinguish this schedule from one on a larger ring with all other nodes being where the open edge is.

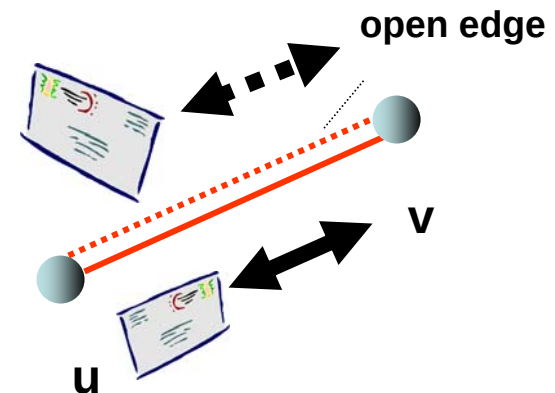
Open schedule for 2-node ring?

In any leader election algorithm, the two nodes must learn about each other! We stop execution when first message is received (on whatever link).

We can do this because it's an **asynchronous world** (no simultaneous arrivals)...

So other edge is **open**:

Nodes don't know, is it an edge, or is it more?

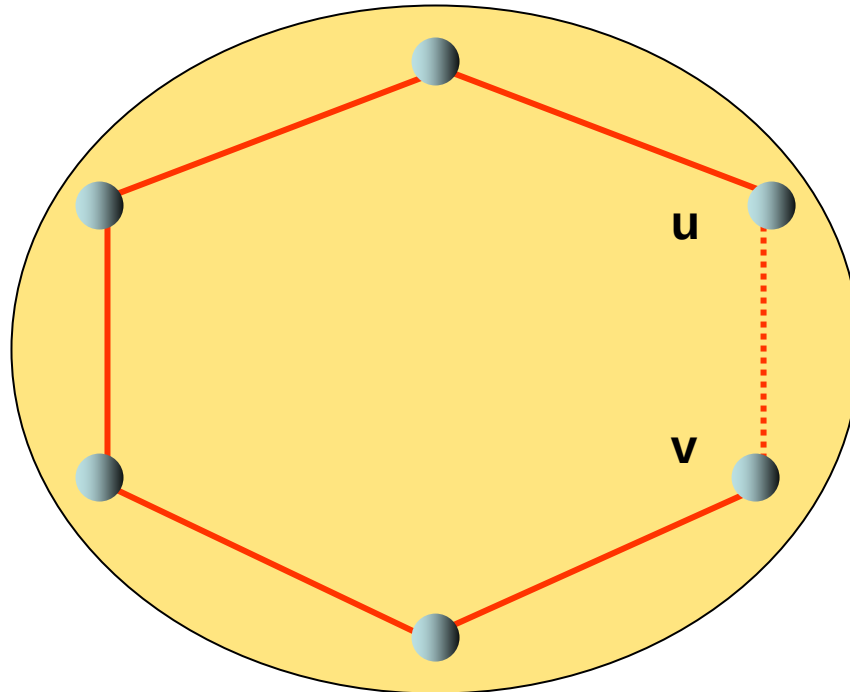


Open Schedules for Larger Rings?

n-node Ring

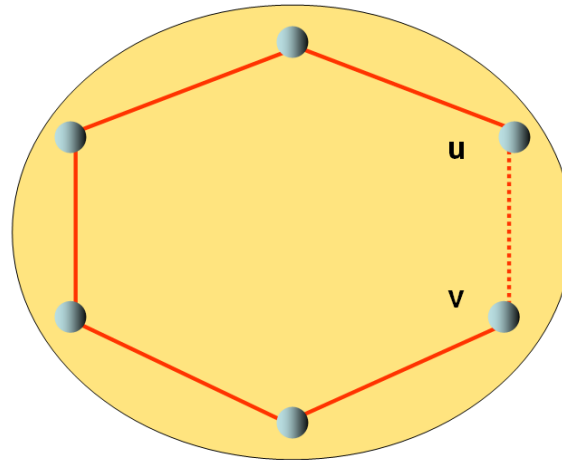
By gluing together **two rings of size $n/2$** for which we have open schedules, an open schedule can be constructed on a ring of size n . Let **$M(n/2)$** denote the number of messages used in each of these schedules by some algorithm ALG. Then, in the entire ring **$2M(n/2) + n/4$** messages have to be exchanged to solve leader election.

Proof? Open schedule?



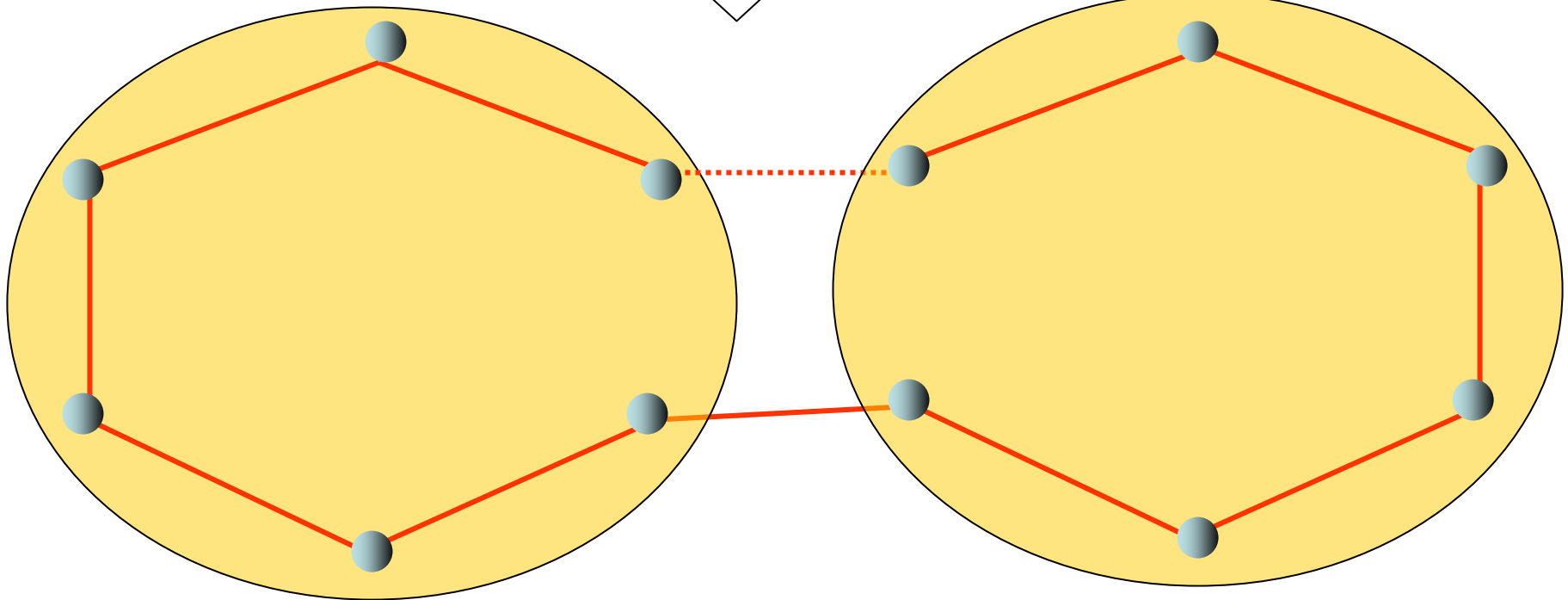
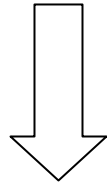
Assume ALG needs $M(n/2)$ messages here...

... how many for the whole ring?



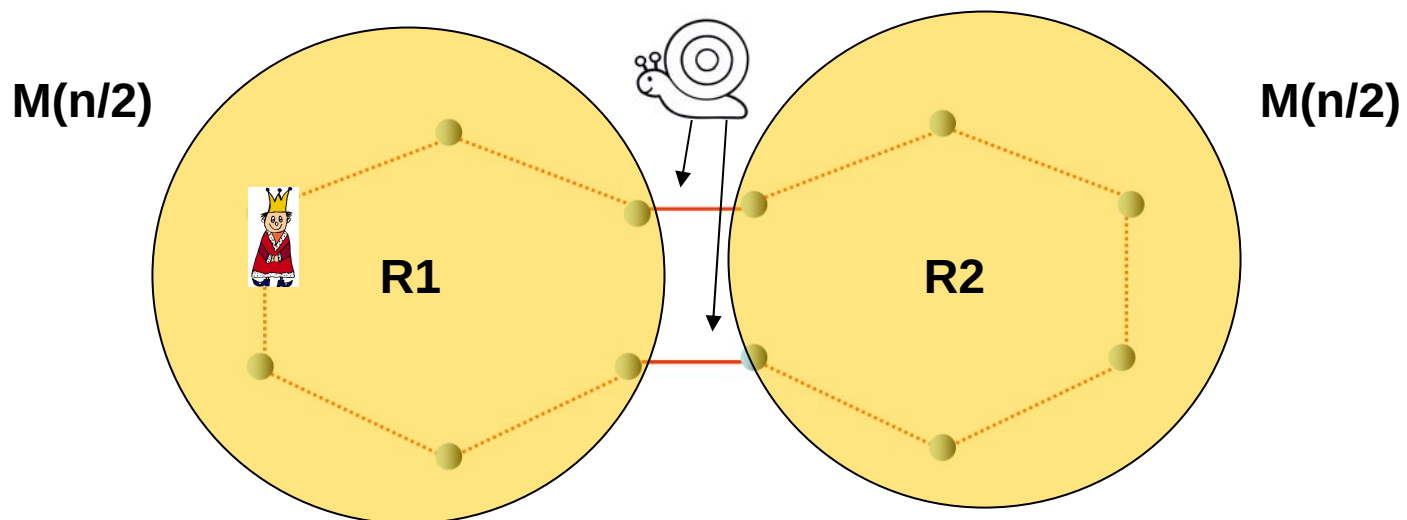
Idea: take two times smaller ring and „close“ one edge...

Open schedule for larger ring?



Proof of Lemma: By Induction

- Consider the ring of size n and divide it in two „subrings“ $R1$ and $R2$. As long as **no message comes from outside**, nodes **cannot distinguish** these two rings from two rings of size $n/2$. (Just delay messages accordingly: all other messages of algorithm are sent.)
- So nodes **exchange $2 \cdot M(n/2)$ messages** (induction hypothesis) in the subrings before learning anything about the other subring. Wlog assume $R1$ has max ID. So each node in $R2$ must learn that ID, which requires **at least $n/2$ message receptions**.
- So there must be an edge connecting the two rings that „produces“ (= **triggers**, but not necessarily transmits!) at least **$n/4$ messages**.
Schedule/close this edge and leave other open... => open schedule for larger ring! And **enough messages!** 😊



Open Schedules for Larger Rings?

Theorem

Any algo needs at least $\Omega(n \log n)$ messages.

Proof by induction: Claim follows from maths...

$$\begin{aligned} M(n) &= 2 \cdot M\left(\frac{n}{2}\right) + \frac{n}{4} \\ &\geq 2 \cdot \left(\frac{n}{8} \left(\log \frac{n}{2} + 1\right)\right) + \frac{n}{4} \\ &= \frac{n}{4} \log n + \frac{n}{4} = \frac{n}{4} (\log n + 1) \end{aligned}$$



**So we are optimal.
Can we do better? ☺**

Breaking the Lower Bound ☺

Take-Away

In synchronous systems, not receiving a message is also information!

Idea for message complexity n ? E.g., find **minimum ID** in environment where nodes have unique but **arbitrary** integer IDs (but n known)...

Sync Leader Election

each node v does the following:

- Divide time into phases of n steps (leaves time for lower-ID nodes to broadcast...)
- If phase = v and did not get a message:
 - v becomes leader
 - v sends „I am leader!“ to everybody!

Breaks message lower bound but we may wait long!
Runtime $O(n \cdot \min ID)$? What is the time – message tradeoff?

Literature for further reading:

- Attiya/Welch (Alg. 3.1 for example)
- Peleg's book (as always 😊)

End of lecture