Distributed Systems

Leader Election

Rik Sarkar

University of Edinburgh
Fall 2015

No fixed master

- We saw in previous weeks that some algorithms require a global coordinator or master
- Agregation works with a master *root*
  - But introduces a single point of failure
- There is no reason for a master process to be fixed
  - When one fails, may be another can take over?

- Today we look at the problem of what to do when a master process fails

Failures

- How do we know that something has failed?
- Let's see what we mean by *failed:*

- Models of failure:
  1. Assume no failures
  2. Crash failures: Process may fail/crash
  3. Message failures: Messages may get dropped
  4. Link failures: a communication link stops working
  5. Some combinations of 2,3,4
  6. More complex models can have recovery from failures
  7. Arbitrary failures: computation/communication may be erroneous

Failure detectors

- Detection of a crashed process
  - (not one working erroneously)

- A major challenge in distributed systems
- A failure detector is a process that responds to questions asking whether a given process has failed
  - A failure detector is not necessarily accurate

Failure detectors

- Reliable failure detectors
  - Replies with “working” or “failed”
- Difficulty:
  - Detecting something is working is easier: if they respond to a message, they are working
  - Detecting failure is harder: if they don’t respond to the message, the message may hev been lost/delayed, may be the process is busy, etc..
- Unreliable failure detector
  - Replies with “suspected (failed)” or “unsuspected”
  - That is, does not try to give a confirmed answer
- We would ideally like reliable detectors, but unreliable ones (that say give “maybe” answers) could be more realistic

Simple example

- Suppose we know all messages are delivered within D seconds

- Then we can require each process to send a message every T seconds to the failure detectors
- If a failure detector does not get a message from process p in T+D seconds, it marks p as "suspected" or "failed"

Simple example

- Suppose we assume all messages are delivered within D seconds

- Then we can require each process to send a message every T seconds to the failure detectors
- If a failure detector does not get a message from process p in T+D seconds, it marks p as "suspected" or "failed" (depending on type of detector)

Synchronous vs asynchronous

- In a synchronous system there is a bound on message delivery time (and clock drift)
- So this simple method gives a reliable failure detector
- In fact, it is possible to implement this simply as a function:
  - Send a message to process p, wait for 2D + ε time
  - A dedicated detector process is not necessary
- In Asynchronous systems, things are much harder

Simple failure detector

- If we choose T or D too large, then it will take a long time for failure to be detected
- If we select T too small, it increases communication costs and puts too much burden on processes
- If we select D too small, then working processes may get labeled as failed/suspected

Assumptions and real world

- In reality, both synchronous and asynchronous are a too rigid
- Real systems, are fast, but sometimes messages can take a longer than usual
  - But not indefinitely long
- Messages usually get delivered, but sometimes not..

Some more realistic failure detectors

- Have 2 values of D: D1, D2
  - Mark processes as working, suspected, failed

- Use probabilities
  - Instead of synchronous/asynchronous, model delivery time as probability distribution
  - We can learn the probability distribution of message delivery time, and accordingly extimate the probability of failure

Using bayes rule

- a=probability that a process fails within time T
- b=probability a message is not received in T+D

- So, when we do not receive a message from a process we want to estimate P(a|b)
  - Probability of a, given that b has occurred

$$P(a \mid b) = \frac{P(b \mid a)P(a)}{P(b)}$$

If process has failed, i.e. a is true, then of course message will not be received! i.e. P(b|a) = 1. Therefore:

$$P(a \mid b) = \frac{P(a)}{P(b)}$$

Leader of a computation

- Many distributed computations need a coordinating or server process
  - E.g. Central server for mutual exclusion
  - Initiating a distributed computation
  - Computing the sum/max using aggregation tree
- We may need to elect a leader at the start of computation
- We may need to elect a new leader if the current leader of the computation fails

The Distinguished leader

Ref: NL

- The leader must have a special property that other nodes do not have
- If all nodes are exactly identical in every way then there is no algorithm to identify one as leader
- Our policy:
  - The node with highest identifier is leader

Node with highest identifier

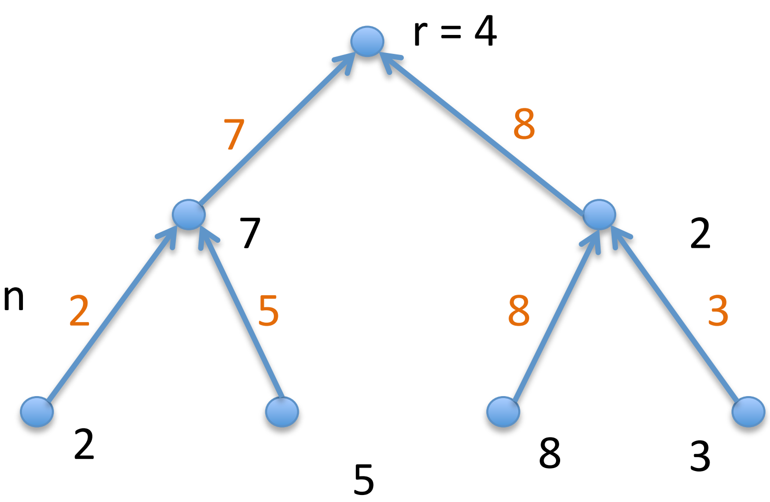
- If all nodes know the highest identifier (say n), we do not need an election
  - Everyone assumes n is leader
  - n starts operating as leader
- But what if n fails? We cannot assume n-1 is leader, since n-1 may have failed too! Or may be there never was process n-1

- Our policy:
  - The node with highest identifier and still surviving is the leader

- We need an algorithm that finds the working node with highest identifier

Strategy 1: Use aggregation tree

- Suppose node r detects that leader has failed, and initiates leader election
- Node r creates a BFS tree
- Asks for max node id to be computed via aggregation
  - Each node receives id values from children
  - Each node computes max of own id and received values, and forwards to parent
- Needs a tree construction
- If n nodes start election, will need n trees
  - $O(n^2)$communication
  - $O(n)$ storage per node



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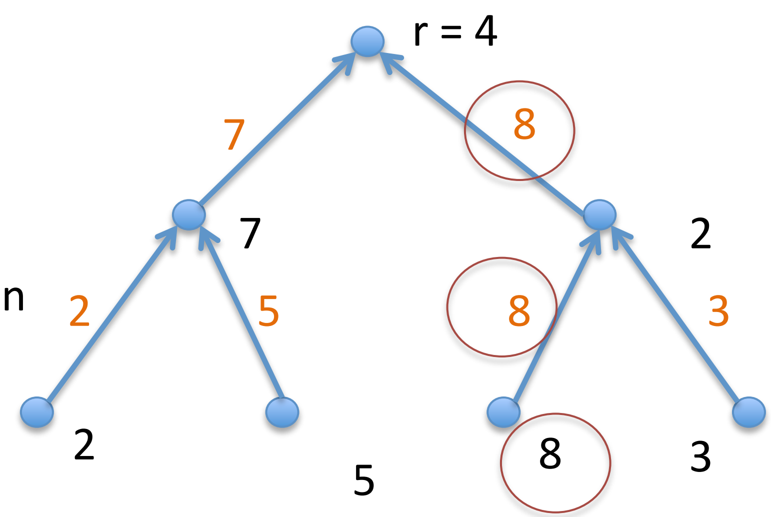
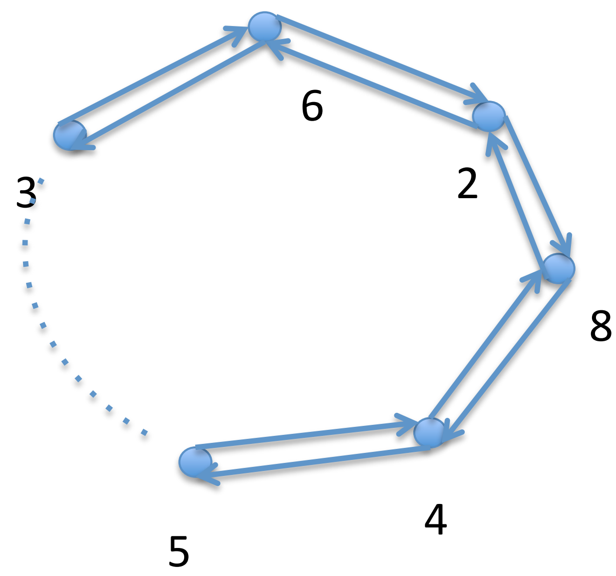


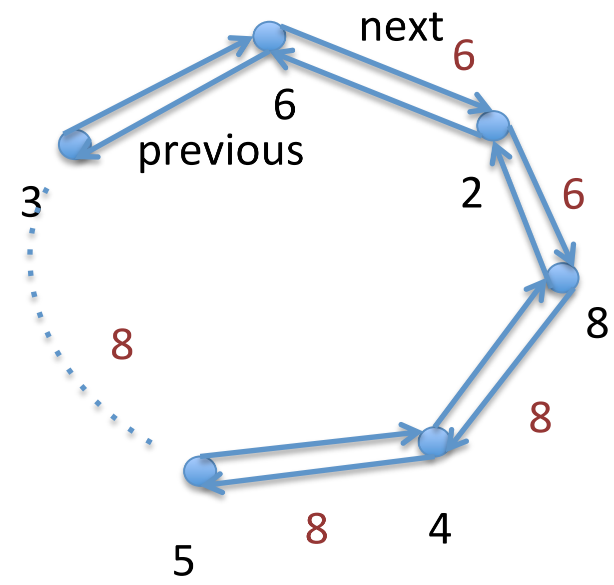
Strategy 2: Use a ring

- Suppose the network is a ring
  - We assume that each node has 2 pointers to nodes it knows about:
    - Next
    - Previous
    - (like a circular doubly linked list)
  - The actual network may not be a ring
  - This can be an *overlay*



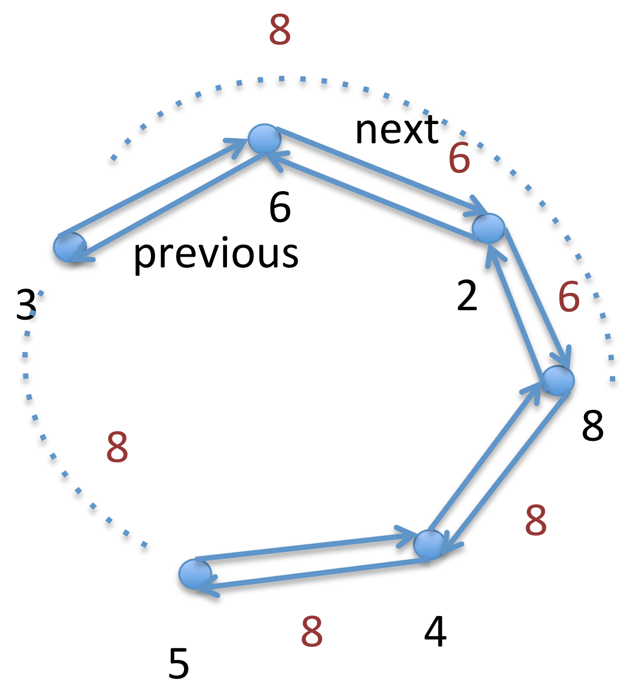
Strategy 2: Use a ring

- Basic idea:
  - Suppose 6 starts election
  - Send "6" to 6.*next*, i.e. 2
  - 2 takes max(2, 6), send to 2.*next*
  - 8 takes max(8,6), sends to 8.*next*
  - etc



Strategy 2: Use a ring

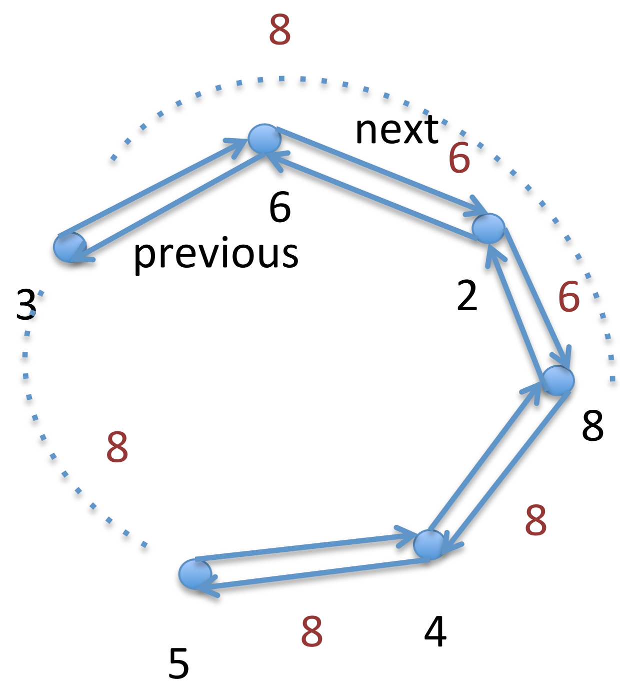
- The value "8" goes around the ring and comes back to 8
- Then 8 knows that "8" is the highest id
  - Since if there was a higher id, that would have stopped 8
- 8 declares itself the leader: sends a message around the ring



Strategy 2: Use a ring

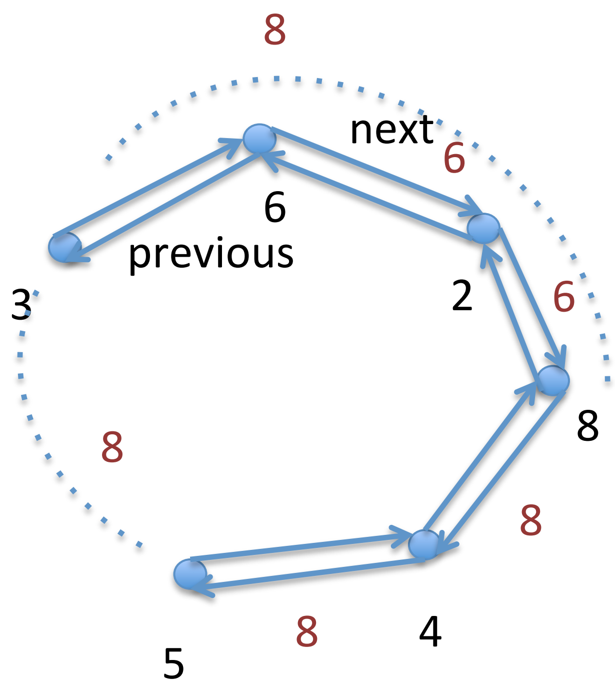
- The problem: What if multiple nodes start leader election at the same time?

- We need to adapt algorithm slightly so that it can work whenever a leader is needed, and works for multiple leader



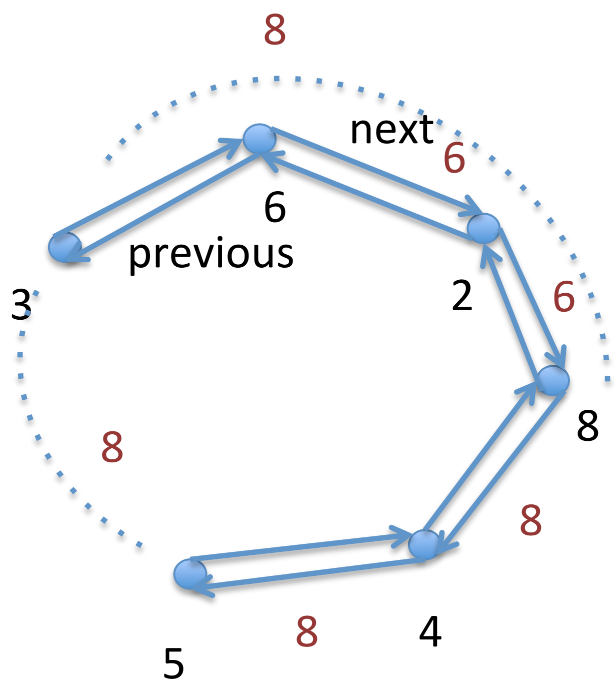
Strategy 2: Use a ring (Algorithm by chang and roberts)

- Every node has a default state: *non-participant*
- Starting node sets state to *participant* and sends *election* message with id to *next*



Strategy 2: Use a ring (Algorithm by chang and roberts)

- If node p receives *election* message m
- If p is non-partcipant:
  - send max(m.id, p.id) to *p.next*
  - Set state to participant
- If p is participant:
  - If m.id > p.id:
    - Send m.id to *p.next*
  - If m.id < p.id:
    - do nothing



Strategy 2: Use a ring (Algorithm by chang and roberts)

- If node p receives e*lection* message m with m.id = p.id

- P declares itself leader
  - Sets p.leader = p.id
  - Sends *leader* message with p.id to p.next
  - Any other node q receiving the leader message
    - Sets q.leader = p.id
    - Forwards leader message to q.next

Strategy 2: Use a ring (Algorithm by chang and roberts)

- Works in an asynchronous system
- Assuming nothing fails while the algorithm is executing

- Message complexity O(n^2)
  - When does this occur?
  - (hint: all nodes start election, and many messages traverse a long distance)

- What is the time complexity?
- What is the storage complexity?

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- k-neighborhood of node p
  - The set of all nodes within distance k of p

- How does p send a message to distance k?
  - Message has a "time to live variable"
  - Each node decrements m.ttl on receiving
  - If m.ttl=0, don't forward any more

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- Basic idea:
  - Check growing regions around yourself for someone with larger id

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- Algorithm operates in phases
- In phase 0, node p sends election message m to both p.next and p.previous with:
  - m.id = p.id and ttl = 1

- Suppose q receives this message
  - Sets m.ttl=0
  - If q.id > m.id:
    - Do nothing
  - If q.id < m.id:
    - Return message to p

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- Algorithm operates in phases
- In phase 0, node p sends election message m to both p.next and p.previous with:
  - m.id = p.id and ttl = 1

- Suppose q receives this message
  - Sets m.ttl=0
  - If q.id > m.id:
    - Do nothing
  - If q.id < m.id:
    - Return message to p
- If p gets back both message, it decides itself leader of its 1-neighborhood, and proceeds to next phase

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- If p is In phase i, node p sends election message m to p.next and p.previous with:
  - m.id = p.id, and m.ttl = 2^i
- A node q on receiving the message (from next/previous)
  - If m.ttl=0: forward suitably to previous/next
  - Sets m.ttl=m.ttl-1
  - If q.id > m.id:
    - Do nothing
  - Else:
    - If m.ttl = 0: return to sending process
    - Else forward to suitably to previous/next
- If p gets both message back, it is the leader of its 2^i neighborhood, and proceeds to phase i+1

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- When $2^i >= n/2$
  - Only 1 process survives: Leader

- Number of rounds: O(log n)

- What is the message complexity?

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

In phase i

- At most one node initiates message in any sequence of 2^{i-1} nodes
- So, $n/2^{i-1}$ candidates
- Each sends 2 messages, going at most 2^i distance, and returning: $2*2*2^i$ messages
- O(n) messages in phase i

There are O(log n)

- Total of O(n log n) messages

Strategy 3: Use a ring – smartly (Hirschberg Sinclair)

- Assume synchronous operation
- Assume nodes do not fail during algorithm run

- What is time complexity?
- What is storage complexity?

Strategy 4: Bully Algorithm

Ref: CDK

- Assume:
  - Each node knows the id of all nodes in the system (some may have failed)
  - Synchronous operation

- Node p decides to initiate election
- p sends election message to all nodes with id > p.id
- If p does not hear "I am alive message" from any node, p broadcasts a message declaring itself as leader
- Any working node q that receives election message from p, replies with own id and "I am alive" message
  - And starts an election (unless it is already in the process of an election)
- Any node q that hears a lower id node being declared leader, starts a new election

Strategy 4: Bully Algorithm

- Assume:
  - Each node knows the id of all nodes in the system (some may have failed)
  - Synchronous operation

- Works even when processes fail
- Works when (some) message deliveries fail.

- What are the storage and message complexities?

Multicast

- Send message to multiple nodes
- A node can join a multicast *group*, and receives all messages sent to that group
- The sender sends only once: to the group address
- The network takes care of delivering to all nodes in the group
- Note: groups are restricted to specific networks such as LANs & WANs
  - Multicast in the university network will not reach nodes outside the network

Multicast

- A special version of broadcast (restricted to a subset of nodes)
- In a LAN
  - Sender sends a broadcast
  - Interested nodes accept the message others reject
- In larger networks we can use a tree
  - Remember trees can be used for broadcast
  - Interested nodes join the tree, and thus get messages
  - All nodes can use the same tree to multicast to the same group

IP Multicast

- IP has a specific multicast protocol
- Addresses from 224.0.0.0 to 239.255.255.255 are reserved for multicast
  - They act as *groups*
  - Some of these are reserved for specific multicast based protocols
- Any message sent to one of the addresses goes to all processes subscribed to the group
  - Must be in the same "network"
  - Basically depends on how routers are configured
- In a LAN, communication is broadcast
- In more complex networks, tree-based protocols can be used

IP Multicast

- Any process interested in joining a group informs its OS
- The OS informs the "network"
  - The network interface (LAN card) receives and delivers group messages to the OS & process
  - The router may need to be informed
  - IGMP – Internet group management protocol

IP Multicast

- Sender sends only once
- Any router also forwards only once
- No acknowledgement mechanism
  - Uses UDP
- No guarantee that intended recipient gets the message
- Often used for streaming media type content
- Not good for critical information

Multicast

- Can we design a reliable protocol?
- If there are multiple messages, can we ensure they are delivered in correct order?