Leader Election

CSE 486: Distributed Systems

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Centralized Decisions

It can often simplify protocols to make centralized decisions.

For example:

- Total ordering with a central scheduler
- Assignment of globally unique names

There are significant disadvantages to centralizing:

- Single points of failure
- Centralized trust
- Latency[1]

[1] This is absolutely a tradeoff!

Leader Elections

Leader elections can address the single point of failure.

They select a centralized decision-maker at run time.

They are most often used:

- When a distributed protocol is bootstrapping
- After a leader has failed

In the latter case they require a failure detector.

Election Properties

Leader elections can be called at different times:

- When any process wants to
- When the current leader wants to
- When any process detects leader failure
- When some set of processes detects leader failure
- At a predetermined time or protocol state
- …

Which policy is used depends on the application!

The Bully Algorithm

The Bully Algorithm [4] was one of the first to be described.

It takes its name from the property that the biggest process wins.

It assumes:

- Every process has a unique ID
- Process IDs form a total ordering
- Communication is reliable
- Messages are delivered in bounded time

Any process can start an election at any time.

States

Processes in the Bully Algorithm have three states:

- Normal
- Election
- Waiting

Processes in the normal state are doing what they do.

Processes in the election state are electing a leader.

Processes in the waiting state are awaiting results.

The safety property must hold:
If p_i and p_j are both in the normal state, they agree on the current leader.

Starting the Election

Suppose that process p_i wishes to start an election.
(Perhaps it thinks the current leader has failed?)

First it moves to the election state.

It proposes itself as leader to all processes with larger IDs.

If any process of larger ID responds, it waits for a new leader.

If no process of larger ID responds, it declares itself leader.

Participating in Election

Suppose that some process p_j hears an election proposal from p_i.

This means that p_j's ID is larger than p_i's ID.
(To whom did p_i send proposals?)

It sends a message to p_i stating that it is alive.

It then starts an election.

Processes that do not hear a proposal hear the results.

Distributing the Results

Once a leader is elected, the results must be distributed.

In order to maintain agreement, this is not quite trivial.

The new leader sends a special message to all processes.
(All processes now have smaller IDs than the newly-elected leader!)

Every process hearing this message moves to the waiting state.

Once every process is in the waiting state, the new leader announces its election.

Every process moves to the normal state

Liveness

This protocol is vulnerable to deadlock!

1. If a process p_j responds to p_i but fails before electing itself
2. If the elected process fails after putting processes in the waiting state and before declaring victory

In both cases:
After some timeout, a blocked process starts a new election.

If the same potential leader is still alive, its election will complete.

If it is not, the next-largest node ID will be elected.

Correctness

How do we know the correct process of largest ID is elected?

Suppose that some process p_i with ID smaller than p_j is elected.

We know that:

- p_i sent an election proposal to p_j.
- p_j did not send an election announcement to p_i.

Therefore, p_j must have failed!

Efficiency of the Bully Algorithm

In the worst case, the bully algorithm sends $O(n^2)$ messages.

Consider: p_i of the lowest priority starts an election.

Every p_j of higher priority will also start an election.

In the best case, it sends $O(n)$ messages.

If the correct process of highest remaining ID continually fails during election, it can time out many times in succession.

Ring Election

Another interesting and simple protocol uses a ring [2].

Processes are arranged in a communication ring.

Each process has a clockwise and counterclockwise neighbor.

Every process has an ID, and IDs form a total ordering.

The algorithm will elect the correct process with the largest ID.

The Protocol

Any process may start an election at any time.

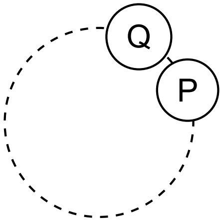
To start an election, a process sends an election message containing its own ID counterclockwise.

On receiving an election message, each process:

- Declares victory if the message contains its ID
- Forwards the message if the message ID is larger than its own ID
- Forwards its own ID if the ID is smaller

Efficiency of the Ring Algorithm

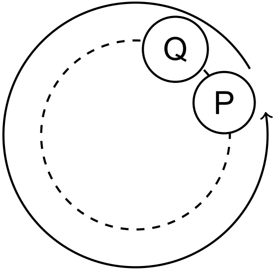
If there are no failures during election, this algorithm is $O(n)$.



Efficiency of the Ring Algorithm

If there are no failures during election, this algorithm is $O(n)$.

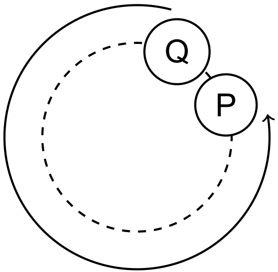
If the process P of largest ID starts the election, n messages are sent.



Efficiency of the Ring Algorithm

If there are no failures during election, this algorithm is $O(n)$.

If the process Q immediately counterclockwise of the winner starts it, $2n-1$ messages are sent.



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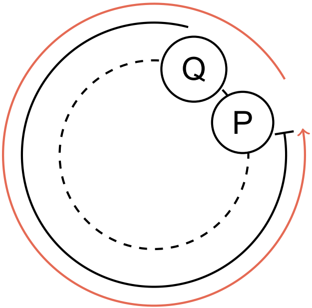

Efficiency of the Ring Algorithm

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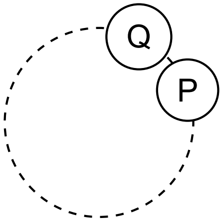
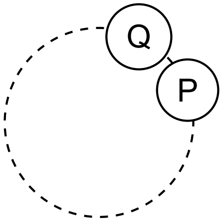


Efficiency of the Ring Algorithm

If there are no failures during election, this algorithm is $O(n)$.

If processes die during election, it can be n^2.



Other Properties of the Ring Algorithm

This protocol is also vulnerable to deadlock.

Timeouts can once again be used to solve this.

Note that even though processes send only counterclockwise, every process must know or be able to find other processes.

Consider what happens when *P*'s counterclockwise neighbor fails!

If we want the guarantees of the bully algorithm, we need another round.

Unique Identifiers

Both of these algorithms require unique IDs.

How do we get those without a coordinator?

We have mentioned cryptographic hashes before.

How they can be used depends on what we're defending against.

Disclaimer

This is not a security course.

Our coverage of security issues will be superficial.

It is easy to draw false conclusions with such analysis.

Take a security course!

Threat Models

We must define a threat model in order to answer this.

The threat model captures:

- Whether you expect to have adversaries
- What kind of resources the adversaries will have
- What failures you are protecting against

For example:

Adverserial processes may try to adopt a process ID larger than any process in the system in order to become the leader. They can spend up to s CPU seconds to accomplish this.

Proof of Work

A common technique for combating this is proof of work.

Proof of work participants must compute a function f that [3]:

- Takes some time to compute
- Is not easily precomputed or amortized
- Given x and y, it is easy to determine if $y = f(x)$

This forces a process to invest effort in a system.

Example Proof of Work

S/Kademlia [1] proposes a proof of work to prevent flooding the DHT with node IDs.

Each node is identified by a cryptographic hash.

That hash must meet several properties:

- It must be the hash of a public key k in a public key cryptosystem: $h = \mathrm{SHA1}(k)$
- If $i = \mathrm{SHA1}(h)$; i must have b leading zero bits

Generating a public key is slow, and selecting for b is hard.

This means that a process must generate many keys, slowly.

Safer Proofs

SHA-1 is badly broken and should not be used.

Generating public/private key pairs is easier than it used to be.

Proof of work must be parameterized and updated.

Some functions can be arbitrarily iterated. For example: H(H(H(...))) for some hash function H.

If generating an ID is hard, generating a specific ID is harder.

Suppose it takes *s* seconds to compute an ID.

Generating the largest ID in a pool now takes $\gg s$ seconds!

Summary

- Centralized authority doesn't mean permanent authority
- Distributed elections can be held
  - Bully algorithm
  - Ring algorithm
- Global identifiers keep cropping up
- Proof of work can make global IDs safer
- Security guarantees require threat models

References I

Required Readings

[5] Ajay D. Kshemkalyani and Mukesh Singhal. *Distributed Computing: Principles, Algorithms, and Systems*. Chapter 5: 5.10. Cambridge University Press, 2008. ISBN: 978-0-521-18984-2.

Optional Readings

[1] Ingmar Baumgart and Sebastien Mies. "S/Kademlia: A Practicable Approach towards Secure Key-Based Routing". In: *International Conference on Parallel and Distributed Systems*. Dec. 2007, pp. 1–8. DOI: 10.1109/ICPADS.2007.4447808. URL: https://search.lib.buffalo.edu/permalink/01SUNY_BUF/12pkqkt/cdi_ieee_primary_4447808.

References II

[2] Ernest Chang and Rosemary Roberts. "An Improved Algorithm for Decentralized Extrema-finding in Circular Configurations of Processes". In: *Communications of the ACM* 22.5 (May 1979), pp. 281–283. DOI: 10.1145/359104.359108. URL: https://search.lib.buffalo.edu/permalink/01SUNY_BUF/12pkqkt/cdi_crossref_primary_10_1145_359104_359108.

[3] Cynthia Dwork and Moni Naor. "Pricing via Processing or Combatting Junk Mail". In: *International Cryptology Conference*. Vol. 740. Springer-Verlag, Aug. 1992, pp. 139–147. DOI: 10.1007/3-540-48071-4_10. URL: https://link.springer.com/chapter/10.1007\%2F3-540-48071-4_10.

References III

[4] Hector Garcia-Molina. “Elections in a Distributed Computing System”. In: *IEEE Transactions on Computers* C-31.1 (Jan. 1982), pp. 48–59. DOI: 10.1109/TC.1982.1675885. URL: https://search.lib.buffalo.edu/permalink/01SUNY_BUF/12pkqkt/cdi_crossref_primary_10_1109_TC_1982_1675885.

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