Distributed Systems

(4th edition, version 01)

Chapter 05: Coordination

Physical clocks

Problem
Sometimes we simply need the exact time, not just an ordering.

Solution: Universal Coordinated Time (UTC)

- Based on the number of transitions per second of the cesium 133 atom (pretty accurate).
- At present, the real time is taken as the average of some 50 cesium clocks around the world.
- Introduces a leap second from time to time to compensate that days are getting longer.

Note
UTC is broadcast through short-wave radio and satellite. Satellites can give an accuracy of about ± 0.5 ms.

Coordination Clock synchronization

Physical clocks 2 / 72

Clock synchronization

Precision
The goal is to keep the deviation between two clocks on any two machines within a specified bound, known as the precision π:

$$\forall t, \forall p, q : |C_p(t) - C_q(t)| \leq \pi$$

with $C_p(t)$ the computed clock time of machine p at UTC time t.

Accuracy
In the case of accuracy, we aim to keep the clock bound to a value α:

$$\forall t, \forall p : |C_p(t) - t| \leq \alpha$$

Synchronization

- Internal synchronization: keep clocks precise
- External synchronization: keep clocks accurate

Coordination Clock synchronization

Clock synchronization algorithms 3 / 72

Clock drift

Clock specifications

- A clock comes specified with its maximum clock drift rate ρ.
- $F(t)$ denotes oscillator frequency of the hardware clock at time t
- F is the clock's ideal (constant) frequency $\Rightarrow$ living up to specifications:

$$\forall t : (1-\rho) \leq \frac{F(t)}{F} \leq (1+\rho)$$

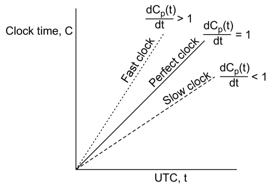
Observation

By using hardware interrupts we couple a software clock to the hardware clock, and thus also its clock drift rate:

$$C_p(t) = \frac{1}{F}\int_0^t F(t)dt \Rightarrow \frac{dC_p(t)}{dt} = \frac{F(t)}{F}$$

$$\Rightarrow \forall t : 1-\rho \leq \frac{dC_p(t)}{dt} \leq 1+\rho$$

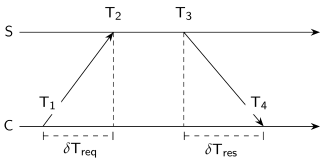
Fast, perfect, slow clocks



Coordination Clock synchronization
Clock synchronization algorithms 4 / 72

Detecting and adjusting incorrect times

Getting the current time from a timeserver



Computing the relative offset θ and delay δ

Assumption: $\delta T_{req} = T_2 - T_1 \approx T_4 - T_3 = \delta T_{res}$

$$\theta = T_3 + ((T_2 - T_1) + (T_4 - T_3))/2 - T_4 = ((T_2 - T_1) + (T_3 - T_4))/2$$

$$\delta = ((T_4 - T_1) - (T_3 - T_2))/2$$

Network Time Protocol

Collect (θ, δ) pairs. Choose θ for which associated delay δ was minimal.

Coordination Clock synchronization
Clock synchronization algorithms 5 / 72

Reference broadcast synchronization

Essence

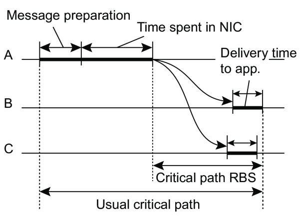
- A node broadcasts a reference message $m \Rightarrow$ each receiving node p records the time $T_{p,m}$ that it received m.
- Note: $T_{p,m}$ is read from p's local clock.

Problem: averaging will not capture drift $\Rightarrow$ use linear regression

NO: $\quad Offset[p,q](t) = \frac{\sum_{k=1}^{M}(T_{p,k} - T_{q,k})}{M}$

YES: $\quad Offset[p,q](t) = \alpha t + \beta$

RBS minimizes critical path



Coordination Clock synchronization
Clock synchronization algorithms 6 / 72

The Happened-before relationship

Issue

What usually matters is not that all processes agree on exactly what time it is, but that they agree on the order in which events occur. Requires a notion of ordering.

The happened-before relation

- If a and b are two events in the same process, and a comes before b, then $a \rightarrow b$.
- If a is the sending of a message, and b is the receipt of that message, then $a \rightarrow b$
- If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$

Note

This introduces a partial ordering of events in a system with concurrently operating processes.

Logical clocks

Problem

How do we maintain a global view of the system's behavior that is consistent with the happened-before relation?

Attach a timestamp $C(e)$ to each event e, satisfying the following properties:

P1 If a and b are two events in the same process, and $a \rightarrow b$, then we demand that $C(a) < C(b)$.

P2 If a corresponds to sending a message m, and b to the receipt of that message, then also $C(a) < C(b)$.

Problem

How to attach a timestamp to an event when there's no global clock $\Rightarrow$ maintain a consistent set of logical clocks, one per process.

Logical clocks: solution

Each process P_i maintains a local counter C_i and adjusts this counter

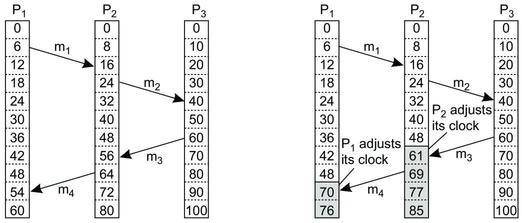
1. For each new event that takes place within P_i, C_i is incremented by 1.
2. Each time a message m is sent by process P_i, the message receives a timestamp $ts(m) = C_i$.
3. Whenever a message m is received by a process P_j, P_j adjusts its local counter C_j to $\max\{C_j, ts(m)\}$; then executes step 1 before passing m to the application.

Notes

- Property P1 is satisfied by (1); Property P2 by (2) and (3).
- It can still occur that two events happen at the same time. Avoid this by breaking ties through process IDs.

Logical clocks: example

Consider three processes with event counters operating at different rates

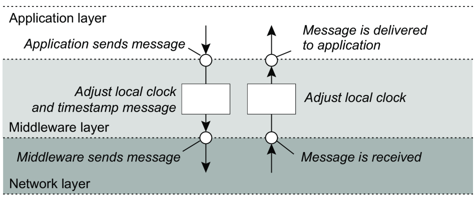


Coordination Logical clocks

Lamport's logical clocks 10 / 72

Logical clocks: where implemented

Adjustments implemented in middleware



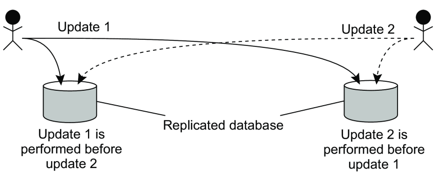
Coordination Logical clocks

Lamport's logical clocks 11 / 72

Example: Totally ordered multicast

Concurrent updates on a replicated database are seen in the same order everywhere

- P_1 adds \$100 to an account (initial value: \$1000)
- P_2 increments account by 1%
- There are two replicas



Result

In absence of proper synchronization:
replica #1 ← \$1111, while replica #2 ← \$1110.

Coordination Logical clocks

Lamport's logical clocks 12 / 72

Example: Totally ordered multicast

Solution

- Process P_i sends timestamped message m_i to all others. The message itself is put in a local queue $queue_i$.
- Any incoming message at P_j is queued in $queue_j$, according to its timestamp, and acknowledged to every other process.

P_j passes a message m_i to its application if:

(1) m_i is at the head of $queue_j$
(2) for each process P_k, there is a message m_k in $queue_j$ with a larger timestamp.

Note

We are assuming that communication is reliable and FIFO ordered.

Coordination Logical clocks

Lamport's logical clocks 13 / 72

Lamport's clocks for mutual exclusion

```python
class Process:
  def __init__(self, chanID, procID, procIDSet):
    self.chan.join(procID)
    self.procID      = int(procID)
    self.otherProcs.remove(self.procID)
    self.queue       = []                        # The request queue
    self.clock       = 0                         # The current logical clock

  def requestToEnter(self):
    self.clock = self.clock + 1                          # Increment clock value
    self.queue.append((self.clock, self.procID, ENTER)) # Append request to q
    self.cleanupQ()                                      # Sort the queue
    self.chan.sendTo(self.otherProcs, (self.clock, self.procID, ENTER)) # Send request

  def ackToEnter(self, requester):
    self.clock = self.clock + 1                          # Increment clock value
    self.chan.sendTo(requester, (self.clock, self.procID, ACK)) # Permit other

  def release(self):
    tmp = [r for r in self.queue[1:] if r[2] == ENTER]  # Remove all ACKs
    self.queue = tmp                                     # and copy to new queue
    self.clock = self.clock + 1                          # Increment clock value
    self.chan.sendTo(self.otherProcs, (self.clock, self.procID, RELEASE)) # Release

  def allowedToEnter(self):
    commProcs = set([req[1] for req in self.queue[1:]]) # See who has sent a message
    return (self.queue[0][1] == self.procID and len(self.otherProcs) == len(commProcs))
```


Coordination Logical clocks

Lamport's logical clocks 14 / 72

Lamport's clocks for mutual exclusion

```python
  def receive(self):
    msg = self.chan.recvFrom(self.otherProcs)[1]        # Pick up any message
    self.clock = max(self.clock, msg[0])                # Adjust clock value...
    self.clock = self.clock + 1                         # ...and increment
    if msg[2] == ENTER:
      self.queue.append(msg)                            # Append an ENTER request
      self.ackToEnter(msg[1])                           # and unconditionally allow
    elif msg[2] == ACK:
      self.queue.append(msg)                            # Append a received ACK
    elif msg[2] == RELEASE:
      del(self.queue[0])                                # Just remove first message
    self.cleanupQ()                                     # And sort and cleanup
```


Coordination Logical clocks

Lamport's logical clocks 15 / 72

Lamport's clocks for mutual exclusion

Analogy with totally ordered multicast

- With totally ordered multicast, all processes build identical queues, delivering messages in the same order
- Mutual exclusion is about agreeing in which order processes are allowed to enter a critical region

Coordination Logical clocks

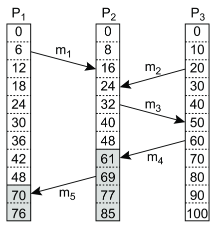
Lamport's logical clocks 16 / 72

Vector clocks

Observation

Lamport's clocks do not guarantee that if $C(a) < C(b)$ that *a* causally preceded *b*.

Concurrent message transmission using logical clocks



Observation

Event *a*: m_1 is received at $T = 16$;
Event *b*: m_2 is sent at $T = 20$.

Note

We cannot conclude that *a* causally precedes *b*.

Coordination Logical clocks

Vector clocks 17 / 72

Causal dependency

Definition

We say that *b* may causally depend on *a* if $ts(a) < ts(b)$, with:

- for all k, $ts(a)[k] \leq ts(b)[k]$ and
- there exists at least one index k' for which $ts(a)[k'] < ts(b)[k']$

Precedence vs. dependency

- We say that *a* causally precedes *b*.
- *b* may causally depend on *a*, as there may be information from *a* that is propagated into *b*.

Coordination Logical clocks

Vector clocks 18 / 72

Coordination Logical clocks

Capturing potential causality

Solution: each P_i maintains a vector VC_i

- $VC_i[i]$ is the local logical clock at process P_i.
- If $VC_i[j] = k$ then P_i knows that k events have occurred at P_j.

Maintaining vector clocks

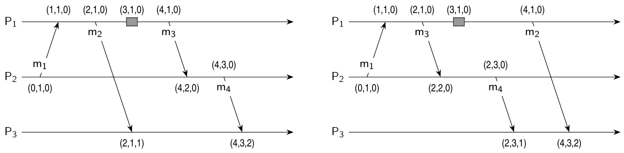
1. Before executing an event, P_i executes $VC_i[i] \leftarrow VC_i[i] + 1$.
2. When process P_i sends a message m to P_j, it sets m's (vector) timestamp $ts(m)$ equal to VC_i after having executed step 1.
3. Upon the receipt of a message m, process P_j sets $VC_j[k] \leftarrow \max\{VC_j[k], ts(m)[k]\}$ for each k, after which it executes step 1 and then delivers the message to the application.

Vector clocks 19 / 72

Coordination Logical clocks

Vector clocks: Example

Capturing potential causality when exchanging messages



(a) (b)

Analysis

Situation	$ts(m_2)$	$ts(m_4)$	$ts(m_2) < ts(m_4)$	$ts(m_2) > ts(m_4)$	Conclusion
(a)	$(2,1,0)$	$(4,3,0)$	Yes	No	m_2 may causally precede m_4
(b)	$(4,1,0)$	$(2,3,0)$	No	No	m_2 and m_4 may conflict

Vector clocks 20 / 72

Coordination Logical clocks

Causally ordered multicasting

Observation

We can now ensure that a message is delivered only if all causally preceding messages have already been delivered.

Adjustment

P_i increments $VC_i[i]$ only when sending a message, and P_j “adjusts” VC_j when receiving a message (i.e., effectively does not change $VC_j[j]$).

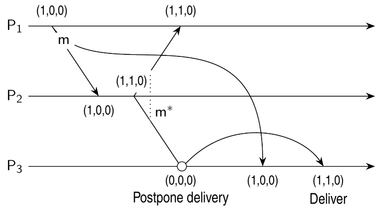
P_j postpones delivery of m until:

1. $ts(m)[i] = VC_j[i] + 1$
2. $ts(m)[k] \leq VC_j[k]$ for all $k \neq i$

Vector clocks 21 / 72

Causally ordered multicasting

Enforcing causal communication



Example

Take $VC_3 = [0,2,2]$, $ts(m) = [1,3,0]$ from P_1. What information does P_3 have, and what will it do when receiving m (from P_1)?

Mutual exclusion

Problem

Several processes in a distributed system want exclusive access to some resource.

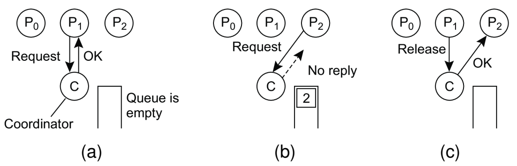
Basic solutions

Permission-based: A process wanting to enter its critical region, or access a resource, needs permission from other processes.

Token-based: A token is passed between processes. The one who has the token may proceed in its critical region, or pass it on when not interested.

Permission-based, centralized

Simply use a coordinator



(a) Process P_1 asks the coordinator for permission to access a shared resource. Permission is granted.

(b) Process P_2 then asks permission to access the same resource. The coordinator does not reply.

(c) When P_1 releases the resource, it tells the coordinator, which then replies to P_2.

Coordination Mutual exclusion

Mutual exclusion: Ricart & Agrawala

The same as Lamport except that acknowledgments are not sent

Return a response to a request only when:

- The receiving process has no interest in the shared resource; or
- The receiving process is waiting for the resource, but has lower priority (known through comparison of timestamps).

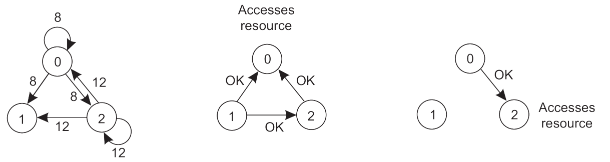
In all other cases, reply is deferred, implying some more local administration.

A distributed algorithm 25 / 72

Coordination Mutual exclusion

Mutual exclusion: Ricart & Agrawala

Example with three processes



(a) (b) (c)

(a) Two processes want to access a shared resource at the same moment.
(b) P_0 has the lowest timestamp, so it wins.
(c) When process P_0 is done, it sends an *OK* also, so P_2 can now go ahead.

A distributed algorithm 26 / 72

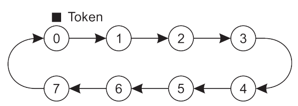
Coordination Mutual exclusion

Mutual exclusion: Token ring algorithm

Essence

Organize processes in a logical ring, and let a token be passed between them. The one that holds the token is allowed to enter the critical region (if it wants to).

An overlay network constructed as a logical ring with a circulating token



A token-ring algorithm 27 / 72

Decentralized mutual exclusion

Principle

Assume every resource is replicated N times, with each replica having its own coordinator $\Rightarrow$ access requires a majority vote from $m > N/2$ coordinators. A coordinator always responds immediately to a request.

Assumption

When a coordinator crashes, it will recover quickly, but will have forgotten about permissions it had granted.

Decentralized mutual exclusion

How robust is this system?

- Let $p = \Delta t / T$ be the probability that a coordinator resets during a time interval Δt, while having a lifetime of T.
- The probability $\mathbb{P}[k]$ that k out of m coordinators reset during the same interval is
$$\mathbb{P}[k] = \binom{m}{k} p^k (1-p)^{m-k}$$
- f coordinators reset $\Rightarrow$ correctness is violated when there is only a minority of nonfaulty coordinators: when $N - (m - f) \geq m$, or, $f \geq 2m - N$.
- The probability of a violation is $\sum_{k=2m-N}^{m} \mathbb{P}[k]$.

Decentralized mutual exclusion

Violation probabilities for various parameter values

N	m	p	Violation	N	m	p	Violation
8	5	3 sec/hour	$< 10^{-5}$	8	5	30 sec/hour	$< 10^{-3}$
8	6	3 sec/hour	$< 10^{-11}$	8	6	30 sec/hour	$< 10^{-7}$
16	9	3 sec/hour	$< 10^{-4}$	16	9	30 sec/hour	$< 10^{-2}$
16	12	3 sec/hour	$< 10^{-21}$	16	12	30 sec/hour	$< 10^{-13}$
32	17	3 sec/hour	$< 10^{-4}$	32	17	30 sec/hour	$< 10^{-2}$
32	24	3 sec/hour	$< 10^{-43}$	32	24	30 sec/hour	$< 10^{-27}$

So....

What can we conclude?

Mutual exclusion: comparison

Algorithm	Messages per entry/exit	Delay before entry (in message times)
Centralized	3	2
Distributed	$2(N-1)$	$2(N-1)$
Token ring	$1,\ldots,\infty$	$0,\ldots,N-1$
Decentralized	$2kN+(k-1)N/2+N, k=1,2,\ldots$	$2kN+(k-1)N/2$

Example: ZooKeeper

Basics (and keeping it simple)

- Centralized server setup
- All client-server communication is nonblocking: a client immediately gets a response
- ZooKeeper maintains a tree-based namespace, akin to that of a filesystem
- Clients can create, delete, or update nodes, as well as check existence.

ZooKeeper race condition

Note

ZooKeeper allows a client to be notified when a node, or a branch in the tree, changes. This may easily lead to race conditions.

Consider a simple locking mechanism

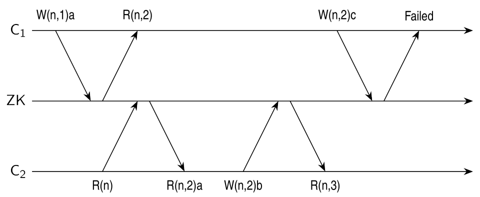
1. A client C_1 creates a node */lock*.
2. A client C_2 wants to acquire the lock but is notified that the associated node already exists.
3. Before C_2 subscribes to a notification, C_1 releases the lock, i.e., deletes */lock*.
4. Client C_2 subscribes to changes to */lock* and blocks locally.

Solution

Use version numbers

Coordination Mutual exclusion

ZooKeeper versioning



Notations

- $W(n,k)a$: request to write a to node n, assuming current version is k.
- $R(n,k)$: current version of node n is k.
- $R(n)$: client wants to know the current value of node n
- $R(n,k)a$: value a from node n is returned with its current version k.

Example: Simple locking with ZooKeeper 34 / 72

Coordination Mutual exclusion

ZooKeeper locking protocol

It is now very simple

1. lock: A client C_1 creates a node $/lock$.
2. lock: A client C_2 wants to acquire the lock but is notified that the associated node already exists $\Rightarrow$ C_2 subscribes to notification on changes of $/lock$.
3. unlock: Client C_1 deletes node $/lock$ $\Rightarrow$ all subscribers to changes are notified.

Example: Simple locking with ZooKeeper 35 / 72

Coordination Election algorithms

Election algorithms

Principle

An algorithm requires that some process acts as a coordinator. The question is how to select this special process dynamically.

Note

In many systems, the coordinator is chosen manually (e.g., file servers). This leads to centralized solutions $\Rightarrow$ single point of failure.

Teasers

1. If a coordinator is chosen dynamically, to what extent can we speak about a centralized or distributed solution?
2. Is a fully distributed solution, i.e. one without a coordinator, always more robust than any centralized/coordinated solution?

36 / 72

Coordination Election algorithms

Basic assumptions

- All processes have unique id's
- All processes know id's of all processes in the system (but not if they are up or down)
- Election means identifying the process with the highest id that is up

37 / 72

Coordination Election algorithms

Election by bullying

Principle

Consider N processes $\{P_0, \ldots, P_{N-1}\}$ and let $id(P_k) = k$. When a process P_k notices that the coordinator is no longer responding to requests, it initiates an election:

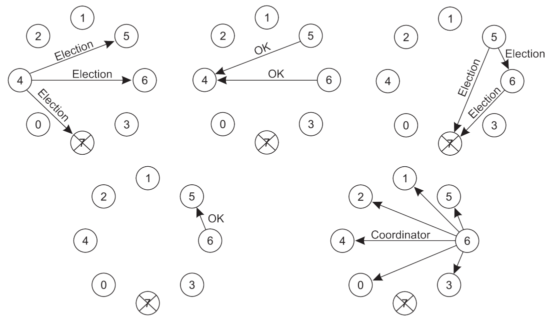
1. P_k sends an *ELECTION* message to all processes with higher identifiers: $P_{k+1}, P_{k+2}, \ldots, P_{N-1}$.
2. If no one responds, P_k wins the election and becomes coordinator.
3. If one of the higher-ups answers, it takes over and P_k's job is done.

The bully algorithm 38 / 72

Coordination Election algorithms

Election by bullying

The bully election algorithm



The bully algorithm 39 / 72

Election in a ring

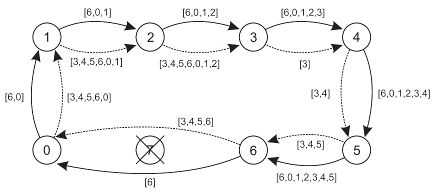
Principle

Process priority is obtained by organizing processes into a (logical) ring. The process with the highest priority should be elected as coordinator.

- Any process can start an election by sending an election message to its successor. If a successor is down, the message is passed on to the next successor.
- If a message is passed on, the sender adds itself to the list. When it gets back to the initiator, everyone had a chance to make its presence known.
- The initiator sends a coordinator message around the ring containing a list of all living processes. The one with the highest priority is elected as coordinator.

Election in a ring

Election algorithm using a ring



- The solid line shows the election messages initiated by P_6
- The dashed one, the messages by P_3

Example: Leader election in ZooKeeper server group

Basics

- Each server s in the server group has an identifier $id(s)$
- Each server has a monotonically increasing counter $tx(s)$ of the latest transaction it handled (i.e., series of operations on the namespace).
- When follower s suspects leader crashed, it broadcasts an *ELECTION* message, along with the pair ($voteID$,$voteTX$). Initially,
  - $voteID \leftarrow id(s)$
  - $voteTX \leftarrow tx(s)$
- Each server s maintains two variables:
  - $leader(s)$: records the server that s believes may be final leader. Initially, $leader(s) \leftarrow id(s)$.
  - $lastTX(s)$: what s knows to be the most recent transaction. Initially, $lastTX(s) \leftarrow tx(s)$.

Example: Leader election in ZooKeeper server group

When s^* receives $(voteID, voteTX)$

- If $lastTX(s^*) < voteTX$, then s^* just received more up-to-date information on the most recent transaction, and sets
  - $leader(s^*) \leftarrow voteID$
  - $lastTX(s^*) \leftarrow voteTX$
- If $lastTX(s^*) = voteTX$ *and* $leader(s^*) < voteID$, then s^* knows as much about the most recent transaction as what it was just sent, but its perspective on which server will be the next leader needs to be updated:
  - $leader(s^*) \leftarrow voteID$

Note

When s^* believes it should be the leader, it broadcasts $\langle id(s^*), tx(s^*) \rangle$. Essentially, we're bullying.

Coordination Election algorithms

Example: Leader election in ZooKeeper 43 / 72

Example: Leader election in Raft

Basics

- We have a (relatively small) group of servers
- A server is in one of three states: *follower*, *candidate*, or *leader*
- The protocol works in terms, starting with term 0
- Each server starts in the *follower* state.
- A leader is to regularly broadcast messages (perhaps just a simple heartbeat)

Coordination Election algorithms

Example: Leader election in Raft 44 / 72

Example: Leader election in Raft

Selecting a new leader

When follower s^* hasn't received anything from the alleged leader s for some time, s^* broadcasts that it volunteers to be the next leader, increasing the term by 1. s^* enters the candidate state. Then:

- If leader s receives the message, it responds by acknowledging that it is still the leader. s^* returns to the follower state.
- If another follower s^{**} gets the election message from s^*, and it is the first election message during the current term, s^{**} votes for s^*. Otherwise, it simply ignores the election message from s^*. When s^* has collected a majority of votes, a new term starts with a new leader.

Observation

By slightly differing the timeout values per follower for deciding when to start an election, we can avoid concurrent elections, and the election will rapidly converge.

Coordination Election algorithms

Example: Leader election in Raft 45 / 72

Elections by proof of work

Basics

- Consider a potentially large group of processes
- Each process is required to solve a computational puzzle
- When a process solves the puzzle, it broadcasts its victory to the group
- We assume there is a conflict resolution procedure when more than one process claims victory

Solving a computational puzzle

- Make use of a secure hashing function $H(m)$:
  - m is some data; $H(m)$ returns a fixed-length bit string
  - computing $h = H(m)$ is computationally efficient
  - finding a function H^{-1} such that $m = H^{-1}(H(m))$ is computationally extremely difficult
- Practice: finding H^{-1} boils down to an extensive trial-and-error procedure

Elections by proof of work

Controlled race

- Assume a globally known secure hash function H^*. Let H_i be the hash function used by process P_i.
- Task: given a bit string $h = H_i(m)$, find a bit string $\tilde{h}$ such that $h^* = H^*(H_i(\tilde{h} \odot h))$ where:
  - h^* is a bit string with K leading zeroes
  - $\tilde{h} \odot h$ denotes some predetermined bitwise operation on $\tilde{h}$ and h

Observation

By controlling K, we control the difficulty of finding $\tilde{h}$. If p is the probability that a random guess for $\tilde{h}$ will suffice: $p = (1/2)^K$.

Current practice

In many PoW-based blockchain systems, $K = 64$

- With $K = 64$, it takes about 10 minutes on a supercomputer to find $\tilde{h}$
- With $K = 64$, it takes about 100 years on a laptop to find $\tilde{h}$

Elections by proof of stake

Basics

We assume a blockchain system in which N secure tokens are used:

- Each token has a unique owner
- Each token has a uniquely associated index $1 \leq k \leq N$
- A token cannot be modified or copied without this going unnoticed

Principle

- Draw a random number $k \in \{1, \ldots, N\}$
- Look up the process P that owns the token with index k. P is the next leader.

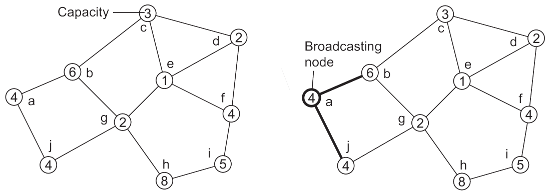
Observation

The more tokens a process owns, the higher the probability it will be selected as leader.

Coordination Election algorithms

A solution for wireless networks

A sample network



Essence

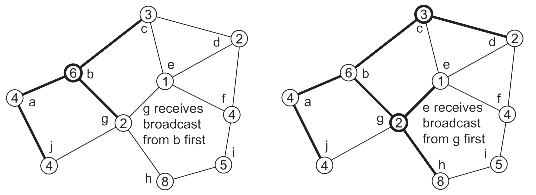
Find the node with the highest capacity to select as the next leader.

Elections in wireless environments 49 / 72

Coordination Election algorithms

A solution for wireless networks

A sample network

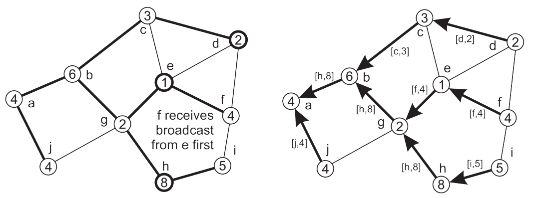


Elections in wireless environments 50 / 72

Coordination Election algorithms

A solution for wireless networks

A sample network



Essence

A node reports back only the node that it found to have the highest capacity.

Elections in wireless environments 51 / 72

Coordination Gossip-based coordination

Gossip-based coordination: aggregation

Typical apps

- Data dissemination: Perhaps the most important one. Note that there are many variants of dissemination.
- Aggregation: Let every node P_i maintain a variable v_i. When two nodes gossip, they each reset their variable to

$$v_i, v_j \leftarrow (v_i + v_j)/2$$

  Result: in the end each node will have computed the average $\bar{v} = \sum_i v_i / N$.
- What happens in the case that initially $v_i = 1$ and $v_j = 0, j \neq i$?

Aggregation 52 / 72

Coordination Gossip-based coordination

Gossip-based coordination: peer sampling

Problem
For many gossip-based applications, you need to select a peer uniformly at random from the entire network. In principle, this means you need to know all other peers. Impossible?

Basics

- Each node maintains a list of c references to other nodes
- Regularly, pick another node at random (from the list), and exchange roughly $c/2$ references
- When the application needs to select a node at random, it also picks a random one from from its local list.

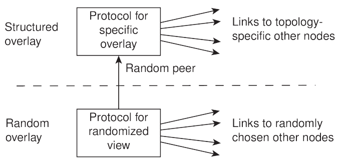
Observation
Statistically, it turns out that the selection of a peer from the local list is indistinguishable from selecting uniformly at random peer from the entire network

A peer-sampling service 53 / 72

Coordination Gossip-based coordination

Gossip-based overlay construction

Essence
Maintain two local lists of neighbors. The lowest is used for providing a peer-sampling service; the highest list is used to carefully select application-dependent neighbors.



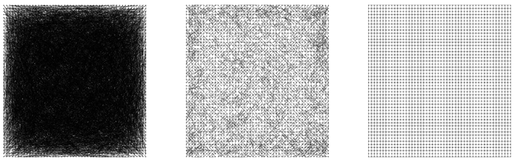
Gossip-based overlay construction 54 / 72

Coordination Gossip-based coordination

Gossip-based overlay construction: a 2D torus

Consider a logical $N \times N$ grid, with a node on each point of the grid.

- Every node must maintain a list of c nearest neighbors
- Distance between node at (a_1, a_2) and (b_1, b_2) is $d_1 + d_2$, with $d_i = \min(N - |a_i - b_i|, |a_i - b_i|)$
- Every node picks a random other node from its lowest-level list, and keeps only the closest one in its top-level list.
- Once every node has picked and selected a random node, we move to the next round



start ($N = 50$) after 5 rounds after 20 rounds

Gossip-based overlay construction 55 / 72

Coordination Gossip-based coordination

A gossip-based 2D torus in Python (outline)

```
def maintainViews():
  for viewType in [viewOverlay, viewPSS]: # For each view, do the same
    peer[viewType] = None
    if time to maintain viewType: # This viewType needs to be updated
      peer[viewType] = selectPeer(viewType)           # Select a peer
      links = selectLinks(viewType, peer[viewType])   # Select links
      sendTo(peer[viewType], Request[viewType], links) # Send links asynchronously

  while True:
    block = (peer[viewOverlay] != None) or (peer[viewPSS] != None)
    sender, msgType, msgData = recvFromAny(block) # Block if expecting something

    if msg == None: # All work has been done, simply return from the call
      return

    for viewType in [viewOverlay, viewPSS]: # For each view, do the same
      if msgType == Response[viewType]:  # Response to previously sent links
        updateOwnView(viewType, msgData) # Just update the own view

      elif msgType == Request[viewType]: # Request for exchanging links
        if peer[viewType] == None:       # No outstanding exchange request
          links = selectLinks(viewType, sender)      # Select links
          sendTo(sender, Response[viewType], links) # Send them asynchronously
          updateOwnView(viewType,msgData)            # Update own view
        else: # This node already has a pending exchange request, ignore this one
          sendTo(sender, IgnoreRequest[viewType])

      elif msgType == IgnoreRequest[viewType]: # Request has been denied, give up
        peer[viewType] = None
```

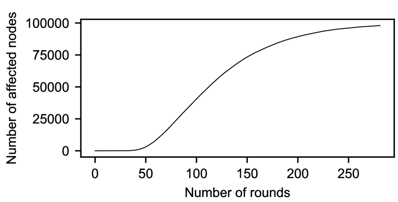

Gossip-based overlay construction 56 / 72

Coordination Gossip-based coordination

Secure gossiping

Dramatic attack

Consider when exchanging references, a set of colluding nodes systematically returns links only to each other ⇒ we are dealing with hub attack.



Situation

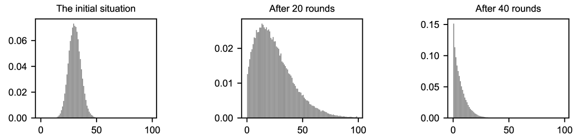
A network with 100,000 nodes, a local list size $c = 30$, and only 30 attackers. The y-axis shows the number of nodes with links only to the attackers. After less than 300 rounds, the attackers have full control.

Secure gossiping 57 / 72

Coordination Gossip-based coordination

A solution: gathering statistics

This is what measuring indegree distributions tells us: which fraction of nodes (y-axis) have how many other nodes pointing to them (x-axis)?



Basic approach

When a benign node initiates an exchange, it may either use the result for gathering statistics, or for updating its local list. An attacker is in limbo: will its response be used for statistical purposes or for functional purposes?

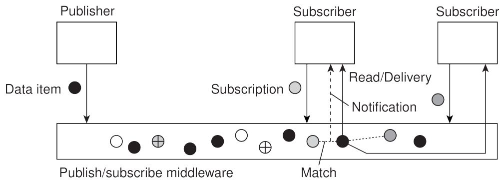
Observation

When gathering statistics may reveal colluders, a colluding node will be forced to behave according to the protocol.

Secure gossiping 58 / 72

Coordination Distributed event matching

Distributed event matching



Principle

- A process specifies in which events it is interested (subscription *S*)
- When a process publishes a notification *N* we need to see whether *S* matches *N*.

Hard part

Implementing the match function in a scalable manner.

59 / 72

Coordination Distributed event matching

General approach

What is needed

- *sub2node*(S): map a subscription S to a nonempty subset **S** of servers
- *not2node*(N): map a notification N to a nonempty subset **N** of servers

Make sure that $\mathbf{S} \cap \mathbf{N} \neq \emptyset$.

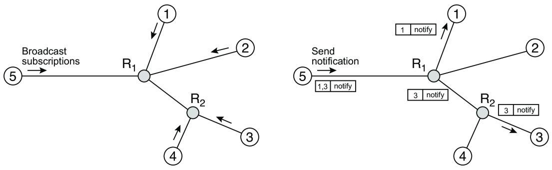
Observations

- Centralized solution is simple: $\mathbf{S} = \mathbf{N} = \{s\}$, i.e. a single server.
- Topic-based publish-subscribe is also simple: each S and N is tagged with a single topic; each topic is handled by a single server (a rendezevous node). Several topics may be handled by same server).
- Content-based publish-subscribe is tough: a subscription takes the form (*attribute*, *value*) pair, with example values:
  - range: "$1 \leq x < 10$"
  - containment: "$x \in \{red, blue\}$"
  - prefix and suffix expressions: "`url.startswith("https")`"

Centralized implementations 60 / 72

Coordination Distributed event matching

Selective routing



(a) (b)

(a) first broadcast subscriptions
(b) forward notifications only to relevant rendezvous nodes

Example of a (partially filled) routing table

Interface	**Filter**
To node 3	$a \in [0,3]$
To node 4	$a \in [2,5]$
Toward router R_1	(unspecified)

Centralized implementations 61 / 72

Coordination Distributed event matching

Gossiping: Sub-2-Sub

Basics

- Goal: To realize scalability, make sure that subscribers with the same interests form just a single group
- Model: There are N attributes $a_1,\ldots,a_N$. An attribute value is always (mappable to) a floating-point number.
- Subscription: Takes forms such as $S = \langle a_1 \rightarrow 3.0, a_4 \rightarrow [0.0,\ 0.5)\rangle$: a_1 should be 3.0; a_4 should lie between 0.0 and 0.5; other attribute values don't matter.

Observations

- A subscription S_i specifies a subset $\mathbf{S_i}$ in a N-dimensional space.
- We are interested only in notifications that fall into $\overline{\mathbf{S}} = \cup \mathbf{S_i}$.

Goal

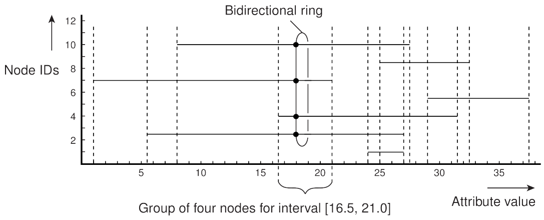
Partition $\overline{\mathbf{S}}$ into M disjoint subspaces $\overline{\mathbf{S}}_1,\ldots,\overline{\mathbf{S}}_M$ such that

- Partitioning: $\forall k \neq m : \overline{\mathbf{S}}_k \cap \overline{\mathbf{S}}_m = \emptyset$ and $\cup_m \overline{\mathbf{S}}_m = \overline{\mathbf{S}}$
- Subscription coverage: $(\overline{\mathbf{S}}_m \cap \mathbf{S_i} \neq \emptyset) \Rightarrow (\overline{\mathbf{S}}_m \subseteq \mathbf{S_i})$

Centralized implementations 62 / 72

Coordination Distributed event matching

Gossiping: Sub-2-Sub



Consider a single attribute

- Nodes regularly exchange their subscriptions through gossiping
- An intersection between two nodes leads to a mutual reference
- If $\mathbf{S_{ijk}} = \mathbf{S_i} \cap \mathbf{S_j} \cap \mathbf{S_k} \neq \emptyset$ and $\mathbf{S_{ij}} - \mathbf{S_{ijk}} \neq \emptyset$, then:
  - nodes i, j, k are grouped into a single overlay network (for $\mathbf{S_{ijk}}$)
  - nodes i, j are grouped into a single overlay network (for $\mathbf{S_{ij}} - \mathbf{S_{ijk}}$)

Centralized implementations 63 / 72

Coordination Distributed event matching

Secure publish-subscribe

We are facing nasty dilemma's

- Referential decoupling: messages should be able to flow from a publisher to subscribers while guaranteeing mutual anonymity ⇒ we cannot set up a secure channel.
- Not knowing where messages come from imposes integrity problems.
- Assuming a trusted broker may easily be practically impossible, certainly when dealing with sensitive information ⇒ we now have a routing problem.

Solution

- Allow for searching (and matching) on encrypted data, without the need for decryption.
- PEKS: accompany encryptyed messages with a collection of (again encrypted) keywords and search for matches on keywords.

Secure publish-subscribe solutions 64 / 72

Coordination Distributed event matching

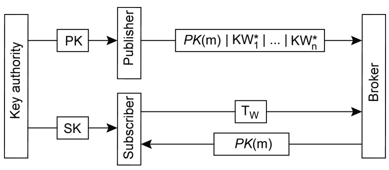
Public-Key Encryption with Keyword Search (PEKS)

Basics

- Use a public key PK, message m and its n keywords $KW_1, \ldots, KW_n$ are stored at a server as the message m^*:

$$m^* = [PK(m)|PEKS(PK, KW_1)|PEKS(PK, KW_2)|\cdots|PEKS(PK, KW_n)]$$

- A subscriber gets the accompanying secret key.
- For each keyword KW_i, a trapdoor T_{KW_i} is generated: $T_W(m^*)$ will return *true* iff $W \in \{KW_1, \ldots, KW_n\}$.



$KW_i^* = PEKS(PK, KW_i)$

Secure publish-subscribe solutions 65 / 72

Coordination Location systems

Positioning nodes

Issue

In large-scale distributed systems in which nodes are dispersed across a wide-area network, we often need to take some notion of proximity or distance into account ⇒ it starts with determining a (relative) location of a node.

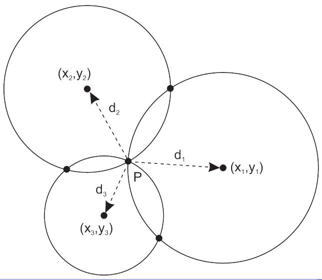
66 / 72

Computing position

Observation

A node P needs $d+1$ landmarks to compute its own position in a d-dimensional space. Consider two-dimensional case.

Computing a position in 2D



Solution

P needs to solve three equations in two unknowns (x_P,y_P):

$$d_i = \sqrt{(x_i - x_P)^2 + (y_i - y_P)^2}$$

Coordination Location systems

GPS: Global Positioning System 67 / 72

Global Positioning System

Assuming that the clocks of the satellites are accurate and synchronized

- It takes a while before a signal reaches the receiver
- The receiver's clock is definitely out of sync with the satellite

Basics

- Δ_r: unknown deviation of the receiver's clock.
- x_r, y_r, z_r: unknown coordinates of the receiver.
- T_i: timestamp on a message from satellite i
- $\Delta_i = (T_{now} - T_i) + \Delta_r$: measured delay of the message sent by satellite i.
- Measured distance to satellite i: $c \times \Delta_i$ (c is speed of light)
- Real distance: $d_i = c\Delta_i - c\Delta_r = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2}$

Observation

4 satellites $\Rightarrow$ 4 equations in 4 unknowns (with Δ_r as one of them)

Coordination Location systems

GPS: Global Positioning System 68 / 72

WiFi-based location services

Basic idea

- Assume we have a database of known access points (APs) with coordinates
- Assume we can estimate distance to an AP
- Then: with 3 detected access points, we can compute a position.

War driving: locating access points

- Use a WiFi-enabled device along with a GPS receiver, and move through an area while recording observed access points.
- Compute the centroid: assume an access point AP has been detected at N different locations $\{\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N\}$, with known GPS location.
- Compute location of AP as $\vec{x}_{AP} = \frac{\sum_{i=1}^{N} \vec{x}_i}{N}$.

Problems

- Limited accuracy of each GPS detection point $\vec{x}_i$
- An access point has a nonuniform transmission range
- Number of sampled detection points N may be too low

Coordination Location systems

When GPS is not an option 69 / 72

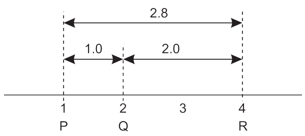
Coordination Location systems

Computing position

Problems

- Measured latencies to landmarks fluctuate
- Computed distances will not even be consistent

Inconsistent distances in 1D space



Solution: minimize errors

- Use N special landmark nodes $L_1, \ldots, L_N$.
- Landmarks measure their pairwise latencies $\tilde{d}(L_i, L_j)$
- A central node computes the coordinates for each landmark, minimizing:

$$\sum_{i=1}^{N} \sum_{j=i+1}^{N} \left(\frac{\tilde{d}(L_i, L_j) - \hat{d}(L_i, L_j)}{\tilde{d}(L_i, L_j)} \right)^2$$

where $\hat{d}(L_i, L_j)$ is distance after nodes L_i and L_j have been positioned.

Logical positioning of nodes 70 / 72

Coordination Location systems

Computing position

Choosing the dimension m

The hidden parameter is the dimension m with $N > m$. A node P measures its distance to each of the N landmarks and computes its coordinates by minimizing

$$\sum_{i=1}^{N} \left(\frac{\tilde{d}(L_i, P) - \hat{d}(L_i, P)}{\tilde{d}(L_i, P)} \right)^2$$

Observation

Practice shows that m can be as small as 6 or 7 to achieve latency estimations within a factor 2 of the actual value.

Logical positioning of nodes 71 / 72

Coordination Location systems

Vivaldi

Principle: network of springs exerting forces

Consider a collection of N nodes $P_1, \ldots, P_N$, each P_i having coordinates $\vec{x}_i$. Two nodes exert a mutual force:

$$\vec{F}_{ij} = \left(\tilde{d}(P_i, P_j) - \hat{d}(P_i, P_j)\right) \times u(\vec{x}_i - \vec{x}_j)$$

with $u(\vec{x}_i - \vec{x}_j)$ is the unit vector in the direction of $\vec{x}_i - \vec{x}_j$

Node P_i repeatedly executes steps

1. Measure the latency $\tilde{d}_{ij}$ to node P_j, and also receive P_j's coordinates $\vec{x}_j$.
2. Compute the error $e = \tilde{d}(P_i, P_j) - \hat{d}(P_i, P_j)$
3. Compute the direction $\vec{u} = u(\vec{x}_i - \vec{x}_j)$.
4. Compute the force vector $F_{ij} = e \cdot \vec{u}$
5. Adjust own position by moving along the force vector: $\vec{x}_i \leftarrow \vec{x}_i + \delta \cdot \vec{u}$.

Logical positioning of nodes 72 / 72