Synchronisation in Distributed Systems

Distributed Systems
Sistemi Distribuiti

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Outline

1. Interaction, Communication, and Time
2. Physical Time
3. Logical Time
4. Toward Coordination
Disclaimer

These Slides Contain Material from [TvS07]

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Slides were made kindly available by the authors of the book

- Such slides shortly introduced the topics developed in the book [TvS07] adopted here as the main book of the course.
- Some of the material from those slides has been re-used in the following, and integrated with new material according to the personal view of the teacher of this course.
- Every problem or mistake contained in these slides, however, should be attributed to the sole responsibility of the teacher of this course.
Outline

1. Interaction, Communication, and Time
2. Physical Time
3. Logical Time
4. Toward Coordination
Communication is just half of the story

- Interaction is a more general issue
- Governing (inter)action is a fundamental issue in (distributed) systems
- Doing the right thing at the right time is essential
- “At the right time” is the critical problem
Time in Distributed System

Synchronisation

- Is there a notion of time in a distributed system?
- Is there a notion of *global* time in a distributed system?
- If not, what can we do about this?
- How can we *synchronise* activities within a distributed system?
Outline

1. Interaction, Communication, and Time
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The Issue of Time

Time in distributed systems

- In centralised systems, time is unambiguous.
- In a distributed system, there is not a *natural* notion of time.
- Is it *possible* to build up a global notion of time in any distributed system?
- Is it *useful* to build up a global notion of time in any distributed system?
Timers

- A *clock* in a computer is actually a *timer* – typically, an oscillating quartz with a *counter* and a *holding register*
- When the counter gets to zero, an interrupt is generated, and the counter is reloaded from the holding register
- Each interrupt is a *clock tick*
Multiple CPUs

- No way to ensure two different crystals oscillate exactly at the same frequency
- Different clocks gradually get out of synch – clock skew is the difference in time
- Need for synchronising algorithms!
- Two approaches
  - global absolute time
  - global relative time
Global Absolute Time I

Absolute time

- Absolute time is handled by BIH (Bureau International de l’Heure) in Paris
- Expressed in terms of Universal Coordinated Time (UTC)
- Broadcasted as a short radio pulse (WWV) by NIST (National Institute of Standard Time) every UTC second, and by satellites providing UTC service
- If one machine in the system has access to an UTC service, an algorithm can be used that synchronises all machines based on this
Global Absolute Time II

Example: NTP

- Network Time Protocol (NTP)
- A time server has the global absolute time, and other machines have to synchronise
- Notice: clocks can only run forward – corrections cannot bring clocks backward
Relative time

- Sometimes, the only thing needed is that there is a shared time, regardless of absolute time.
- So, algorithms based on active servers polling other servers to find out the average time, and the required estimated corrections as well.
- No machine is required to have UTC time.

Examples

- The Berkeley Algorithm: time daemons in all machines poll and respond to each other, and agree on a common time.
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Physical time not always needed

- Till now, we have implicitly assumed that synchronisation is related to physical time
- However, we have also seen the case where the only need is a shared notion of time (a shared clock) among the processes of a distributed system, with no need for it to be exactly the “real” time
- As a step further, we may observe that often the only need for a distributed system is a shared clock, even unrelated to real time
- A notion of logical time is both possible and useful
Logical Clocks [Lam78]

Synchronisation is possible with no need to be absolute

- If two processes do not interact, there is no need of synchronisation—lack of synchronisation would not be observable
- Often, what really matters is not the exact time when events occur, but the *order* in which events occur
- Example: UNIX `make`

Logical clocks

- Synchronisation of non-physical, *logical clocks* is then both admissible and useful
Notation

Relation: $a \rightarrow b$ reads “$a$ happens before $b$”, and means that all processes agree that $a$ occurs first, then $b$ occurs.

- $a \rightarrow b$ can be directly observed in two situations:
  1. if $a$ and $b$ are events of the same process, and $a$ comes before $b$, then $a \rightarrow b$ — local events are ordered by local time.
  2. if a message is sent by process with an event $a$, and received by another process with an event $b$, then $a \rightarrow b$ — a message takes a finite, positive, non-zero amount of time to propagate from sender to receiver.

- $a \rightarrow b$ is a transitive relation: $a \rightarrow b$, $b \rightarrow c$ imply $a \rightarrow c$.

- $happens$-$before$ defines a partial ordering over the events in a distributed system: when neither $a \rightarrow b$ nor $b \rightarrow a$ can be observed, then nothing can be said on their ordering — $a$ and $b$ are said to be concurrent.
Measuring time with logical clocks:

- A shared notion of time for an event \( a \): time value \( C(a) \) is such that every process agrees upon it.
- Time value should be thought as the value of a logical clock upon which processes agree.
- Time values are such that \( a \rightarrow b \) implies \( C(a) < C(b) \) — that is, time values should be assigned so that \( C(a) < C(b) \).
  - If \( a \) and \( b \) are events of the same process, and \( a \) comes before \( b \), then \( C(a) < C(b) \).
  - If a message is sent by process with an event \( a \), and received by another process with an event \( b \), then \( C(a) < C(b) \).
- Since neither physical nor logical clocks can run backward, any correction to clock time should go forward (increasing), never backward (decreasing).
Lamport’s Algorithm I

Concurrent message transmission using logical clocks

[TvS07]
Lamport’s Algorithm II

Lamport’s algorithm corrects the clocks

[TvS07]
Lamport’s Algorithm III

Middleware support for Lamport’s logical clocks

[TvS07]
Lamport’s Algorithm IV

Implementation of Lamport’s logical clocks

- Each process $P_i$ maintains a *local* counter $C_i$.
- Local counters are updated following three steps:
  1. before executing an event, $P_i$ executes $C_i \leftarrow C_i + 1$
  2. when sending a message $m$ to $P_j$, process $P_i$ sets $m$’s timestamp $ts(m)$ to $C_i$ after updating its counter (see step above)
  3. upon reception of a message $m$, process $P_j$ adjusts its local counter such that $C_j \leftarrow \max(C_j, ts(m))$, then goes back to step (1) and delivers the message to the application.

! Sometimes, it is required that no two events occur exactly at the same time – process label can be added as a decimal number to the timestamp.
Lamport’s Algorithm V

Distributed implementation of global time

- $C_i$ is local time at process $P_i$
- $a$ is an event in a distributed system
- $\forall a \in P_i, C \leftarrow C_i(a)$

$\rightarrow$ $C$ is the \textit{global time} for the distributed system
Totally-ordered multicast

- A replicate database exists of the accounts of a bank in LA and NY
- A customer adds $100 to his account, while at the same time a bank employee applies a 1% increment to the account
- Given that the original account contained $1000, it may easily happens that, say, the LA replica records $1110, the NY one $1111
  → Inconsistency due to concurrent updates over a distributed replicated database
An Example II

Inconsistency in a replicated database after two concurrent updates [TvS07]
The Solution: Totally-ordered Multicast I

Assumptions

- A group of processes multicasting each other
- Each msg is timestamped by the sender with its local logical time
- Also the sender conceptually receives the multicasted msg
- Messages from the same sender are received in the same order they are sent, and no message is lost
The Solution: Totally-ordered Multicast II

Algorithm

- Each process maintains a local queue of all messages received, ordered according to its timestamp
- Every message received is acknowledged with a multicasted message, timestamped according to Lamport’s algorithm
  - Timestamp of a received message is lower than the timestamp of the acks
  - Every process has essentially the same queue
- Only when all acknowledgements have been received, the middleware can deliver a queued message to the application
- Since all queues are equal, all messages are delivered to the application level at the same time on all the machines in the distributed system
The Solution: Totally-ordered Multicast III

Result

- A totally-ordered multicasting is perceived at the application level — as provided by the middleware layer.
- In the example above, either the client or the employee command is issued first on all replicas.
  - All replicas will be consistently updated.
  - No idea, however, on whether the final record will be $1110$ or $1111$...
The problem

- In essence, $a \rightarrow b$ implies $C(a) < C(b)$, whereas $C(a) < C(b)$ does not imply $a \rightarrow b$
  - so that, for instance, time values could be totally ordered when events are not
  - when events are unrelated, comparison of time values is meaningless
- Lamport’s logical clocks say nothing about that
- Something more is needed
- To say in particular whether $a$ and $b$ are (un)related
Vector Clocks II

Concurrent message transmission using logical clocks

[TvS07]
Vector Clocks III

Causality

- $m_1$ is received before $m_2$ is sent, according to Lamport’s clock: can we conclude anything about $m_1$ and $m_2$?
- In general, the problem is that Lamport’s clocks do not capture causality
- Vector clocks capture causality
Logical Time

Vector Clocks IV

**Definition**

- A vector clock $VC(a)$ assigned to an event $a$ is such that
  $\exists b, VC(a) < VC(b) \rightarrow a$ causally precedes $b$

- Each process $P_i$ maintains a vector $VC_i$ such that
  - $VC_i[i]$ is the number of events occurred so far at $P_i$ — basically, the logical clock of $P_i$
  - Every new event occurring in $P_i$ increments $VC_i[i]$
  - $VC_i[j] = k$ means that $P_i$ knows that $k$ events have occurred at $P_j$ — basically, the logical clock of $P_j$ according to $P_i$’s best knowledge
  - Every message from $P_i$ is timestamped with vector $VC_i$
Logical Time

Vector Clocks V

Algorithm

- Before any event is executed at $P_i$, $VC_i[i] \leftarrow VC_i[i] + 1$
- A message $m$ from $P_i$ to $P_j$ timestamped with vector $VC$ — $ts(m) = VC$
- A message $m$ received by $P_j$ makes it adjust $VC_j$ such that $\forall k, VC_j[k] \leftarrow \max(VC_j[k], ts(m)[k]$ — then $m$ is delivered up to the application level
Every process knows how many events have preceded the sending of the received message at the sender process—information about the “chain of events” is preserved and shared among processes.

Each $ts(m)[i]$ refers to the events causally preceding $m$ within each process $P_i$.

$ts(m)$ tells how many events may causally precede the sending of $m$, on which $m$ may causally depend.

As a result, for instance, the delivery of a message to the application level could be suspended until all preceding messages from the same source are received.
Enforcing Causal Communication

Causally-ordered multicasting

- Using vector clocks, a message could be delivered only when all messages causally preceding it have been received.
- ...assuming that all messages are multicasted in a group.
  - Weaker than totally-ordered multicasting: if two messages are not causally related, they could be delivered to applications in any order.
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Beyond Synchronisation I

Ordering events is not enough
- Sometimes, more articulated policies are required
- For instance, to ensure that concurrent accesses to a shared resource could harm its consistency, or corrupt it

Mutual exclusion
- A number of algorithms — centralised, decentralised, distributed — for instance, Token Ring
- We do not review them here
- The main point: some of them are based on a coordinator, all of them are *coordination* algorithms
Election algorithms

- Many distributed algorithms require a \textit{coordinator} to be elected.
- Again, we do not review them: election algorithms are (used by) coordination algorithms.

It is not merely a matter of time

- Synchronisation is about \textit{when} things happen.
- Actions are more than sending messages.
- Interaction does not merely translate into suitably-ordered distributed actions — undifferentiated actions.
- Actions have a nature, and meaningful interaction within a distributed system typically depends on such a nature.
The problem of coordination

- Governing interaction based both on time, and on the nature of actions, and aimed at the achievement of some global objective for the distributed system
- This is the problem of *coordination*
Summing Up

Time in distributed systems
- The issue of time
- Physical time / clock
- Logical time / clock
- Causality and vector clocks

Toward coordination
- What do we do when we have some coherent notion of time?
- Coordinators and distributes algorithms

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