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
These Slides Contain Material from [Tanenbaum and van Steen, 2007]

Slides were made kindly available by the authors of the book

- Such slides shortly introduced the topics developed in the book [Tanenbaum and van Steen, 2007] 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
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1. Interaction, Communication, and Time
2. Physical Time
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Communication & Interaction in Distributed System

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?
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
Physical 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)
- Broadcasting 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
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
Global Relative Time

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.
Physical vs. Logical Time

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 [Lamport, 1978]

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 happens-before**

- $a \rightarrow b$ 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.
Logical Time

Measuring time with logical clocks: \textit{time values}

- A shared notion of time for an event $a$: \textit{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 $C(a) < C(b)$
  1. if $a$ and $b$ are events of the same process, and $a$ comes before $b$, then $C(a) < C(b)$
  2. 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
[Tanenbaum and van Steen, 2007]
Lamport’s Algorithm II

Lamport’s algorithm corrects the clocks
[Tanenbaum and van Steen, 2007]

(b)
Lamport’s Algorithm III

Middleware support for Lamport’s logical clocks
[Tanenbaum and van Steen, 2007]
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 *global time* for the distributed system
An Example I

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 happen 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
[Tanenbaum and van Steen, 2007]
The Solution: Totally-ordered Multicast I

Assumptions

- A group of processes multicasting each other
- Each message is timestamped by the sender with its local logical time
- Also the sender conceptually receives the multicasted message
- 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
Concurrent message transmission using logical clocks
[Tanenbaum and van Steen, 2007]
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
Definition

A vector clock $VC(a)$ assigned to an event $a$ is such that

$\exists b, \ VC(a) < VC(b) \rightarrow a \text{ causally precedes } b$

Each process $P_i$ maintain 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 $VC_i$
Vector Clocks V

Algorithm

- Before any event is executed at $P_i$, $\text{VC}_i[i] \leftarrow \text{VC}_i[i] + 1$
- A message $m$ from $P_i$ to $P_j$ timestamped with vector $\text{VC}$ — $ts(m) = \text{VC}$
- A message $m$ received by $P_j$ makes it adjust $\text{VC}_j$ such that $\forall k, \text{VC}_j[k] \leftarrow \max(\text{VC}_j[k], ts(m)[k])$ — then $m$ is delivered up to the application level
Result

- 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 *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 *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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