Distributed Synchronization

Overview

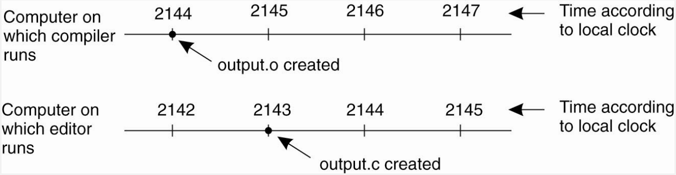
- Synchronization of distributed processes requires new concepts in addition to synchronization of processes in single multi-core systems.
- Topics:
  - Notion of *global time*: absolute time versus relative time
  - *Election algorithms*: for electing a *coordinator* on-the-fly
  - *Distributed mutual exclusion*

Clocks on Computing Devices

- A computer timer is a quartz crystal that oscillates at a well defined frequency.
- Each oscillation decrements a counter by one. When the counter goes down to zero, an interrupt is generated and the counter is reloaded from a holding register.
- Each interrupt is called a clock tick (and can be set to interrupt certain number of times per second).
- The time is stored on a battery-backed CMOS RAM. At every clock tick, the interrupt service procedure adds one to the stored time.
- With one computer even if the time is off it is usually not a problem. With n computers, all n crystals will run at slightly different rates, causing the software clocks to gradually get out of sync. This difference in time values is called clock skew.

Clock Skew

- Clock skew illustrated on a shared file system:

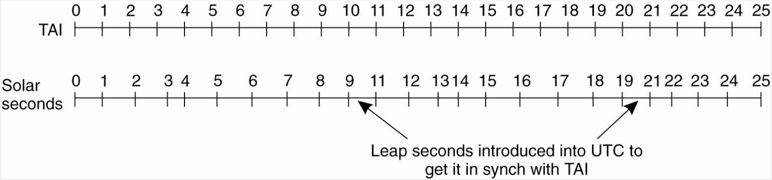


- When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.
- **In-class Exercise**: Come up with an example where clock skew causes a build system to compile a file unnecessarily.
- **In-class Exercise**: Come up with another scenario where a build system misses that a file has changed due to clock skew.

How to Measure Real Time?

- Measure a large number of days and average them and then divide by 86400 to obtain mean solar second. However, this value is changing as Earth's rotation is slowing over time.
- Atomic time: one second = time taken for Cesium 133 atom to make 9,192,631,770 transitions. The International Atomic Time (TAI) is the average of about 50 Cesium clocks around the world. TAI is the mean number of ticks of the Cesium 133 atom since midnight, 1st Jan, 1958 reported by the *Bureau International de l'Heure* in Paris.
- A leap second is introduced whenever the discrepancy between TAI and solar time grows to 800 msec. About 30 leap seconds have been introduced since 1958. This is known as the Universal Coordinated Time (UTC).
- UTC is broadcast over short-wave by NIST on station WWV (and from satellites). See `http://www.nist.gov`.

Leap Seconds



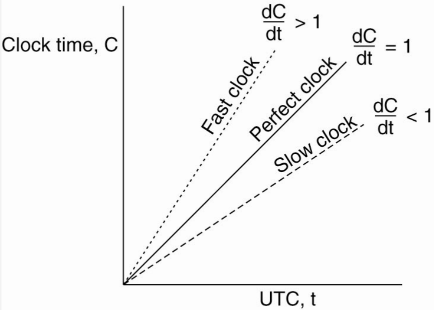
- TAI seconds are of constant length, unlike solar seconds. Leap seconds are introduced when necessary to keep in phase with the sun.

Global Positioning System (GPS)

- GPS is a satellite-based distributed geographical positioning system consisting of 31 satellites at an orbit of around 20,000 km above Earth.
- Each satellite has four atomic clocks, which are regularly calibrated from Earth.
- Each satellite continuously broadcasts its position and timestamps its message with its local time.
- A GPS receiver can compute its own position using three satellites, assuming that the receiver has accurate time. Otherwise it requires four satellites.
- Typical accuracy is 1-5m but can be as good as less than one foot

GPS Animation

Clock Synchronization Algorithms

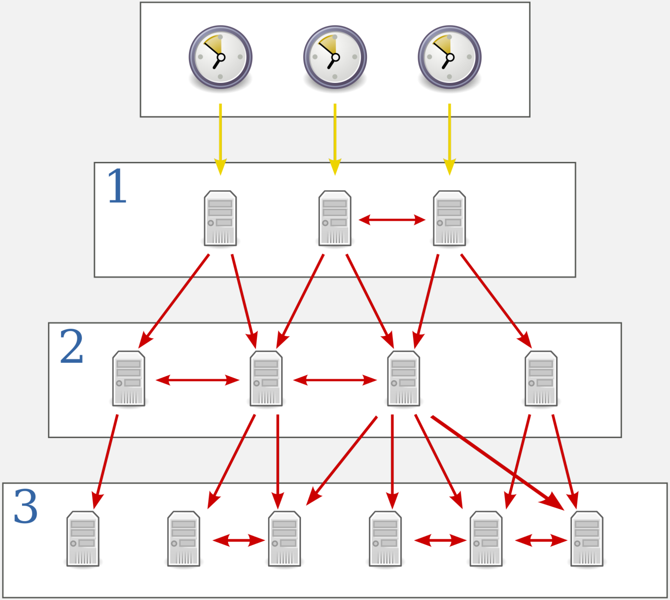


- The relation between clock time and UTC when clocks tick at different rates.
- Let maximum drift rate be ρ. Then $1-\rho \leq dC/dt \leq 1+\rho$ where dC/dt is the rate of drift of the clock relative to UTC. Ideally, we want dC/dt to be 1.To ensure two clocks never differ more than δ, the clocks must be synchronized at least every $\delta/2\rho$ seconds.

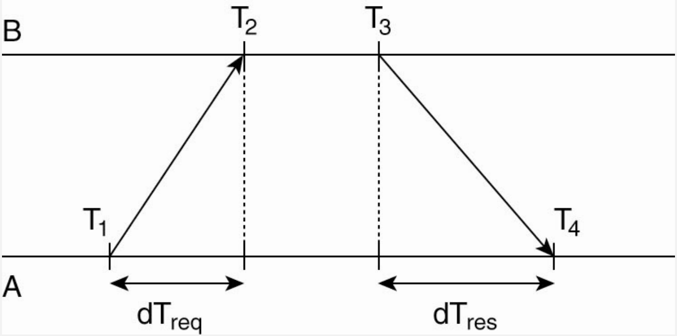
Network Time Protocol (1)

- NTP can achieve worldwide accuracy in the range 1-50 msec. Widely used on the Internet.
- Uses combination of various advanced clock synchronization algorithms (RFC1305).
- Uses a distributed shortest paths algorithm to determine who gets served by whom. Has mechanisms for dealing gracefully with servers being down.
- Clients need to slow down or speed up local clocks to sync up gradually with a server.

Network Time Protocol (2)



Network Time Protocol (3)



- Getting the current time from a time server. Relative offset $\theta = T3 - ((T2 - T1) + (T4 - T3))/2$

Network Time Protocol (4)

- NTP can be setup pair-wise between servers. Both servers ask each other for time and calculate the θ and δ, where

$$\delta = ((T2 - T1) + (T4 - T3))/2$$

- Eight pairs of θ and δ are buffered and the minimal value is taken as the delay between the servers
- A server with a reference clock such as a WWV receiver or an atomic clock is a stratum-1 server. When A contacts B it will only adjusts its clock if its stratum number if higher than B. Moreover, after the synchronization, A's stratum level becomes one more than B's level

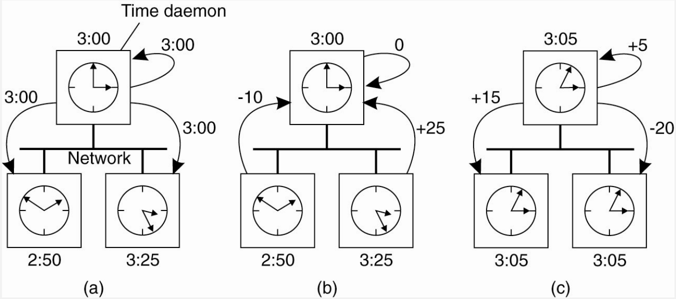
Synchronized Time in the Lab

- The command pdsh runs a parallel/distributed shell across the nodes.

```
[amit@onyx ~]$ pdsh -w node[01-63] date | sort
node01: Wed Mar  9 06:18:26 MST 2016
node02: Wed Mar  9 06:18:26 MST 2016
node03: Wed Mar  9 06:18:26 MST 2016
node04: Wed Mar  9 06:18:26 MST 2016
node05: Wed Mar  9 06:18:26 MST 2016
node06: Wed Mar  9 06:18:26 MST 2016
node07: Wed Mar  9 06:18:26 MST 2016
node08: Wed Mar  9 06:18:26 MST 2016
node11: Wed Mar  9 06:18:26 MST 2016
node12: Wed Mar  9 06:18:26 MST 2016
.
.
.
node62: Wed Mar  9 06:18:26 MST 2016
node63: Wed Mar  9 06:18:26 MST 2016
[amit@onyx ~]$
```

- Try `pdsh -w node[01-63] date -rfc-3339=ns | sort` to see time in nanoseconds resolution.
- The cluster uses NTP (Network Time Protocol) daemons on each node to keep the machines synchronized.

Berkeley Time Algorithm

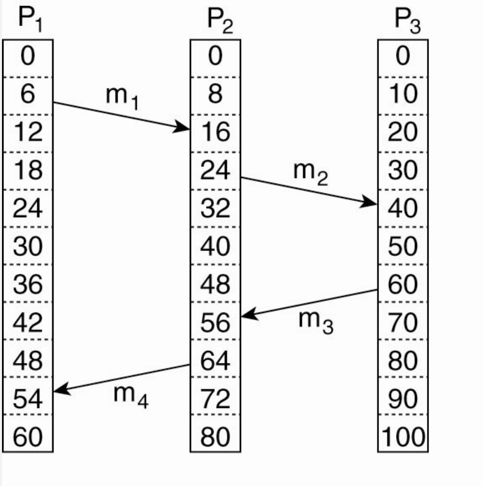


- The time daemon asks all other machines for their clock values.
- The machines answer.
- The time daemon tells everyone how to adjust their clock.
- **In-class Exercise**. How would you implement the Berkeley Time Algorithm?

Logical Clocks

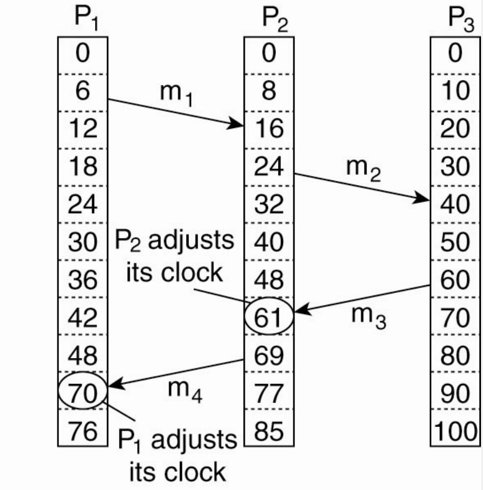
- For many purposes, it is sufficient that machine agree on the same time even though that time may not agree with real world.
- If two process do not interact, it is not necessary that their clocks be synchronized. Furthermore, if all processes agree on the order in which events occur, then they need not agree on the time.
- A logical clock is a mechanism for capturing chronological and causal relationships in a distributed system.
  - The first implementation, the Lamport timestamps, was proposed by Leslie Lamport in 1978 (Turing Award in 2013).
- Some noteworthy logical clock algorithms:
  - Lamport timestamps, which are monotonically increasing software counters.
  - Vector clocks, that allow for partial ordering of events in a distributed system.
  - Version vectors, order replicas, according to updates, in an optimistic replicated system.
  - Matrix clocks, an extension of vector clocks that also contains information about other processes' views of the system.

Lamport's Logical Clocks (1)



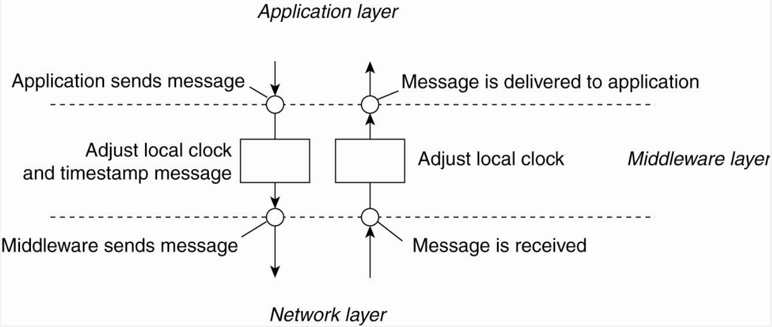
- Three processes, each with its own clock.

Lamport's Logical Clocks (2)



- Lamport's algorithm corrects the clock by adjusting the timestamps.

Lamport's Logical Clocks (3)



- The positioning of Lamport's logical clocks in a distributed system.

Lamport's Logical Clocks (4)

- C is the timestamp function that is defined as follows:
  1. If a happens before b in the same process, $C(\texttt{a}) < C(\texttt{b})$
  2. If a represents sending and b receiving of a message, then $C(\texttt{a}) < C(\texttt{b})$
  3. For all distinct events a and b, $C(\texttt{a}) \neq C(\texttt{b})$
- The time is always adjusted forward. Each message carries the sending time according to the sender's clock. If receiver's time is prior to the sending time, the receiver fast forwards its clock to be 1 more than the sending time.
- In addition, between every two events the clock must tick at least once.
- No two events ever occur at exactly the same time. Tag process ids to low bits of time to make time be unique.

Lamport's Logical Clocks (5)

To implement Lamport's logical clocks, each process P_i maintains a *local counter* C_i that is updated as follows:

Step 1. Before executing an event, P_i executes

$$C_i \leftarrow C_i + 1$$

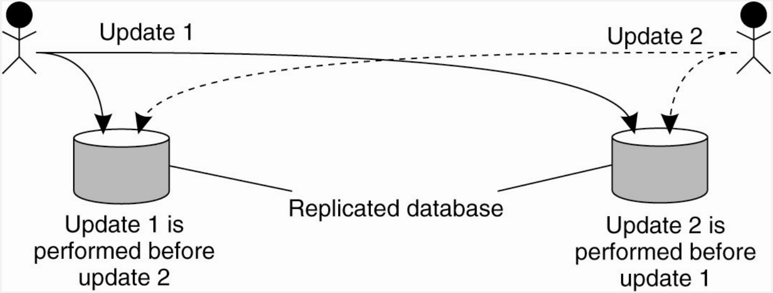
Step 2. When process P_i sends a message m to P_j, it sets m's timestamp $ts(m)$ equal to C_i after having executed the previous step.

Step 3. Upon the receipt of a message m, process P_j adjusts its own local counter as

$$C_j \leftarrow \max\{C_j, ts(m)\}$$

after which it then executes the first step and delivers the message to the application.

Example: Totally Ordered Multicasting (1)

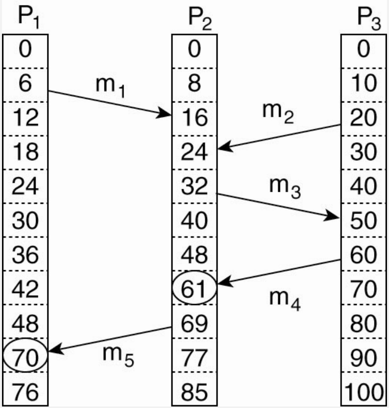


- Updating a database and leaving it in an inconsistent state.
- Lamport timestamps can be sued to fix this problem.

Example: Totally Ordered Multicasting (2)

- Totally Ordered Multicast: A multicast operation by which all messages are delivered in the same order to each receiver.
  - Can be implemented using Lamport's logical clock algorithm.
- Each message is time-stamped with the current (logical) time of the sender.
  - Assumption. Messages from one receiver are ordered and messages aren't lost.
- A process puts received messages into a queue ordered by timestamps. It acknowledges the messages with a multicast to all other processes. Eventually the local queues are the same at all processes.
- A process can deliver a queued message to an application only if it is at the head of queue and has been acknowledged by each other process.

Vector Clocks (1)



- Concurrent message transmission using Lamport logical clocks. Knowing that m_1 was received before m_2 doesn't tell us if they are connected.
- Lamport clocks do not capture causality. We need *vector clocks* to capture causality.

Vector Clocks (2)

- Vector clock: A vector clock $VC(\texttt{a})$ assigned to an event a has the property that if $VC(\texttt{a}) < VC(\texttt{b})$ for some event b, then event a is known to causally precede event b.
- Vector clocks are constructed by letting each process P_i maintain a vector VC_i with the following two properties:

Step 1. $VC_i[i]$ is the number of events that have occurred so far at P_i. In other words, $VC_i[i]$ is the local logical clock at process P_i.

Step 2. If $VC_i[j] = k$ then P_i knows that k events have occurred at P_j. It is thus P_i's knowledge of the local time at P_j

Vector Clocks (3)

Step 2 is carried out by piggybacking vectors along with messages. The details are shown below:

- Before an event (send/receive or internal event), P_i executes

$$VC_i[i] \leftarrow VC_i[i] + 1$$

- When process P_i sends a message m to P_j, it sets m's (vector) timestamp $ts(\mathtt{m})$ equal to VC_i after having executed the previous step.
- Upon the receipt of a message m, process P_j adjusts its own vector by setting:

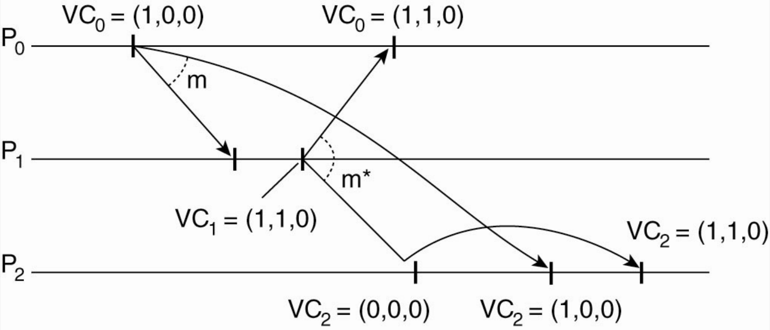
$$VC_j[k] \leftarrow \max\{VC_j[k], ts(\mathtt{m})[k]\}, \forall k$$

  after which it executes the first step and delivers the message to the application.

Example: Enforcing Causal Communication (1)

- Causally-ordered multicasting: We want to ensure that a message is delivered only if all messages that casually precede it have been delivered. We assume that the message are multicast within the group.
- Clocks are adjusted only when sending or receiving a message.
- Then if P_j receives a message m from P_i with vector timestamp $ts(\mathtt{m})$, the delivery is delayed until the following conditions are met:
  - $$ts(m)[i] = VC_j[i] + 1$$
    (m is the next process P_j was expecting from P_i)
  - $$ts(m)[k] \leq VC_j[k], \forall k \neq i$$
    (P_j has seen all the messages that have been seen by P_i when it sent message m)

Example: Enforcing Causal Communication (2)



- At time (1,0,0): P_0 sends message m to P_1 and P_2.
- After receipt by P_1, it decides to send m^* to P_2.
- On P_2: The message m^* arrives sooner than m. The delivery of m^* is delayed by P_2 until m has been received and delivered to P_2's application layer.

Whose problem is it?

- Middleware deals with message ordering:
  - The middleware cannot tell what the message contains so only potential causality is captured.
  - Two messages sent by the same process are always marked as causally related.
- Middleware cannot be aware of external communication. Ordering issues can be adequately solved by looking at the application for which the communication is taking place. This is known as the end-to-end argument.

References

- Time, clocks, and the ordering of events in a distributed system. Leslie Lamport. *Communications of the ACM* 21 (7): 558–565, 1978.
- Time is an illusion. Lunchtime doubly so. George V. Neville-Neil. *Communications of the ACM*, January 2016, Vol. 59. No. 1, pages 50–55. [Note: this article is only accessible on campus]