Distributed systems

Lecture 4: Clock synchronisation; logical clocks

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Last time

- Started to look at time in distributed systems
  - Coordinating actions between processes
- Physical clocks 'tick' based on physical processes (e.g. oscillations in quartz crystals, atomic transitions)
  - Imperfect, so gain/lose time over time
  - (wrt nominal perfect 'reference' clock (such as UTC))
- The process of gaining/losing time is **clock drift**
- The difference between two clocks is called **clock skew**
- **Clock synchronization** aims to minimize clock skew between two (or a set of) different clocks

The clock synchronization problem

From last lecture

- In distributed systems, we'd like all the different nodes to have the same notion of time, but
  - quartz oscillators oscillate at slightly different frequencies (time, temperature, manufacture)
- Hence clocks tick at different rates:
  - create ever-widening gap in perceived time
  - this is called **clock drift**
- The difference between two clocks at a given point in time is called **clock skew**
- Clock synchronization aims to minimize clock skew between two (or a set of) different clocks

Dealing with drift

- A clock can have positive or negative drift with respect to a reference clock (e.g. UTC)
  - Need to [re]synchronize periodically
- Can't just set clock to 'correct' time
  - Jumps (particularly backward!) can confuse apps
- Instead aim for gradual compensation
  - If clock fast, make it run slower until correct
  - If clock slow, make it run faster until correct

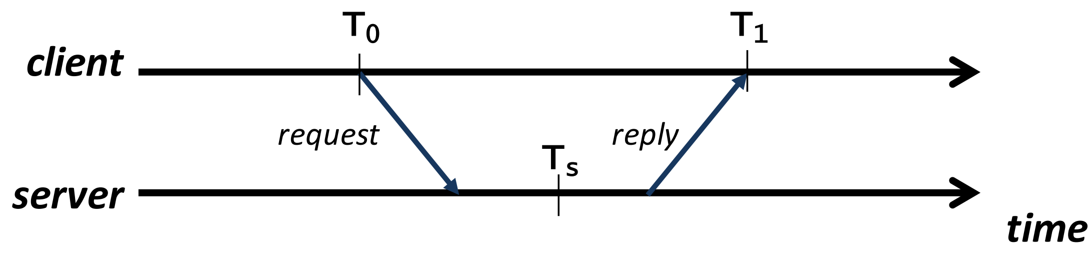
Compensation

- Most systems relate real-time to cycle counters or periodic interrupt sources
  - E.g. calibrate CPU **Time-Stamp Counter (TSC)** against **CMOS Real-Time Clock (RTC)** at boot, and compute scaling factor (e.g. cycles per ms)
  - Can now convert TSC differences to real-time
  - Similarly can determine how much real-time passes between periodic interrupts: call this **delta**
  - On interrupt, add delta to software real-time clock
- Making small changes to delta gradually adjusts time
  - Once synchronized, change delta back to original value
  - (Or try to estimate drift & continually adjust delta)
  - Minimise time discontinuities from **stepping**

Obtaining accurate time

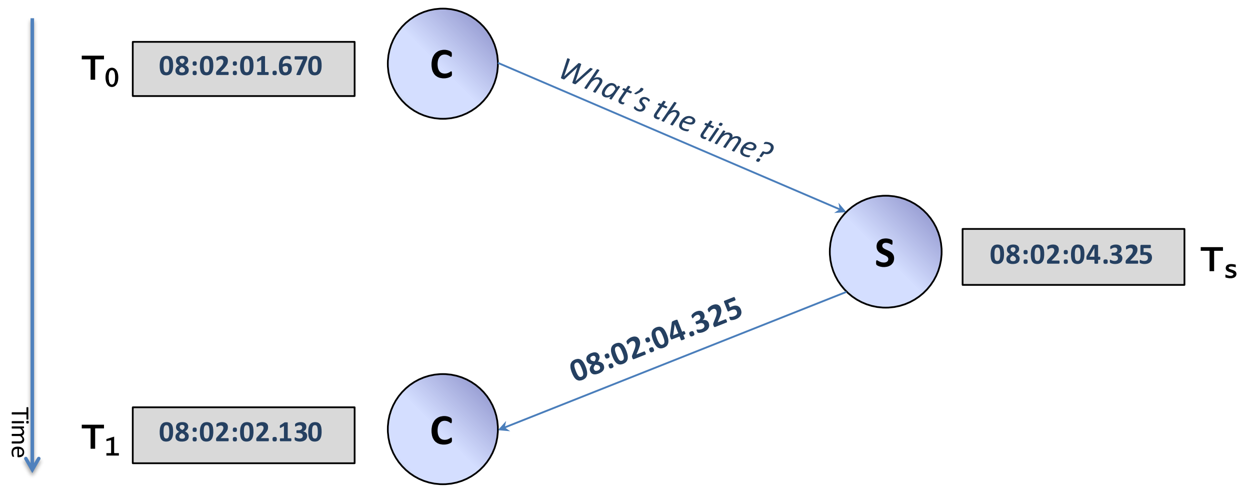
- Of course, need some way to know correct time (e.g. UTC) in order to adjust clock!
  - could attach a GPS receiver (or GOES receiver) to computer, and get ±1ms (or ±0.1ms) accuracy…
  - …but too expensive/clunky for general use
  - (RF in server rooms and data centres non-ideal)
- Instead can ask some machine with a more accurate clock over the network: a **time server**
  - e.g. send RPC getTime() to server
  - What's the problem here?

Cristian's Algorithm (1989)



- Attempt to compensate for network delays
  - Remember local time just before sending: T_0
  - Server gets request, and puts T_s into response
  - When client receives reply, notes local time: T_1
  - Correct time is then approximately $(T_s + (T_1 - T_0) / 2)$
  - (assumes symmetric behaviour...)

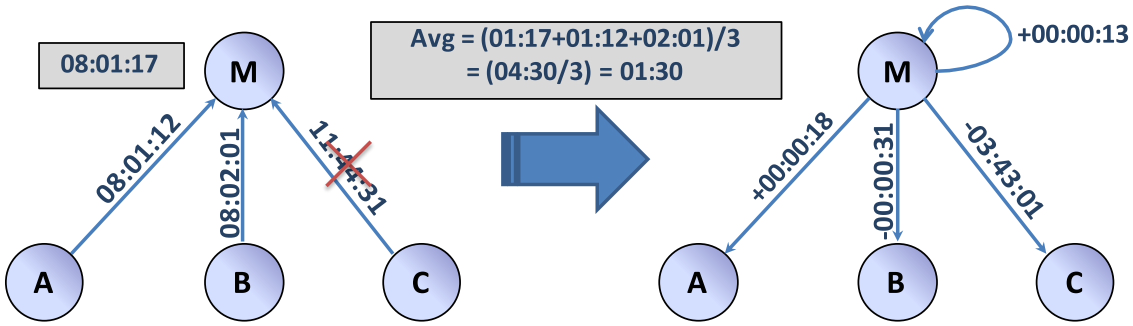
Cristian's Algorithm: Example



- RTT = 460ms, so one way delay is [approx] 230ms.
- Estimate correct time as (08:02:04.325 + 230ms) = 08:02:04.555
- Client gradually adjusts local clock to gain 2.425 seconds

Berkeley Algorithm (1989)

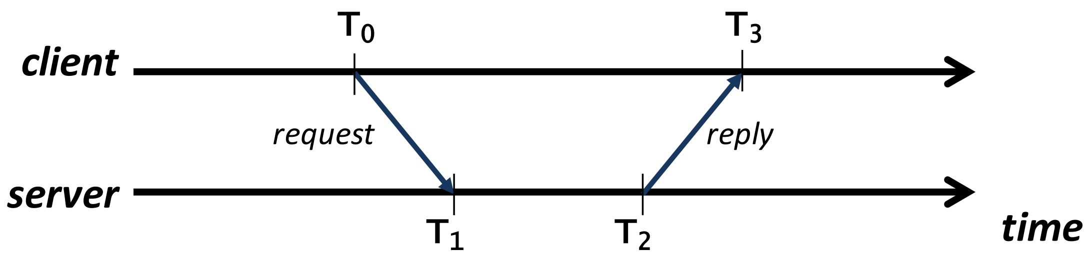
- Don’t assume have an accurate time server
- Try to synchronize a set of clocks to the average
  – One machine, M, is designated the master
  – M periodically polls all other machines for their time
  – (can use Cristian’s technique to account for delays)
  – Master computes average (including itself, but ignoring outliers), and sends an adjustment to each machine



Network Time Protocol (NTP)

- Previous schemes designed for LANs; in practice today’s systems use NTP:
  – Global service designed to enable clients to stay within (hopefully) a few ms of UTC
- Hierarchy of clocks arranged into strata
  – Stratum0 = atomic clocks (or maybe GPS, GEOS)
  – Stratum1 = servers directly attached to stratum0 clock
  – Stratum2 = servers that synchronize with stratum1
  – … and so on
- Timestamps made up of seconds and ‘fraction’
  – e.g. 32 bit seconds-since-epoch; 32 bit ‘picoseconds’

NTP algorithm

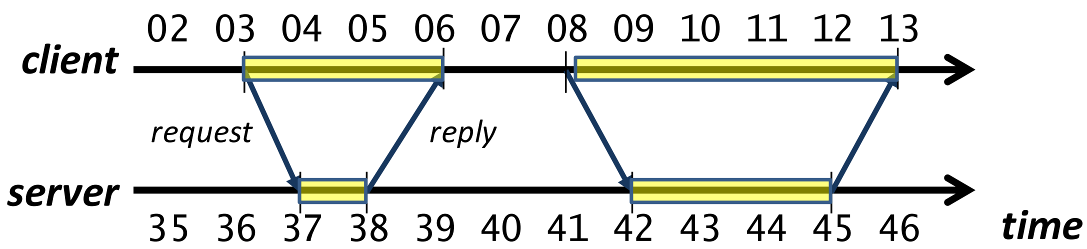


- UDP/IP messages with slots for four timestamps
  - systems insert timestamps at earliest/latest opportunity
- Client computes:
  - Offset O = $((T_1-T_0) + (T_2-T_3)) / 2$
  - Delay D = $(T_3-T_0) – (T_2-T_1)$
- Relies on symmetric messaging delays to be correct (but now excludes variable processing delay at server)

Measured difference in average timestamps: (T1+T2)/2 – (T0+T3)/2

Estimated two-way communication delay minus processing time

NTP example



- First request/reply pair:
  - Total message delay is ((6-3) - (38-37)) = 2
  - Offset is ((37-3) + (38-6)) / 2 = 33
- Second request/reply pair:
  - Total message delay is ((13-8) - (45-42)) = 2
  - Offset is ((42-8) + (45-13)) / 2 = 33

NTP: additional details (1)

- NTP uses multiple requests per server
  - Remember <offset, delay> in each case
  - Calculate the **filter dispersion** of the offsets & discard outliers
  - Chooses remaining candidate with the smallest delay
- NTP can also use multiple servers
  - Servers report **synchronization dispersion** = estimate of their quality relative to the root (stratum 0)
  - Combined procedure to select best samples from best servers (see RFC 5905 for the gory details)

NTP: additional details (2)

- Various operating modes:
  - **Broadcast** ("multicast"): server advertises current time
  - **Client-server** ("procedure call"): as described on previous
  - **Symmetric**: between a set of NTP servers
- Security is supported
  - Authenticate server, prevent replays
  - Cryptographic cost compensated for

Physical clocks: summary

- Physical devices exhibit **clock drift**
  - Even if initially correct, they tick too fast or too slow, and hence time ends up being wrong
  - Drift rates depend on the specific device, and can vary with time, temperature, acceleration, …
- Instantaneous difference between clocks is **clock skew**
- **Clock synchronization algorithms** attempt to minimize the skew between a set of clocks
  - Decide upon a target correct time (atomic, or average)
  - Communicate to agree, compensating for delays
  - In reality, will still have 1-10ms skew after sync ;-(

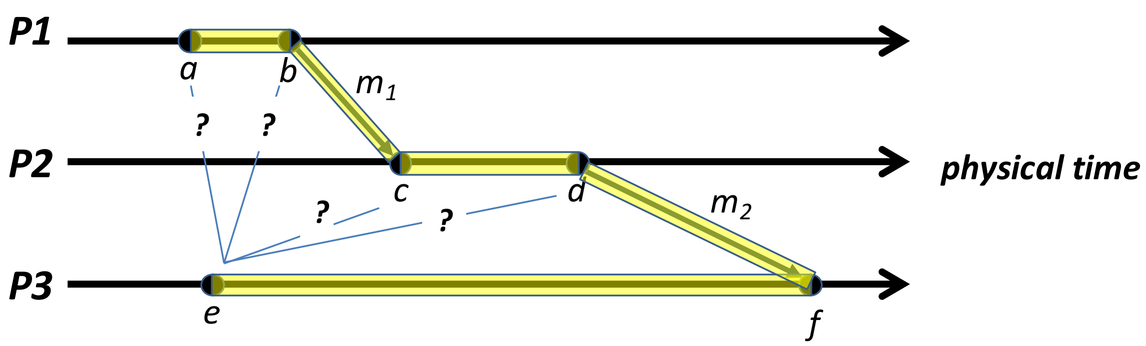
Ordering

- One use of time is to provide ordering
  - If I withdrew £100 cash at 23:59.44…
  - And the bank computes interest at 00:00.00…
  - Then interest calculation shouldn't include the £100
- But in distributed systems we can't perfectly synchronize time => cannot use this for ordering
  - Clock skew can be large, and may not be trusted
  - And over large distances, relativistic events mean that ordering depends on the observer
  - (similar effect due to finite 'speed of Internet' ;-)

The "happens-before" relation

- Often don't need to know <u>when</u> event *a* occurred
  - Just need to know if *a* occurred before or after *b*
- Define the **happens-before** relation, ***a* → *b***
  - If events *a* and *b* are within the same process, then *a* → *b* if *a* occurs with an earlier local timestamp
  - Messages between processes are ordered ***causally***, i.e. the event *send(m)* → the event *receive(m)*
  - Transitivity: i.e. if *a* → *b* and *b* → *c*, then *a* → *c*
- Note that this only provides a partial order:
  - Possible for neither *a* → *b* nor *b* → *a* to hold
  - We say that *a* and *b* are **concurrent** and write *a* ~ *b*

Example

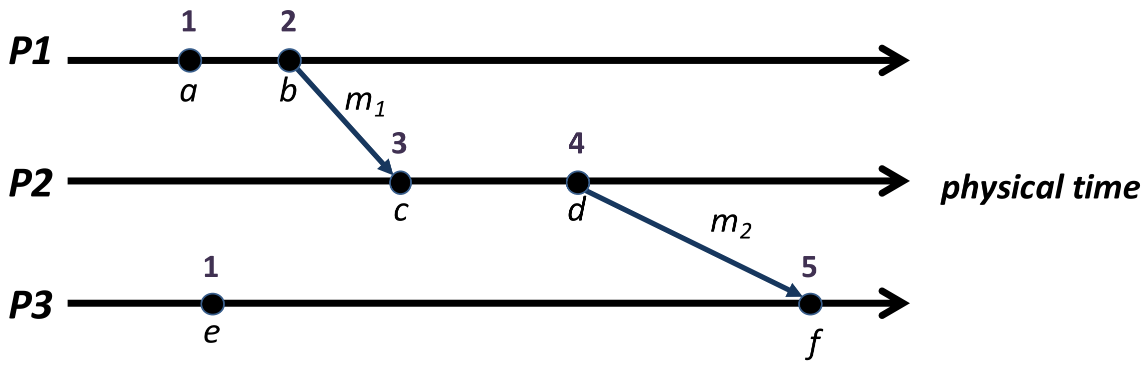


- Three processes (each with 2 events), and 2 messages
  - Due to process order, we know *a* → *b*, *c* → *d* and *e* → *f*
  - Causal order tells us *b* → *c* and *d* → *f*
  - And by transitivity *a* → *c*, *a* → *d*, *a* → *f*, *b* → *d*, *b* → *f*, *c* → *f*
- However event *e* is **concurrent** with *a*, *b*, *c* and *d*

Implementing Happens-Before

- One early scheme due to Lamport [1978]
  - Each process P_i has a logical clock L_i
    - L_i can simply be an integer, initialized to 0
  - L_i is incremented on every local event *e*
    - We write $L_i(e)$ or $L(e)$ as the timestamp of *e*
  - When P_i sends a message, it increments L_i and copies the value into the packet
  - When P_i receives a message from P_j, it extracts L_j and sets $L_i := \mathbf{max}(L_i, L_j)$, and then increments L_i
- Guarantees that if $a \rightarrow b$, then $L(a) < L(b)$
  - However if $L(x) < L(y)$, this doesn't imply $x \rightarrow y$!

Lamport Clocks: Example

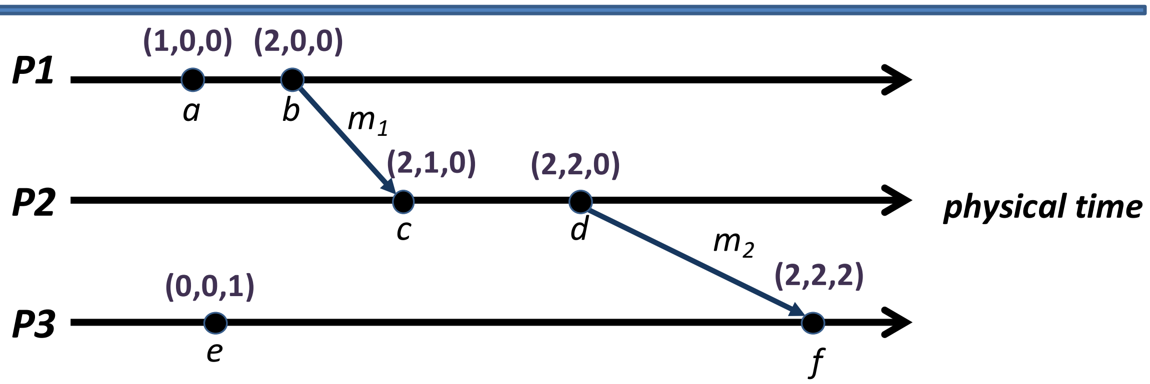


- When P_2 receives m_1, it extracts timestamp 2 and sets its clock to max(0, 2) before increment
- Possible for events to have duplicate timestamps
  - e.g. event *e* has the same timestamp as event *a*
- If desired can break ties by looking at pids, IP addresses, …
  - this gives a **total order**, but doesn't imply happens-before!

Vector clocks

- With Lamport clocks, given L(*a*) and L(*b*), we can't tell if $a \rightarrow b$ or $b \rightarrow a$ or $a \sim b$
- One solution is **vector clocks**:
  - An ordered list of logical clocks, one per-process
  - Each process P_i maintains $V_i[]$, initially all zeroes
  - On a local event *e*, P_i increments $V_i[i]$
    - If the event is message send, new $V_i[]$ copied into packet
  - If P_i receives a message from P_j then, for all k = 0, 1, …, it sets $V_i[k]$:= **max**($V_j[k]$, $V_i[k]$), and increments $V_i[i]$
- Intuitively $V_i[k]$ captures the number of events at process P_k that have been observed by P_i

Vector clocks: example



- When P_2 receives m_1, it **merges** the entries from P_1's clock
  - choose the maximum value in each position
- Similarly when P_3 receives m_2, it merges in P_2's clock
  - this incorporates the changes from P_1 that P_2 already saw
- Vector clocks ***explicitly track the transitive causal order***: *f*'s timestamp captures the history of *a*, *b*, *c* & *d*

Using vector clocks for ordering

- Can compare vector clocks piecewise:
  - $V_i = V_j$ iff $V_i[k] = V_j[k]$ for k = 0, 1, 2, …
  - $V_i \leq V_j$ iff $V_i[k] \leq V_j[k]$ for k = 0, 1, 2, …
  - $V_i < V_j$ iff $V_i \leq V_j$ and $V_i \neq V_j$
  - $V_i \sim V_j$ otherwise

e.g. [2,0,0] versus [0,0,1]

- For any two event timestamps T(a) and T(b)
  - if $a \rightarrow b$ then $T(a) < T(b)$; **and**
  - if $T(a) < T(b)$ then $a \rightarrow b$
- Hence can use timestamps to determine if there is a causal ordering between any two events
  - i.e. determine whether $a \rightarrow b$, $b \rightarrow a$ or $a \sim b$

Does this seem familiar? Recall Time-Stamp Ordering and Optimistic Concurrency Control for transactions last term.

Summary + next time (ironically)

- The clock synchronisation problem
- Cristian's Algorithm, Berkeley Algorithm, NTP
- Logical time via the happens-before relation
- Vector clocks

- More on vector clocks
- Consistent cuts
- Group communication
- Enforcing ordering vs. asynchrony
- Distributed mutual exclusion