Time, Clocks, and the Ordering of Events in a Distributed System

Phil Gibbons

15-712 F15

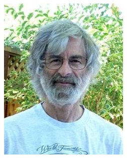
Lecture 5

Today's Reminders

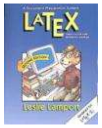
- **Welcome Kevin**
  - Office Hours: 2-4 pm Tues @ CIC 4th floor & by appointment
- **Papers through end of September now posted**
- **Will grade one summary from each of you soon**
  - Looking into sharing summaries after deadline
- **Waitlist (33 currently enrolled)**

Time, Clocks, and the Ordering of Events in a Distributed System

Leslie Lamport [CACM 1978]



- **ACM Turing Award 2013:**
  - "For fundamental contributions to the theory and practice of distributed and concurrent systems, notably the invention of concepts such as causality and logical clocks, safety and liveness, replicated state machines, and sequential consistency."



- **IEEE John von Neumann Award 2008**
  - Other winners: Brooks, Lampson
- **Dijkstra Prize (test-of-time award for distributed computing) in 2000 (this paper), 2005, and 2014**

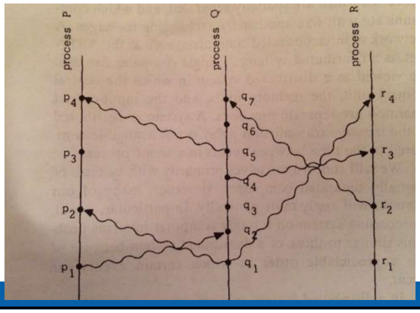
Happened Before

"A system is distributed if the message transmission delay is not negligible compared to the time between events in a single process."

- **"Happened before" is only a partial ordering of events**
- **Must define without using physical clocks. Why?**
  - System specification may not include real clocks
  - Real clocks do not keep precise physical time (clock skew)

Happened Before Definition

- **The smallest relation satisfying:**
  - Two events on same process are ordered
  - Message receipt ordered after associated message send
  - Transitivity: $a \rightarrow b$ and $b \rightarrow c$ implies $a \rightarrow c$



Logical Clocks (aka. Lamport Clocks)

- **Clock Condition: If $a \rightarrow b$ then Clock(a) < Clock(b)**

- **Satisfied if two conditions hold:**
  - **C1:** If a and b are events in process P_i, and a comes before b, then $Clock_i(a) < Cloc\ \ _i(b)$
  - **C2:** If a is the sending of a message by process P_i and b is the receipt of that message by process P_j then $Clo\ \ \ _i(a) < Clock_j(b)$

- **An implementation using timestamps:**
  - **IR1:** Each process P_i increments C_i between any two successive events
  - **IR2:** (i) Send $T_m = C_i(a)$ along with the message from a.
    (ii) Upon receiving that message, P_j sets its C_j to be ≥ its present value and > T_m

Total Order of the Events

- **Order events by the Lamport clock values; Breaking ties arbitrarily (e.g., using process ids)**
  - Fairness issues in breaking ties…

Use in Distributed Mutual Exclusion

- **Goals:**
  I. Must release granted resource before can be granted again
  II. Grant resources in order they are made
  III. Every request is eventually granted
  (assuming no process fails to release a granted resource)

- **Straightforward centralized solution fails**

<Draw figure: P_1 sends request to P_0, P_1 sends message to P_2, P_2 receives message then sends request to P_0, but P_2's request arrives at P_0 before P_1's request. Granting P_2's request first violates (II)>

- **Assume in-order delivery of messages from P_i to P_j**

Use in Distributed Mutual Exclusion

- **Request resource:** P_i **sends** $T_m{:}P_i$ requests resource **to every other process & puts in its local request queue**

- **When receive** $T_m{:}P_i$ requests resource, **place it on local request queue & send timestamped ack to** P_i

- **Release resource:** P_i **removes any** $T_m{:}P_i$ requests resource **message from local queue & sends timestamped** P_i releases resource **message to every other process**

- **When receive** P_i releases resource **message, remove any** $T_m{:}P_i$ requests resource **message from local queue**

- P_i **is granted the resource when (i)** $T_m{:}P_i$ requests resource **in local queue is ordered before any other request in local queue and (ii)** P_i **has received a message from every other process that is timestamped LATER than** T_m

Problem & Generalization

- **Problem: System halts if one process fails**
  - With logical time, no way to distinguish a failed process from a paused/delayed/slow process

- **Generalization: Works for any synchronization that can be specified in terms of a State Machine** $\langle C, S, e{:}\, C \times S \rightarrow S \rangle$
  - E.g., C is all possible requests/releases resource commands, S is the queue of waiting request commands, e is the transition function
  - Run same basic algorithm: A process can execute a command timestamped T when it has learned of all commands issued by all other processes with timestamps ≤ T

Vector Clocks

- **Each local clock is a vector of N values for N processes**

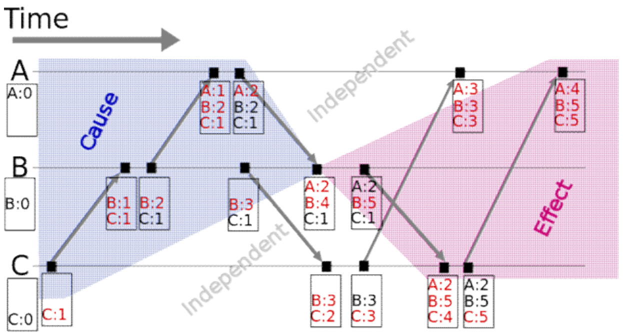
- P_i **increments i'th value of local clock on internal event**

- **Include entire vector clock when send message**

- **When** P_j **receives a message with clock V:**
  - Increment j'th value of local clock
  - Set local clock to be elementwise max of its local clock and V

Vector Clocks

On Receive of V: $V_j[j]$++; V_j = **elementwise-max**(V, V_j)



V < V' if ≤ on each element and < on at least one element

Vector Clocks satisfy Clock Condition?

- **Clock Condition: If $a \rightarrow b$ then Clock(a) < Clock(b)**

- **Satisfied if two conditions hold:**
  - **C1:** If a and b are events in process P_i, and a comes before b, then $Clock_i(a) < Clock_i(b)$
  - **C2:** If a is the sending of a message by process P_i and b is the receipt of that message by process P_j then $Clock_i(a) < Clock_j(b)$

- **Answer: Yes!**
  - (v1,…,vi,…vN) < (v1,…,vi+1,…vN)

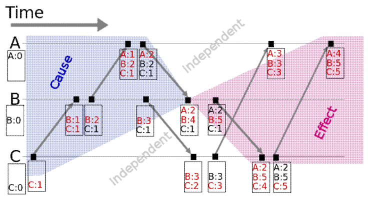
    $V_i(a)$ **sent to j** new $V_j(b)$
  - (v1,…,vN) < (max(v1,x1),…,max(vj,xj+1),…max(vN,xN))

V < V' if ≤ on each element and < on at least one element

Vector Clock Properties

- **Just showed: $a \rightarrow b$ implies $V(a) < V(b)$**

- **Not hard to show: $V(a) < V(b)$ implies $a \rightarrow b$**



- **Pros and Cons of Vector Clocks vs. Lamport's timestamps?**
  - Pro: more precise (iff)
  - Cons: much larger clocks, more complex

Anomalous Behavior

- **With respect to out-of-band communication**
  - Issue request A, call friend to have him issue request B
  - Yet B can get lower timestamp than A

- **Strong Clock Condition: $a \Rightarrow b$ implies $C(a) < C(b)$, where ⇒ denotes happened-before when also include out-of-band events**

**"One of the mysteries of the universe is that
it is possible to construct a system of physical clocks which,
running quite independently of each one another,
will satisfy the Strong Clock Condition."**

Physical Clocks

- **Let $C_i(t)$ denote the reading of clock C_i at physical time t**
  - Assume $C_i(t)$ is a continuous, differentiable function of t, except for isolated jump discontinuities where clock is reset
  - PC1: [assumed upper bound on rate of clock drift] There exists constant $\kappa \ll 1$ s.t. for all i: $\left|\frac{dC_i(t)}{dt} - 1\right| < \kappa$

- **Goal: Bound pairwise clock skew to at most ϵ**
  - PC2: For all i, j: $|C_i(t) - C_j(t)| < \epsilon$ for small constant ϵ

- **How small must κ, ϵ be to avoid anomalous behavior?**
  - Let μ be the minimum physical time needed to transmit out-of-band communication
  - Can ensure that $C_i(t+\mu) - C_j(t) > 0$ if we have $\frac{\epsilon}{1-\kappa} \le \mu$

Physical Clocks

- **A distributed implementation:**
  - **IR1':** If P_i does not receive a message at physical time t then $\frac{dC_i(t)}{dt} > 0$
  - **IR2':** (i) P_i sends $T_m = C_i(t)$ along with its message.
    (ii) Upon receiving that message at time t',
    P_j sets $C_j(t') = \max\left(\lim_{\delta \to 0} C_j(t' - |\delta|), T_m + \mu_m\right)$

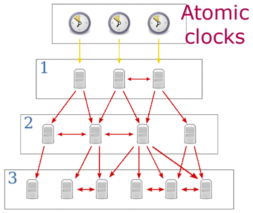
    where μ_m is the minimum delay for any message

- **Theorem: Max clock skew is bounded by $d(2\kappa\tau + \xi)$**

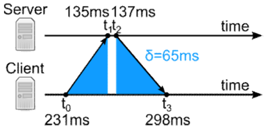
  i.e., (max number of hops) x [2 x (rate of clock skew) x (max time between point-to-point messages) + (max unpredictable message delay)]

Pros: No need for reference clocks; Clocks never set backwards
Cons: Skew versus real time; Frequent neighbor communications

Network Time Protocol (NTP)



- **In operation since before 1985**
- **Hierarchy of stratums**
- **Roundtrip delay δ**
- **Want $t_0 + \theta = t_1 - \frac{\delta}{2}$ and $t_3 + \theta = t_2 + \frac{\delta}{2}$**
- **Solve to get $\theta = \frac{(t_1 - t_0) + (t_2 - t_3)}{2}$**
- **Add θ to current clock**
  - $\theta = -128.5$, so clock = 169.5 ms



- **Typically sync within 10s of millisecs on public internet**

Monday's Paper

Eraser: A Dynamic Data Race Detector for Multi-Threaded Programs

Stefan Savage, Michael Burrows, Greg Nelson, Patrick Sobalvarro, Thomas E. Anderson [SOSP'97]