Synchronization

Lamport Logical Clock and Clock Vectors

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Roadmap

The Happened-Before Relation

Lamport Clocks and Timestamps

Vector Clocks and Timestamps

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The Happened-Before Relation

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Vector Clocks and Timestamps

Events

- Often, there is no need for synchronized clocks
  - Sometimes, we just need to order **events**

Event is an action that takes place in the execution of an algorithm

Sending of a message
Delivery of a message
Computation step

Execution of a distributed algorithm by process i can be defined as a sequence of events:

$$e_i^0 e_i^1 e_i^2 \ldots$$

- Each event in an execution is an instance of a given **event type**

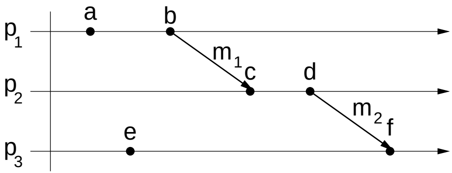
The Happened-Before Relation ($\rightarrow$)

HB1 If e and e' are events that happen in that order in the same process, then $e \rightarrow e'$

HB2 If e is the sending of a message m and e' is the reception of that message, then $e \rightarrow e'$

HB3 If $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$

- That is, the HB relation is transitive



- The HB relation is a partial order. For example:

$$a \not\rightarrow e \wedge e \not\rightarrow a$$

  - Events like a and e are **concurrent**: $a || e$

- The HB relation captures the **potential causality** between events

Roadmap

The Happened-Before Relation

Lamport Clocks and Timestamps

Vector Clocks and Timestamps

Lamport Clocks and Timestamps

Lamport clock is a logical clock used to assign (Lamport) timestamps to events

- Each process in the system has its own Lamport clock L_i

(Lamport) clock condition For any events e and e':

$$e \rightarrow e' \Rightarrow L(e) < L(e')$$

Or equivalently:

$$L(e) \geq L(e') \Rightarrow e \not\rightarrow e'$$

Satisfying the Clock Condition

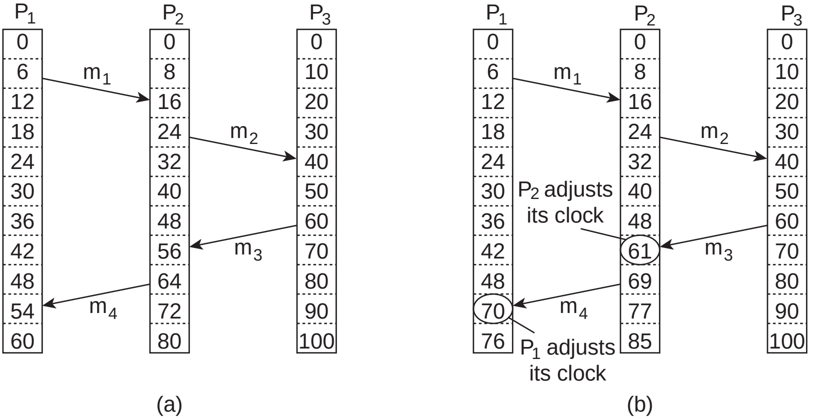
C1 If e and e' are events in process p_i and occur in that order, then $L_i(e) < L_i(e')$

C2 If

e is the sending of a message by process p_i, and
e' is the receipt of that message by a process p_j

then $L_i(e) < L_j(e')$

(Physical Clocks vs. Lamport Clocks)



- Free-running physical clocks cannot be used as Lamport clocks
  - If the clock resolution is small enough C1 is easy to ensure
  - The problem is with C2

Lamport Clocks and Timestamps (2/3)

- The timestamp of an event at process i is assigned by L_i, the Lamport clock at the process i

Lamport Clock Update Rules To satisfy the Clock Condition a Lamport clock must be updated **before** assigning its value to the event as follows:

LC1 if e is not the receiving of a message, just increment L_i

LC2 if e is the receiving of a message m:

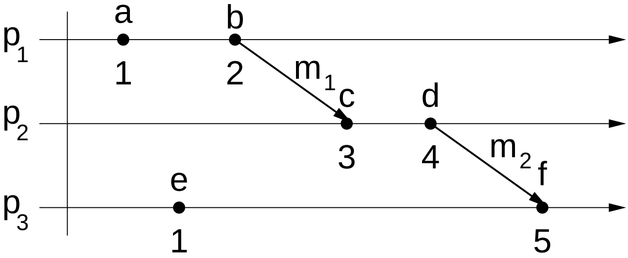
$$L_i = max(L_i, TS(m)) + 1$$

where $TS(m)$ is the timestamp of the corresponding sending event

- Implementing LC2 requires piggybacking the timestamp of the sending event on every message

IMP. Incrementing a Lamport clock is **not** an event

Lamport Clocks and Timestamps (3/3)



- If we need to order all events we can use the pair (**extended Lamport timestamp**):

  $$(L(e), i)$$

  where *i* is the process where *e* happens
  - How would you define that order, so that it "extends" the HB relation?
  - Although total, this order is somewhat arbitrary
- Actually, Lamport claims that the reason for Lamport clocks is precisely to obtain a total order.

State Machine

- Indeed, a total order allows to solve any synchronization problem

Idea Specify the synchronization in terms of a state machine:

Set of commands, C
Set of states, S
State transition function, $t : C \times S \rightarrow S'$

- I.e., the execution of a command, c, changes the current state s to a new state s', formally: $t(c, s) = s'$

Synchronization is achieved, if all processes execute the same set of commands in the same order

> *A process can execute a command timestamped T when it has learned of all commands issued by all other processes with timestamps less than or equal to T. The precise algorithm is straightforward, and we will not bother to describe it.*

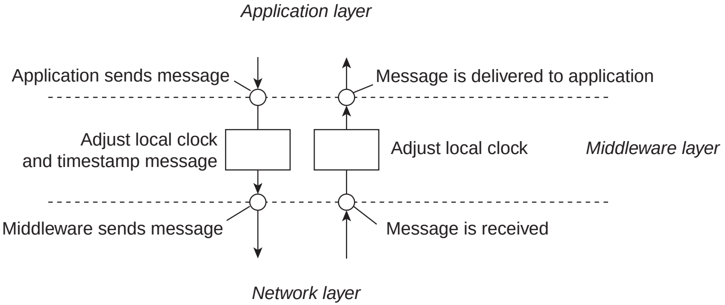
The problem is that the failure of a single process blocks the system

Use of Lamport Clocks: Total Order Multicast (1/2)

Problem How to ensure that if m and m' are delivered by processes i and j, then they deliver m and m' in the same order?

Solution Use **extended** Lamport timestamps to timestamp messages, and **deliver** the messages in the order of these timestamps

Deliver vs. Receive this is similar to what happens with TCP to ensure order in point-to-point communication



Use of Lamport Clocks: Total Order Multicast (2/2)

Assumptions The communication channel is:

- Reliable
- FIFO

- Each process keeps its own Lamport clock
- The only relevant events are the sending and receiving of multicast messages
- Just before multicasting a message, the LC is incremented and its value used to timestamp the message
- Upon receiving a message *m*, a process:
  1. Inserts the message in a queue of messages ordered by their extended Lamport timestamps;
  2. Updates the Lamport clock to $LC = max(TS(m), LC)$
- A message is delivered to the application only when:
  - It is at the head of the queue
  - It is **stable**
    - If there is a message on the queue from every other process
- To reduce the delivery delay, can use acknowledgments

Roadmap

Vector Clocks (1/3)

Observation The main limitation of Lamport clocks is that:

$$L(e) < L(e') \not\Rightarrow e \rightarrow e'$$

Idea Use an array of timestamps, one per processor

- Due to Mattern, Fidge and Schmuck

Rules Each process p_i keeps its own vector V_i, which it updates as follows:

VC1 if e is not the receiving of a message, just increment $V_i[i]$

VC2 if e is the receiving of a message m:

$$V_i[i] = V_i[i] + 1$$
$$V_i[j] = max(V_i[j], TS(m)[j])$$

- **Initially** $V_i[j] = 0$, for all j
- The timestamp of the sending event is piggybacked on the corresponding message ($TS(m) = V(send(m))$)

Basically

$V_i[i]$ is the number of events timestamped by p_i

$V_i[j]$ is the number of events in p_j that p_i **knows** about

Vector Clocks (2/3)

Let V and V' be vector timestamps

Vector Timestamps Comparison We define the relation $<$ between vector timestamps:

$$V < V' \textit{ iff } \forall_j : V[j] \leq V'[j] \wedge \exists_i : V[i] < V'[i]$$

Vector Clock Condition

$$\begin{aligned} e \rightarrow e' &\Rightarrow V(e) < V(e') \\ V(e) < V(e') &\Rightarrow e \rightarrow e' \end{aligned}$$

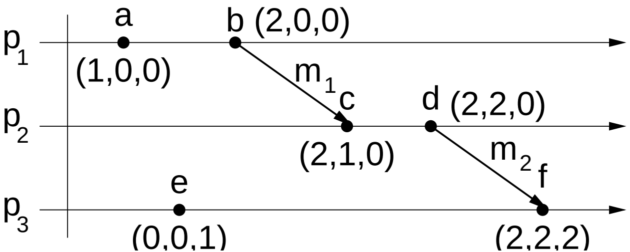
On the other hand:

$$\neg(V(e) < V(e')) \wedge \neg(V(e') < V(e)) \Rightarrow e || e'$$

Conclusion Vector timestamps can be used to determine whether the HB relation holds between any two pairs of events

- Lamport clocks allow to conclude **only** if the HB does **not** hold

Vector Clocks (3/3)



- *a* and *e* are concurrent events
- The main issue with vector clocks is that we need *n timestamps* per event, whereas *Lamport clocks* need only one
  - But there is no way to avoid it (Charron-Bost).
- **Hidden** communication channels can lead to **anomalous** behavior
  - I.e. to the violation of the Clock Condition

  for both Lamport clocks and vector clocks.
  - Lamport claims that only synchronized (physical) clocks may eliminate such anomalies

Vector Clocks Use: Causal Order Multicast (1/2)

Problem How to ensure that if $m \rightarrow m'$ and process i delivers m', then it must have previously delivered m

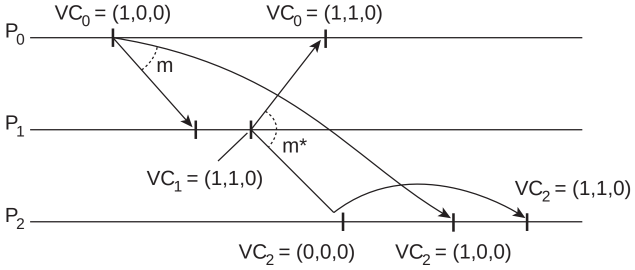
Solution Use vector clocks to timestamp messages, and **deliver** the messages in the order of these timestamps (as defined above)

- Each process keeps its own vector clock
- The only relevant events are the sending and receiving of multicast messages
- Just before multicasting a message, the sender updates its VC after which it timestamps the message
- Upon receiving a message m, a receiver inserts the message in the queue of received messages
- Process i delivers message m to the application only when:

$$V_i[j] \geq TS(m)[j], \forall j \neq k, \text{ where } k \text{ is the sender of } m$$
$$V_i[k] = TS(m)[k] - 1$$

After which it should update its VC (no need to increment $V_i[i]$)

Vector Clocks Use: Causal Order Multicast (2/2)



Observations

- $VC_i[i]$, counts the number of messages multicasted by p_i
- $VC_i[j]$, $i \neq j$, counts the number of messages multicasted by p_j that p_i has delivered to the application
- The communication channels need to be reliable, but not FIFO. Why?

Question does the total order multicast protocol (with Lamport timestamps) also ensure causal order?

Further Reading

- Tanenbaum and van Steen, Section 6.2 of *Distributed Systems*, 2nd Ed.
- Leslie Lamport, *Time, Clocks and the Ordering of Events in a Distributed System*, Communications of the ACM 21(7): 558-565 (1978)
- F. Mattern, "Virtual Time and Global States of Distributed Systems", in Proc. Workshop on Parallel and Distributed Algorithms, Elsevier, pp. 215-226.
- C. Baquero and N. Preguiça, "Why logical clocks are easy", Communications of the ACM 59(4): 43-47 (2016)