Distributed Systems Fundamentals

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Lamport's Clocks

Introduction

Lamport's clocks keep a virtual time among distributed systems. The goal is to provide an ordering upon events within the system.

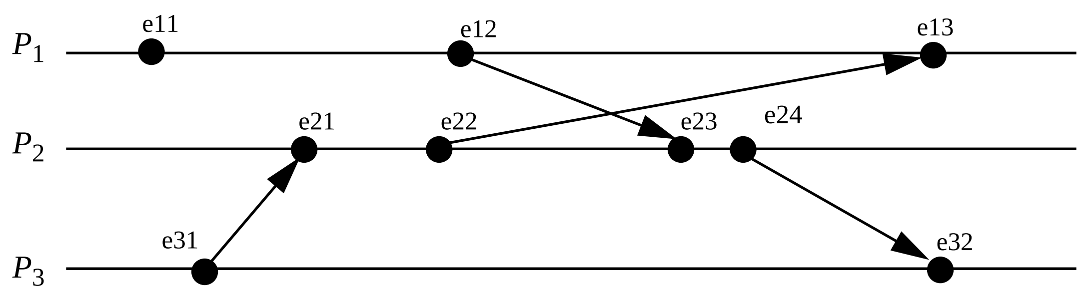
Notation

- P_i process
- C_i. clock associated with process P_i

Protocol

1. Increment clock C_i between any two successive events in process P_i: $C_i \leftarrow C_i + d$ ($d > 0$)
2. Let event a be the sending of a message by process P_i; it is given the timestamp $t^a = C_i(a)$. Let b be the receipt of that message by P_j. Then when P_j receives the message, $C_j \leftarrow \max(C_j, t^a + d)$ ($d > 0$)

Example



Assume all clocks start at 0, and d is 1 (that is, each event incrememts the clock by 1). At event e_{12}, $C_1(e_{12}) = 2$. Event e_{12} is the sending of a message to P_2. When P_2 receives the message (event e_{23}), its clock $C_2 = 2$. The clock is reset to 3. Event e_{24} is P_2's sending a message to P_3. That message is received at e_{32}. C_3 is 1 (as one event has passed). By rule 2, C_3 is reset to the maximum of $C_2(c_{24})$+1 and the current value of C_3, so C_3 becomes 5.

Problem

Clearly, if a $\rightarrow$ b, then $C(a) < C(b)$. But if $C(a) < C(b)$, does $a \rightarrow b$?
The answer, surprisingly, is not necessarily. In the above example, $C_3(e_{31}) = 1 < 2 = C_1(e_{12})$. But e_{31} and e_{12} are causally unrelated; that is, $e_{31} \not\rightarrow e_{12}$. However, $C_1(e_{11}) < C_3(e_{32})$, and clearly $e_{11} \rightarrow e_{32}$. Hence one cannot say one way or the other.

Vector Clocks

Introduction

This is based upon Lamport's clocks, but each process keeps track of what is believes the other processes' interrnal clocks are (hence the name, vector clocks). The goal is to provide an ordering upon events within the system.

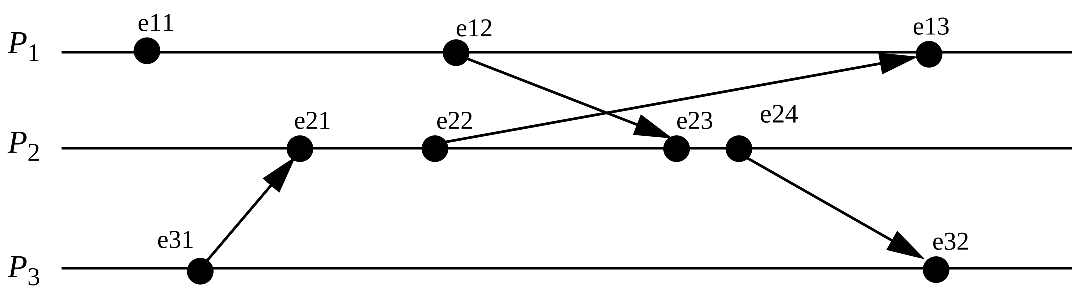
Notation

- n processes
- P_i process
- C_i. vector clock associated with process P_i; jth element is $C_i[j]$ and contains P_i's latest value for the current time in process P_k.

Protocol

1. Increment clock C_i between any two successive events in process P_i: $C_i[i] \leftarrow C_i[i] + d$ ($d > 0$)
2. Let event a be the sending of a message by process P_i; it is given the vector timestamp $t^a = C_i(a)$. Let b be the receipt of that message by P_j. Then when P_j receives the message, it updates its vector clock for all $k = 1, \ldots, n$: $C_j[k] \leftarrow \max(C_j[k], t^a[k] + d)$ ($d > 0$)

Example



Here is the progression of time for the three processes:
e_{11}: $C_1 = (1, 0, 0)$
e_{31}: $C_3 = (0, 0, 1)$
e_{21}: $C_2 = (0, 0, 1)$ as $t^a = C_3(e_{31}) = (0, 0, 1)$ and previously, C_3 was $(0, 0, 1)$
e_{22}: $C_2 = (0, 1, 1)$
e_{12}: $C_1 = (2, 0, 0)$
e_{23}: $C_2 = (2, 1, 1)$ as $t^a = C_1(e_{12}) = (2, 0, 0)$ and previously, C_2 was $(0, 1, 1)$
e_{24}: $C_2 = (2, 2, 1)$
e_{13}: $C_1 = (2, 1, 1)$ as $t^a = C_2(e_{22}) = (0, 1, 1)$ and previously, C_1 was $(2, 0, 0)$
e_{32}: $C_3 = (2, 2, 1)$ as $t^a = C_2(e_{24}) = (2, 2, 1)$ and previously, C_3 was $(0, 0, 1)$
Notice that $C_1(e_{11}) < C_3(e_{32})$, so $e_{11} \rightarrow e_{32}$, but $C_1(e_{11})$ and $C_3(e_{31})$ are incomparable, so e_{11} and e_{31} are concurrent.

Birman-Schiper-Stephenson Protocol

Introduction

The goal of this protocol is to preserve ordering in the sending of messages. For example, if *send*(m_1) → send(m_2), then for all processes that receive both m_1 and m_2, *receive*(m_1)→ *receive*(m_2). The basic idea is that m_2 is not given to the process until m_1 is given. This means a buffer is needed for pending deliveries. Also, each message has an associated vector that contains information for the recipient to determine if another message preceded it. Also, we shall assume all messages are broadcast. Clocks are updated only when messages are sent.

Notation

- n processes
- P_i process
- C_i. vector clock associated with process P_i; jth element is $C_i[j]$ and contains P_i's latest value for the current time in process P_k.
- t^m vector timestamp for message m (stamped *after* local clock is incremented)

Protocol

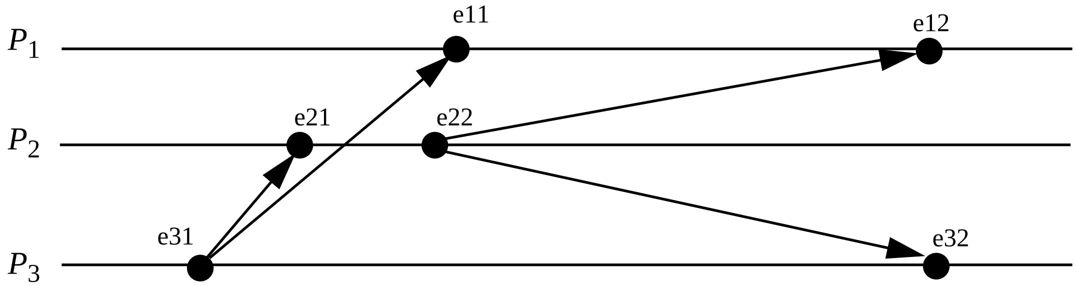
P_i* sends a message to *P_j

1. P_i increments $C_i[i]$ and sets the timestamp $t^m = C_i[i]$ for message m.

P_j* receives a message from *P_i

1. When P_j, $j \neq i$, receives m with timestamp t^m, it delays the message's delivery until *both*:
   a. $C_j[i] = t^m[i] - 1$; and
   b. for all $k \leq n$ and $k \neq i$, $C_j[k] \geq t^m[k]$.
2. When the message is delivered to P_j, update P_j's vector clock
3. Check buffered messages to see if any can be delivered.

Example



Here is the protocol applied to the above situation:

e_{31}: P_3 sends message a; $C_3 = (0, 0, 1)$; $t^a = (0, 0, 1)$

e_{21}: P_2 receives message a. As $C_2 = (0, 0, 0)$, $C_2[3] = t^a[3] - 1 = 1 - 1 = 0$ and $C_2[1] \geq t^a[1]$ and $C_2[2] \geq t^a[2] = 0$. So the message is accepted, and C_2 is set to (0, 0, 1)

e_{11}: P_1 receives message a. As $C_1 = (0, 0, 0)$, $C_1[3] = t^a[3] - 1 = 1 - 1 = 0$ and $C_1[1] \geq t^a[1]$ and $C_1[2] \geq t^a[2] = 0$. So the message is accepted, and C_1 is set to (0, 0, 1)

e_{22}: P_2 sends message b; $C_2 = (0, 1, 1)$; $t^b = (0, 1, 1)$

e_{12}: P_1 receives message b. As $C_1 = (0, 0, 1)$, $C_1[2] = t^b[2] - 1 = 1 - 1 = 0$ and $C_1[1] \geq t^b[1]$ and $C_1[3] \geq t^b[2] = 0$. So the message is accepted, and C_1 is set to (0, 1, 1)

e_{32}: P_3 receives message b. As $C_3 = (0, 0, 1)$, $C_3[2] = t^b[2] - 1 = 1 - 1 = 1$ and $C_1[1] \geq t^b[1]$ and $C_1[3] \geq t^b[2] = 0$. So the message is accepted, and C_3 is set to (0, 1, 1)

Now, suppose t^a arrived as event e_{12}, and t^b as event e_{11}. Then the progression of time in P_1 goes like this:

e_{11}: P_1 receives message b. As $C_1 = (0, 0, 0)$, $C_1[2] = t^b[2] - 1 = 1 - 1 = 0$ and $C_1[1] \geq t^b[1]$, but $C_1[3] < t^b[3]$, so the message is held until another message arrives. The vector clock updating algorithm is not run.

e_{12}: P_1 receives message a. As $C_1 = (0, 0, 0)$, $C_1[3] = t^a[3] - 1 = 1 - 1 = 0$, $C_1[1] \geq t^a[1]$, and $C_1[2] \geq t^a[2]$. The message is accepted and C_1 is set to (0, 0, 1). Now the queue is checked. As $C_1[2] = t^b[2] - 1 = 1 - 1 = 0$, $C_1[1] \geq t^b[1]$, and $C_1[3] \geq t^b[3]$, that message is accepted and C_1 is set to (0, 1, 1).

Schiper-Eggli-Sandoz Protocol

Introduction

The goal of this protocol is to ensure that messages are given to the receiving processes in order of sending. Unlike the Birman-Schiper-Stephenson protocol, it does not require using broadcast messages. Each message has an associated vector that contains information for the recipient to determine if another message preceded it. Clocks are updated only when messages are sent.

Notation

- n processes
- P_i process
- C_i. vector clock associated with process P_i; jth element is $C_i[j]$ and contains P_i's latest value for the current time in process P_k.
- t^m vector timestamp for message m (stamped *after* local clock is incremented)
- t^i current time at process P_i
- V_i vector of P_i's previously sent messages; $V_i[j] = t^m$, where P_j is the destination process and t^m the vector timestamp of the message; $V_i[j][k]$ is the kth component of $V_i[j]$.
- V^m vector accompanying message m

Protocol

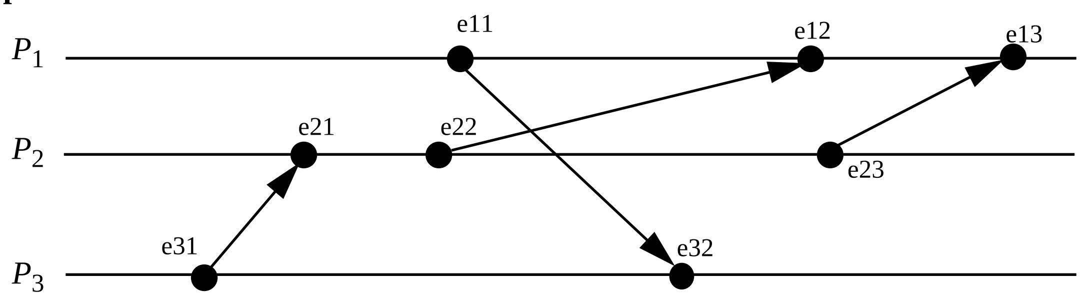
P_i sends a message to P_j

1. P_i sends message m, timestamped t^m, and V_i, to process P_j .
2. P_i sets $V_i[j] = t^m$.

P_j receives a message from P_i

1. When P_j, $j \neq i$, receives m, it delays the message's delivery if *both*:
   a. $V^m[j]$ is set; and
   b. $V^m[j] < t^j$
2. When the message is delivered to P_j, update all set elements of V_j with the corresponding elements of V^m, except for $Vj[j]$, as follows:
   a. If $Vj[k]$ and $Vm[k]$ are uninitialized, do nothing.
   b. If $Vj[k]$ is uninitialized and $Vm[k]$ is initialized, set $Vj[k] = Vm[k]$.
   c. If both $Vj[k]$ and $Vm[k]$ are initialized, set $Vj[k][k'] = \max(Vj[k][k'], Vm[k][k'])$ for all $k' = 1, \ldots, n$
3. Update P_j's vector clock.
4. Check buffered messages to see if any can be delivered.

Example



Here is the protocol applied to the above situation:

e_{31}: P_3 sends message a to P_2 . C_3 = (0, 0, 1); t^a = (0, 0, 1), V^a = (?, ?, ?); V_3 = (?, (0, 0, 1), ?)

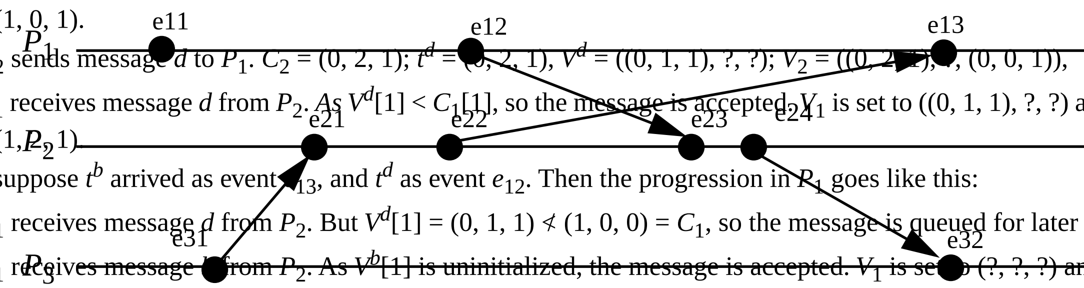
e_{21}: P_2 receives message a from P_1. As $V^a[2]$ is uninitialized, the message is accepted. V_2 is set to (?, ?, ?) and C_2 is set to (0, 0, 1).

e_{22}: P_2 sends message b to P_1. C_2 = (0, 1, 1); t^b = (0, 1, 1), V^b = (?, ?, ?); V_2 = ((0, 1, 1), ?, ?)

e_{11}: P_1 sends message c to P_3. C_1 = (1, 0, 0); t^c = (1, 0, 0), V^c = (?, ?, ?); V_1 = (?, ?, (1, 0, 0)),

e_{12}: P_1 receives message b from P_2. As $V^b[1]$ is uninitialized, the message is accepted. V_1 is set to (?, ?, ?) and C_1 is set to (1, 1, 1).

e_{32}: P_3 receives message c from P_1. As $V^c[3]$ is uninitialized, the message is accepted. V_3 is set to (?, ?, ?) and C_3 is set to (1, 0, 1).



e_{23}: P_2 sends message d to P_1. C_2 = (0, 2, 1); t^d = (0, 2, 1), V^d = ((0, 1, 1), ?, ?); V_2 = ((0, 2, 1), ?, (0, 0, 1)),

e_{13}: P_1 receives message d from P_2. As $V^d[1] < C_1[1]$, so the message is accepted. V_1 is set to ((0, 1, 1), ?, ?) and C_1 is set to (1, 2, 1).

Now, suppose t^b arrived as event e_{13}, and t^d as event e_{12}. Then the progression in P_1 goes like this:

e_{12}: P_1 receives message d from P_2. But $V^d[1]$ = (0, 1, 1) $\not<$ (1, 0, 0) = C_1, so the message is queued for later delivery.

e_{13}: P_1 receives message b from P_2. As $V^b[1]$ is uninitialized, the message is accepted. V_1 is set to (?, ?, ?) and C_1 is set to (1, 1, 1). The message on the queue is now checked. As $V^d[1]$ = (0, 1, 1) < (1, 1, 1) = C_1, the message is now accepted. V_1 is set to ((0, 1, 1), ?, ?) and C_1 is set to (1, 2, 1).

Chandy-Lamport Global State Recording Protocol

Introduction

The goal of this distributed algorithm is to capture a consistent global state. It assumes all communication channels are FIFO. It uses a distinguished message called a *marker* to start the algorithm.

Protocol

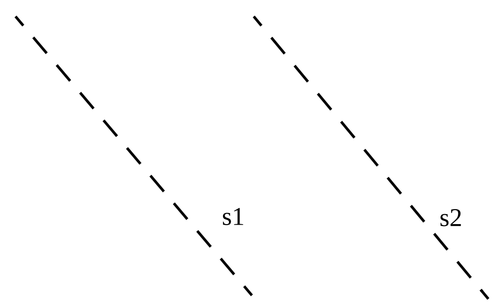
P_i sends marker

1. *Pi* records its local state
2. For each C_{ij} on which P_i has not already sent a marker, P_i sends a marker *before* sending other messages.

P_i receives marker from Pj

1. If P_i has *not* recorded its state:
   a. Record the state of C_{ji} as empty
   b. Send the marker as described above
2. If P_i has recorded its state LS_i
   a. Record the state of C_{ji} to be the sequence of messages received between the computation of LS_i and the marker from C_{ji}.

Example



Here, all processes are connected by communications channels Cij. Messages being sent over the channels are represented by arrows between the processes.

Snapshot s_1:

P_1 records LS_1, sends markers on C_{12} and C_{13}

P_2 receives marker from P_1 on C_{12}; it records its state LS_2, records state of C_{12} as empty, and sends marker on C_{21} and C_{23}

P_3 receives marker from P_1 on C_{13}; it records its state LS_3, records state of C_{13} as empty, and sends markers on C_{31} and C_{32}.

P_1 receives marker from P_2 on C_{21}; as LS_1 is recorded, it records the state of C_{21} as empty.

P_1 receives marker from P_3 on C_{31}; as LS_1 is recorded, it records the state of C_{31} as empty.

P_2 receives marker from P_3 on C_{32}; as LS_2 is recorded, it records the state of C_{32} as empty.

P_3 receives marker from P_2 on C_{23}; as LS_3 is recorded, it records the state of C_{23} as empty.

Snapshot s_2: now a message is in transit on C_{12} and C_{21}.

P_1 records LS_1, sends markers on C_{12} and C_{13}

P_2 receives marker from P_1 on C_{12} after the message from P_1 arrives; it records its state LS_2, records state of C_{12} as empty, and sends marker on C_{21} and C_{23}

P_3 receives marker from P_1 on C_{13}; it records its state LS_3, records state of C_{13} as empty, and sends markers on C_{31} and C_{32}.

P_1 receives marker from P_2 on C_{21}; as LS_1 is recorded, and a message has arrived since LS_1 was recorded, it records the state of C_{21} as containing that message.
P_1 receives marker from P_3 on C_{31}; as LS_1 is recorded, it records the state of C_{31} as empty.
P_2 receives marker from P_3 on C_{32}; as LS_2 is recorded, it records the state of C_{32} as empty.
P_3 receives marker from P_2 on C_{23}; as LS_3 is recorded, it records the state of C_{23} as empty.

Huang's Termination Detection Protocol

Introduction

The goal of this protocol is to detect when a distributed computation terminates.

Notation

- n processes
- P_i process; without loss of generality, let P_0 be the *controlling agent*
- W_i. weight of process P_i; initially, $W_0 = 1$ and for all other i, $W_i = 0$.
- $B(W)$ computation message with assigned weight W
- $C(W)$ control message sent from process to controlling agent with assigned weight W

Protocol

P_i sends a computation message to P_j

1. Set W_i' and W_j to values such that $W_i' + W_j = W_i$, $W_i > 0$, $W_j > 0$. (W_i' is the new weight of P_i.)
2. Send $B(W_j)$ to P_j

P_j receives a computation message $B(W)$ from P_i

1. $W_j = W_j + W$
2. If P_j is idle, P_j becomes active

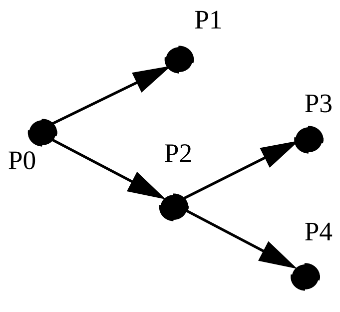
P_i becomes idle:

1. Send $C(W_i)$ to P_0
2. $W_i = 0$
3. P_i becomes idle

P_i receives a control message $C(W)$:

1. $W_i = W_i + W$
2. If $W_i = 1$, the computation has completed.

Example



The picture shows a process P_0, designated the *controlling agent*, with $W_0 = 1$. It asks P_1 and P_2 to do some computation. It sets W_1 to 0.2, W_2 to 0.3, and W_3 to 0.5. P_2 in turn asks P_3 and P_4 to do some computations. It sets W_3 to 0.1 and W_4 to 0.1.
When P_3 terminates, it sends C(W_3) = C(0.1) to P_2, which changes W_2 to 0.1 + 0.1 = 0.2.
When P_2 terminates, it sends C(W_2) = C(0.2) to P_0, which changes W_0 to 0.5 + 0.2 = 0.7.
When P_4 terminates, it sends C(W_4) = C(0.1) to P_0, which changes W_0 to 0.7 + 0.1 = 0.8.
When P_1 terminates, it sends C(W_1) = C(0.2) to P_0, which changes W_0 to 0.8 + 0.2 = 1.
P_0 thereupon concludes that the computation is finished.
Total number of messages passed: 8 (one to start each computation, one to return the weight).