A NEW ALGORITHM TO IMPLEMENT CAUSAL ORDERING

André SCHIPER, Jorge EGGLI, Alain SANDOZ

Ecole Polytechnique Fédérale de Lausanne
Département d'Informatique
CH-1015 Lausanne, Switzerland
schiper@elma.epfl.ch.bitnet

Abstract

This paper presents a new algorithm to implement causal ordering. Causal ordering was first proposed in the ISIS system developed at Cornell University. The interest of causal ordering in a distributed system is that it is cheaper to realize than total ordering. The implementation of causal ordering proposed in this paper uses logical clocks of Mattern-Fidge (which define a partial order between events in a distributed system) and presents two advantages over the implementation in ISIS: (1) the information added to messages to ensure causal ordering is bounded by the number of sites in the system, and (2) no special protocol is needed to dispose of this added information when it has become useless. The implementation of ISIS presents however advantages in the case of site failures.

Keywords: distributed algorithms, ordering.

1. Introduction

The notion of global time does not exist in a distributed system. Each site has its own clock, and it is impossible to order two events E_1 and E_2 occurring on different sites of the system unless they communicate. It is however often necessary to order events in a distributed system.

One possible construction of a total ordering of events in a distributed system is described in [Lamport 78]. It is built using logical clocks defined in the same paper. To progress however, the algorithm requires each site to have received at least one message from every other site in the system, which means systematic acknowledgements of messages.

There does however exist a weaker ordering than total ordering: causal ordering. The implementation of such an ordering needs less message exchanging (no acknowledgements like the ones above are needed), and can prove to be sufficient in some applications.

This causal ordering should not be confused with the causality in the definition of logical clocks, which we call here "causal timestamping". Let us give an example enabling us to distinguish causal ordering from causal timestamping. Suppose an event SEND(M_1), corresponding to the site S_1 sending message M_1, and timestamped with logical time T_1. Suppose then a second event SEND(M_2), with timestamp T_2, occurring on site S_2 after S_2 has received message M_1. Lamport's logical clocks ensure that $T_1<T_2$. Thanks to this "causal timestamping", event SEND(M_1) precedes event SEND(M_2) for every site in the system which will ever know of these events. This does not say anything about the order in which the messages M_1 and M_2 arrive at any given site in the system. Causal ordering of the events SEND(M_1) and SEND(M_2) means that every recipient of both M_1 and M_2 receives message M_1 before message M_2. This is not automatically the case in a distributed system, as shown in figure 1, where site S_3 gets message M_2 before message M_1, even though event SEND(M_1) occurs before event SEND(M_2).

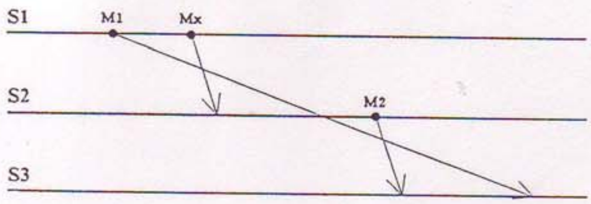


Figure 1. An example of the violation of causal ordering.

Causal ordering is described in [Birman 87] and has been implemented in the ISIS system developed at Cornell University [Birman 88a]. The implementation of causal ordering which we present here differs however from that of ISIS. It presents two advantages: (1) the information added to messages to ensure causal ordering of events is bounded (in the sense defined in section 4.2) by the number of sites in the system, and (2) the implementation does not require any complicated algorithm to clean up this additional information. The implementation of ISIS presents however advantages in the case of site failures. Causal ordering is also achieved through the *conversation abstraction* [Peterson 87]; this implementation however, uses explicit "send before" relations between messages, which is not the case in ours. The rest of the paper is organized in the following way: in section 2, we formally define causal ordering and show the usefulness of this notion. In section 3, we briefly present the idea of the implementation of causal ordering in ISIS. Finally in section 4, we develop a new algorithm to implement causal ordering.

2. Causal ordering of events

Causal ordering is linked to the relation "happened before" between events, noted "$\rightarrow$", which we classically define as the transitive closure of the relation R described below (to simplify, we shall speak of sites rather than processes). Two events E_1 and E_2 are related according to R, iff any of the following two conditions is true:

1. E_1 and E_2 are two events occurring on the same site, E_1 before E_2;

2. E_1 corresponds to the sending of a message M from one site, and E_2 corresponds to the reception of the same message M on any other site.

With the relation $\rightarrow$, we can formally define the causal ordering of two events E_1=SEND(M_1) and E_2=SEND(M_2), noted $E_1 \overset{c}{\rightarrow} E_2$, as follows:

$E_1 \overset{c}{\rightarrow} E_2$ iff (if $E_1 \rightarrow E_2$, then any recipient of both M_1 and M_2 receives message M_1 before message M_2)

To illustrate the usefulness of causal ordering, consider the handling of some replicated data on every site of a distributed system [Joseph 86, Birman 88b]. Each site controls one copy of the replicated data and can update it. To ensure mutual exclusion of updates, let's introduce a token. The site in possession of the token can update the data. Every write operation W_i on the local copy performed by a site S is immediately broadcasted to every other site (see figure 2).

In the example of figure 2, we have SEND(W_1)$\rightarrow$SEND(W_2)$\rightarrow$SEND(W_3)$\rightarrow$SEND(W_4). Precedence of SEND(W_2) over SEND(W_3) is ensured by the sending of the token, since (1) SEND(W_2)$\rightarrow$SEND(token), and (2) reception of the token happens before SEND(W_3). The causal ordering ensures that every site receives the updates in the same order (i.e. the order in which they happened initially). So every site updates its local copy in that order, which ensures global consistency of the set of copies.

It is important to realize that this ordering between events in the distributed system is not a total, but only a partial ordering. To see this, just consider a second replicated data, modified independently from the first one, and controlled by another token. Let's note X_j the updates of this data. Causal ordering of the events SEND(X_j), ensures again that every site sees these updates in the same order. However, one site S may well receive first some operation W_i and then X_j, whereas a second site S' might receive X_j before W_i. This shows that causal ordering of events is weaker than total ordering. Construction of a total ordering is however more expensive to achieve in terms of number of messages exchanged. The low cost of the implementation of causal ordering makes it an interesting tool for the development of distributed applications. Note that in the example above, if W and X are independent, there is no need for causal ordering of SEND(W_i) and SEND(X_j).

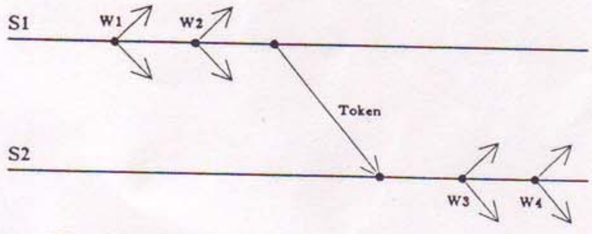


Figure 2. Handling of replicated data using causal ordering.

3. Implementation of causal ordering in ISIS

The implementation of causal ordering in ISIS is described in [Birman 87]. However, ISIS implements causal ordering together with atomic broadcasts (atomic broadcasts ensure that a broadcasted message is received by all sites that do not fail, or by none). For clarity, we shall only be interested here in the realization of causal ordering. The idea is the following: every message M carries along with itself every other message sent before M it might know of. To achieve this, every site S handles a buffer (noted BUFF_S) which contains, in their order of emission, every message received or sent by S (that is, every message preceding any future message emitted by S). Sending a message M from S to any site S' will require the following actions: message M is first inserted into buffer BUFF_S, a packet P is then built containing all the messages in BUFF_S, and finally this packet is sent to the destination site S' of M. When it arrives at S', the following actions are executed for every message in P: (1) if the message is already in buffer BUFF_S' (every message is given a unique id), it has already arrived at S' and is ignored. Else the message is inserted in BUFF_S'; (2) every message in the packet, of which S' is the destination site, is delivered to S' in the correct order.

As an example, consider figure 1. The packet sent from site S_1 to S_2 (resulting from the emission of message M_x) contains, in order, messages M_1 and M_x. The packet sent from S_2 to S_3 (resulting from the emission of message M_2) contains messages M_1, M_x, and M_2 (transmission of M_x is not necessary, but does take place if the algorithm described in [Birman 87] is respected). So message M_1 is carried from site S_1 to S_3 over two different paths: $\langle S_1,S_3 \rangle$ and $\langle S_1,S_2,S_3 \rangle$. In this way, site S_3 will always receive message M_1 before message M_2.

The algorithm, as described here, still has one major drawback: the information contained in BUFF_S increases indefinitely. Some protocol must be added to retrieve obsolete messages from the buffers. The simplified idea is the following: periodically each site S independently builds a request packet P containing the ids of messages in its buffer BUFF_S. Packet P is broadcasted to every other site. When some site S' receives the packet, it notes the source site S along with the identifiers (the corresponding messages must not be sent to S any more!) and acknowledges back to S. When S has received an acknowledgement from every site, the messages identified in packet P can be deleted from BUFF_S. This is because, if messages sent from S' to S are received in the order of emission, every message that could have been identified in P and nevertheless sent from S' to S meanwhile, will have been received by S before it receives the acknowledgement; afterwards, these messages will not be sent from S' to S any more. Note that the protocol initialized by S does not allow S' to delete messages from its own buffer: some message M identified in P could still be on the way to S', sent by another site S''. After deleting message M from BUFF_S', S' would not be able to recognize the replicated message M.

4. Another algorithm to implement causal ordering

4.1. Some reflexions on the violation of causal ordering

The basic idea of our algorithm is the following. Rather than carrying around with a message every message which precedes it, let's try to answer the following question when a message M arrives at a site S: will any message preceding M arrive at S in the future? If the answer is yes, message M must not be delivered immediately. It will only be delivered to S when every message causally preceding M has arrived. For the moment, let's try to answer an easier question: is it possible to know that the causal ordering has been transgressed when a message arrives at a site?

If we consider Lamport's logical clocks, we can state the following proposition:

> *Proposition 1: if the causal order has been violated, then there exists a message M, timestamped T(M), which arrives at destination S when the local time T(S) is greater than T(M).*

Proof: consider two messages M_1 and M_2 sent to S, such that $SEND(M_1) \rightarrow SEND(M_2)$. It follows from the definitions that $T(M_1)<T(M_2)$. Suppose the causal ordering has been violated, i.e. M_2 arrives at S before M_1. After delivery of M_2, the logical time at S becomes greater than $T(M_2)$: $T(M_2)<T(S)$. Therefore, when M_1 arrives at S, T(S) is greater than $T(M_1)$, which completes the proof.

However, the converse of Proposition 1 is not true, as shown in figure 3 where a message M, timestamped T(M), arrives at site S which has logical time T(S) such that T(M)<T(S). This does not mean that the causal order has been violated, which shows that T(M)<T(S) is a necessary, but not sufficient, condition for causal ordering violation.

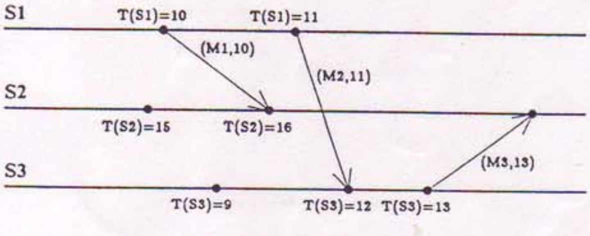


Figure 3. Transgression of causality cannot be detected with Lamport's logical clocks.

So there is no way of answering our second question about causality violation knowing only T(S) and T(M). The problem with Lamport's logical clocks is that they define a total order, whereas there exists only a partial ordering of the events in a distributed system.

A logical clock defining a weaker, partial order is the tool which will be sufficient to infer that the causal ordering was transgressed. This logical clock was recently proposed in [Mattern 89] and [Fidge 88]. For the sake of clarity, lets rapidly recall the principle. The logical time is defined by a vector of length N, where N is the number of sites in the system. We will note this logical time VT (vector time), VT(S) for the logical time on site S, and VT(M) for the timestamp of message M. The logical time of a site evolves in the following way (see figure 4):

- when a local event occurs at site S_i, the i^{th} entry to the vector $VT(S_i)$ is incremented by one: $VT(S_i)[i]:=VT(S_i)[i]+1$.
- when S_i receives a message M, timestamped VT(M), the rule states:
  - for $j=i$, $VT(S_i)[j]:=VT(S_i)[j]+1$;
  - for $j\neq i$, $VT(S_i)[j]:=\max(VT(S_i)[j],VT(M)[j])$.

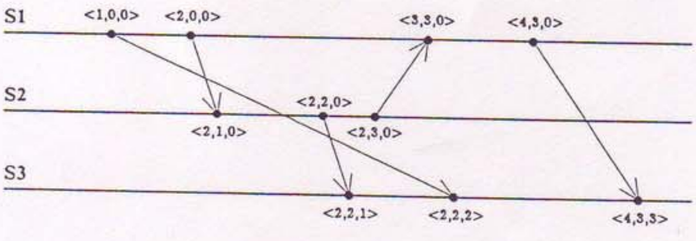


Figure 4. Mattern-Fidge logical clocks.

We also define the ordering relation "<" between logical vector times as follows: $VT_1<VT_2$ iff $VT_1[i]\leq VT_2[i]$, for all i. This relation is trivially reflexive, antisymetric and transitive. Having defined relation <, it is possible to show that, given two events E_1 and E_2, then $E_1 \rightarrow E_2$ *iff*

$VT(E_1)<VT(E_2)$, where VT(E) is the value of VT(S) just after occurrence of event E on site S. In other words, events E_1 and E_2 are concurrent iff $not(VT(E_1)<VT(E_2))$ and $not(VT(E_2)<VT(E_1))$.

The logical time in the system being so defined, we now proceed to prove the following proposition:

> *Proposition 2: the causal ordering of events in the system is violated iff there exists a message M, timestamped VT(M), which arrives at destination S when local time VT(S) is such that $VT(M)<VT(S)$.*

Proving the implication "causal ordering violation $\Rightarrow$ there exists M, $VT(M)<VT(S)$" is similar to the proof given above concerning Lamport's logical clocks. To prove the converse, we need the following lemma (the proof is given in [Schiper 89]):

> *Lemma 1: consider an event E_1, timestamped $VT(E_1)$, occurring at site S_i. For every event E_2 such that $VT(E_1)[i]\leq VT(E_2)[i]$, $E_1\rightarrow E_2$ is true.*

Using lemma 1, we can now prove "there exists M, $VT(M)<VT(S)$ $\Rightarrow$ causal ordering violation".

Proof: Suppose a message M was sent to site S by site S_i. If $VT(M)<VT(S)$, then in particular, $VT(M)[i]\leq VT(S)[i]$. Consider M' the message which made VT(S)[i] take its current value (recall $S\neq S_i$!). Then $VT(M')[i]=VT(S)[i]$. By lemma 1, it follows from $VT(M)[i]\leq VT(M')[i]$ that $SEND(M)\rightarrow SEND(M')$. Since M' arrived at S before M, the causal ordering has been violated.

4.2. The causal ordering algorithm

We are now going to present our algorithm for achieving causal ordering. As in the algorithm described in section 3, we also associate with each site S a buffer, noted ORD_BUFF_S, which will be sent along with the messages emitted by S. However, the contents of this buffer are not messages, but ordered pairs (S',VT), where S' is a destination site of some message and VT a timestamp vector. Unlike the earlier buffer BUFF_S, this one is bounded in size in the following sense: it holds at most (N-1) pairs, where N is the number of sites in the system. Note however that the time vectors in this buffer are not bounded, since their entries depend on the number of events having occurred on each site. The existence of an algorithm enabling to bound the time vectors in the system is an open problem. The causal ordering algorithm is composed of three parts:

- the insertion of a new pair in ORD_BUFF_S when site S sends a new message;
- the delivery of a message and the merge of the accompanying buffer with the destination site's own buffer;

- the deletion of obsolete pairs in the site's buffer (this part needs no exchange of messages).

4.2.1. Emission of a message

Consider a message M, timestamped VT(M) the logical time of emission, and sent from site S_1 to site S_2. The contents of ORD_BUFF_S_1 are sent along with the message. After the message is sent, the pair (S_2,VT(M)) is inserted in ORD_BUFF_S_1 (note that this pair was not sent with M). This information will be sent along with every message M' emitted from S_1 after message M. The meaning of this pair in the buffer is that *no message carrying the pair can be delivered to S_2 as long as the local time of S_2 is not such that $VT(M)<VT(S_2)$*. This ensures that any message M', emitted after M with destination S_2, will not be delivered before M, because the *only* way for S_2 to have a logical time greater than VT(M), is to receive message M or a message M' which depends causally on M, i.e. SEND(M)$\rightarrow$SEND(M'). However, no message emitted after M will be delivered to S_2 before its logical time is greater than VT(M).

What happens if ORD_BUFF_S_1 already contains a pair (S_2,VT) when (S_2,VT(M)) is to be inserted in the buffer? The older pair can simply be discarded. To see this, we need the following lemma (see also point 4.2.2 and [Schiper 89] for a proof):

> *Lemma 2: for any site S, and any pair (S',VT) in buffer ORD_BUFF_S, the logical time VT(S) at S is such that: VT<VT(S).*

Since, by lemma 2, VT is a time vector such that VT<VT(M), the pair (S_2,VT) becomes obsolete after the insertion of the pair (S_2,VT(M)). It follows that an ordering buffer contains at most (N-1) pairs, that is at most one for every site different from the site it is associated with.

Note that for the protocol to be correct there is no need to suppose that messages sent between two given sites arrive in the order in which they are emitted. If a message M_2 was to overtake message M_1, then M_2 would carry knowledge of M_1 in its accompanying buffer, and so the protocol ensures proper delivery independently of the order of arrival of messages.

Let's complete this point by noting that the algorithm adjusts well to the case of broadcasting a message M to a set DEST of destination sites. The solution consists of sending to every site S in DEST, *in the buffer accompanying M*, all the pairs (S',VT(M)), where S' is in DEST and S'$\neq$S.

4.2.2. Arrival of a message

Suppose a message M arrives at its destination site S_2. If the buffer accompanying M contains no ordered pair (S_2,VT), then the message can be delivered. If such a pair does however figure in that buffer (there is at most one), message M cannot be delivered to S_2 as long as VT<VT(S_2) is not true.

When a message can be delivered to site S_2, two actions must be undertaken: (1) merge the accompanying buffer with the destination site's own buffer, and (2) update the site's logical time. Consider the first point. Suppose the existence of a pair (S,VT), $S \neq S_2$, in the buffer accompanying message M. If ORD_BUFF_S_2 does not contain any pair (S,...), then (S,VT) is introduced in the buffer (if $S=S_2$, the pair need not be introduced in ORD_BUFF_S_2). Now, if a pair (S,VT_1) already figures in the site's buffer, the meaning of these two pairs is the following:

- (S,VT_1): no message can be delivered to S as long as VT_1<VT(S) is not true;
- (S,VT): no message can be delivered to S as long as VT<VT(S) is not true.

Conjunction of these two conditions can be translated into a single pair (S,VT_{SUP}) where VT_{SUP}=sup(VT_1,VT)[1]. Indeed, VT_{SUP} is the smallest time vector such that VT_1<VT_{SUP} and VT<VT_{SUP}.

Note finally that delivery of a message forces the local time to progress, so that delivering of another message may be possible.

4.2.3. Example

Figure 5 shows an example illustrating a few typical situations solved by the causal ordering algorithm. In this figure, the end of an arrow points to the moment at which a message arrives at a destination site, whereas the corresponding circled number indicates the order in which the messages are delivered. Consider messages M_3 and M_5 sent to site S_4. The events SEND(M_3) and SEND(M_5) are concurrent, so messages M_3 and M_5 are delivered in the order of arrival. Now consider messages M_1, M_4 and M_6, sent to site S_3. The order of emission is SEND(M_1)→SEND(M_4)→SEND(M_6). The messages are delivered in this order.

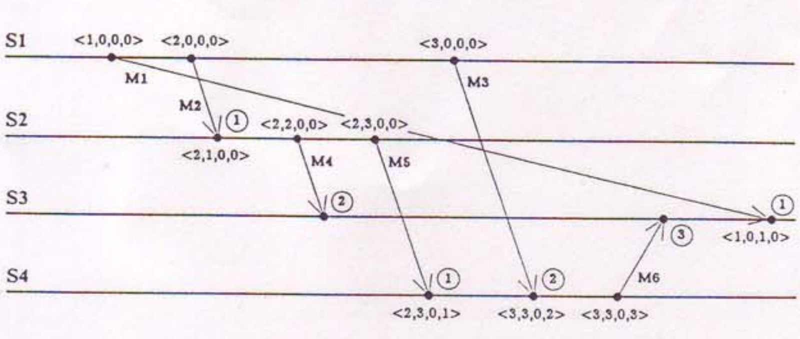
4.2.4. Deletion of an obsolete pair in the ordering buffer

As has already been indicated, the number of pairs in the ordering buffer of a site is bounded. It can however be interesting to delete obsolete pairs from a buffer. The simplest solution consists of comparing message timestamps with buffer timestamps when messages are delivered. Namely, if message M, timestamped VT(M) and sent by site S_1, is delivered to site S_2, then compare VT(M) with the time vector of the pair (S_1,VT) in ORD_BUFF_S_2. If VT<VT(M), then the pair has become obsolete and can be deleted from the local buffer, since the local time on S_1 is already greater than VT.

[1] sup(VT1,VT2)[i]=max(VT1[i],VT2[i])

4.2.5. Proof of the algorithm

Up to this point, we have tried to justify each step of the causal ordering algorithm. This however cannot be considered as a valid proof of its correctness. We are going to show in two steps that the causal ordering is indeed respected. The first step is the proof of the safety of the algorithm, the second its liveness.



The circled numbers indicate on each site the delivery order of messages

ORD_BUFF_S1	
before emission of M1:	empty
(= carried by M1)	
before emission of M2:	(S3,<1,0,0,0>)
before emission of M3:	(S2,<2,0,0,0>)
	(S3,<1,0,0,0>)
after emission of M3:	(S2,<2,0,0,0>)
	(S3,<1,0,0,0>)
	(S4,<3,0,0,0>)

ORD_BUFF_S2	
after delivery of M2:	(S3,<1,0,0,0>)
(= before emission of M4)	
before emission of M5:	(S3,<2,2,0,0>)
after emission of M5:	(S3,<2,2,0,0>)
	(S4,<2,3,0,0>)

ORD_BUFF_S3	
after delivery of M1:	empty
after delivery of M4:	. empty
after delivery of M6:	(S2,<2,0,0,0>)

ORD_BUFF_S4	
after delivery of M5:	(S3,<2,2,0,0>)
after delivery of M3:	(S2,<2,0,0,0>)
	(S3,<2,2,0,0>)
(= before emission of M6)	
after emission of M6:	(S2,<2,0,0,0>)
	(S3,<3,3,0,3>)

Figure 5. Example of the causal ordering algorithm.

Proof of the algorithm.

1. Safety: We must show that the handling of messages by the algorithm respects the causal ordering, i.e. if two messages M_1 and M_2 are sent to some site S and $SEND(M_1) \rightarrow SEND(M_2)$, then message M_1 is delivered to site S before message M_2. An equivalent statement is: if message M_1 is sent to site S, then no message M_2 such that $SEND(M_1) \rightarrow SEND(M_2)$ is delivered to S until M_1 itself has been delivered to S. This is what we are going to show. But first let's infer a couple of remarks from the algorithm.

Remark 1: by definition of the relation "happened before", it follows from $SEND(M_1) \rightarrow SEND(M_2)$ that there exists some maximal sequence $E_0,..,E_m$ of events such that $SEND(M_1)=E_0 \rightarrow E_1 \rightarrow .. \rightarrow E_{m-1} \rightarrow E_m = SEND(M_2)$ (we define maximality as follows: for all $0 \leq k < m$, and for every event E not in the sequence, $E_k \rightarrow E \rightarrow E_{k+1}$ is not true). This sequence need not be unique, but does exist. Then either event E_1 is the delivery of M_1 on its destination site S, or, by maximality, it is a local event on the emission site S_i of M_1. The first case will not be considered in the proof since we will suppose message M_1 has not yet been delivered. In the second case, the pair $(S, VT(M_1))$ has been introduced in ORD_BUFF_S_i when event E_1 occurs. By point 4.2.2, we then have $VT(M_1) < VT$ where (S,VT) is the pair accompanying message M_2 to S.

Remark 2: consider again message M_1 and site S_i sending M_1. As suggested in sections 4.1 and 4.2.1, the only way for any other site S' to have a local time with $VT(M_1)[i] \leq VT(S')[i]$ (or more generally such that $VT(M_1) < VT(S')$) is to have received a message M such that $SEND(M_1) \rightarrow SEND(M)$.

We can now proceed with the proof. We are going to show by induction on the events of destination site S that until message M_1 sent by S_i is delivered, none of these events is the delivery of a message M such that $SEND(M_1) \rightarrow SEND(M)$.

Base step: consider $E(S)_1$ the first event on destination site S and suppose $E(S)_1$ is not the delivery of M_1. Before event $E(S)_1$ occurs, $VT(S)[i]=0$, as every other component of $VT(S)$. For every message M in the system such that $SEND(M_1) \rightarrow SEND(M)$, M is accompanied by a pair (S,VT), and $VT[i] \geq 1 > VT(S)[i]$ (by remark 1, and since $E(S)_1$ is not the delivery of message M_1). So $VT < VT(S)$ is not true. Therefore, in application of the algorithm, event $E(S)_1$ is not the delivery of message M.

Induction step: now consider $E(S)_n$ the n^{th} event on S and assume as induction hypothesis that none of the preceding events $E(S)_1,..,E(S)_{n-1}$ on S is the delivery of a message M such that $SEND(M_1) \rightarrow SEND(M)$. If M_1 has not yet been delivered, it follows from this hypothesis and remark 2 that $VT(E(S)_{n-1})[i] < VT(M_1)[i]$. Now remark 1 says that, if VT is the time vector of the pair (S,VT) accompanying a message M with $SEND(M_1) \rightarrow SEND(M)$, then $VT(M_1)[i] \leq VT[i]$, so VT is not such that $VT < VT(E(S)_{n-1}) = VT(S)$. The algorithm then ensures that $E(S)_n$ is not the delivery of a message M such that $SEND(M_1) \rightarrow SEND(M)$.

We can thus infer that, as long as message M_1 has not been delivered to S, no message happening after M_1 can be delivered to that site.

2. *Liveness:* To complete the proof, we must still show the liveness of our algorithm, i.e. that in the absence of failures every message in the system is indeed delivered.

Proof: ad absurdo. Suppose some message M has arrived at site S, and is never delivered. At the time of arrival, M was accompanied by a pair (S,VT) such that, for some i, $VT(S)[i]<VT[i]$. The number of messages that must be delivered to S before M is finite (it is smaller than the sum of $(VT[i]-VT(S)[i])$ over all such i). In the absence of failures and after some finite time, all these messages will have arrived at S. If every such message had been delivered, then we would have $VT(S)>VT$ and M could be delivered: contradiction. (This is because if $VT(S)>VT$ is not true, again $VT(S)[i]<VT[i]$, for some i. Let's call $n=VT[i]$. Then the n^{th} event on site i was the emission of a message M' for S. If M' has been delivered to site S, then $VT(S)[i]>VT(M')[i]>VT[i]$: contradiction.)

So there exists at least another message M' which will not be delivered to S and should be before M. If (S,VT') is the pair corresponding to S in the accompanying buffer of M', then $VT'<VT$ and $VT'[i]<VT[i]$ for some i. We can thus apply the same reasoning to M' as to M, which completes the proof by finite decreasing induction.

4.3. Failures

Up to this point, we have not considered failures (this is because our implementation preserves the causal ordering even in the case of failures). Some failures however can have surprising effects. Consider figure 6, where message M_1 is sent from site S_1 to site S_2 before message M_2 is sent to site S_3. A communication failure might prevent message M_1 from arriving at its destination, but not message M_2 from arriving at S_3, though sent afterwards. To see this, consider the following sequence: message M_1 is sent to S_2, but arrives with a parity error; then M_2 is sent but site S_1 breaks down before retransmission of M_1 is done.

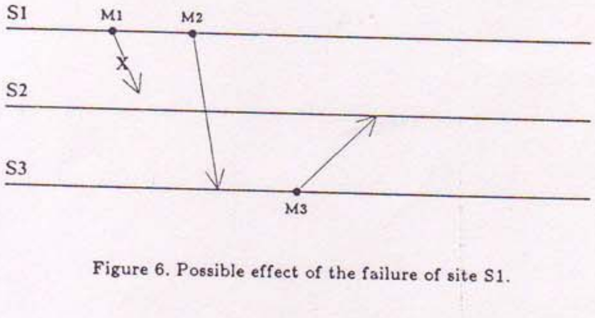


Figure 6. Possible effect of the failure of site S1.

What effect does this have on the causal ordering algorithm? Referring to figure 6, we see that message M_3 will arrive at site S_2 together with a pair $(S_2,VT(M_1))$. If M_1 is not delivered, M_3 will never be! As a matter of fact, site S_3 will never be able to communicate with site S_2 again (meaning messages from S_3 will never be delivered to S_2), since every other message from S_3 to S_2 will pile up behind message M_3, waiting for message M_1. For the same reason, any site having received a message from site S_3 will be prevented by the algorithm of communicating with site S_2. This of course is not a satisfying way to implement causal ordering in the case of failures.

Solutions to this problem can be conceived, but, as we will see, they need some sort of rollback mechanism to be introduced (i.e. in figure 6, for site S_3 to recover a state preceding delivery of message M_2). Let's note that the ISIS implementation resists to this kind of failure, since message M_1 (which is at the heart of the problem) is sent to site S_2 along two different paths: $\langle S_1,S_2\rangle$ and $\langle S_1,S_3,S_2\rangle$, so that message M_3 cannot arrive at S_2 before M_1. This example clearly suggests that the only way to completely solve the problem of failures without rollback is an implementation like the one of ISIS.

Let's show how failures could be treated in our context. Once a failure has been discovered (in the example of figure 6, most likely by site S_2) the remaining working sites must first agree to the time of failure, and then take appropriate actions to rewind their own logical time. Consider a failure of site S_i (site number i). To reach a global agreement on the time of failure, each site S must proceed as follows:

- consider the set $P=\{(S,VT_j)\}$ of all pairs accompanying a message M_j waiting to be delivered to S;
- consider then the subset $P_k=\{(S,VT_{jk})\}$ of P of pairs such that $VT_{jk}[i]>VT(S)[i]$. These pairs carry evidence of some message, emitted by the broken down site S_i, and not yet delivered to S;
- consider finally the number $MIN(S)=\min_k\{VT_{jk}[i]\}$. MIN(S) indicates the number on S_i of the oldest event SEND(M) such that message M was never delivered to site S.

When considering the minima of MIN(S) over all the remaining working sites S, we get globally the oldest event SEND(M) on S_i such that message M was never delivered. Call N this event number on S_i. The failure must have occurred on site S_i after event (N-1). Every site S such that $VT(S)[i]>(N-1)$ must rewind its clock. A general way of doing this is to introduce a rollback mechanism. Depending on the considered application's semantic however, there could exist a cheaper solution (or no solution at all).

5. Conclusion

We have shown in this paper how pairs (S,VT), composed of the destination site of some message, and of a Mattern-Fidge logical time vector, make it possible to ensure causal ordering. Such a pair (S,VT) carried by a message M says that the message cannot be delivered to site S before the local time VT(S) has become greater than VT. Actually, the pair (S,VT) indicates that at least one message preceding M must still be delivered to S. Compared to this, the implementation of ISIS forces any given message to carry along every causally preceding message in the system, whereas in our scheme, the message carries only some bounded information concerning their existence. On the other hand, we have seen that the implementation of ISIS does not need any special mechanism to treat failures, which can also be of advantage depending on the considered application. Actually a precise quantitative evaluation of the costs of these algorithms should be done. Depending on the characteristics of the application (semantics, real time aspects, etc...) the better suited algorithm could be chosen. We do not rule out the possibility of an algorithm combining advantages of both the ISIS system and our own implementation. Moreover, and independently from these considerations, we think that the proposed causal ordering algorithm will contribute to a better understanding of ordering problems in a distributed system, and, in particular, of the relation of causality.

Acknowledgments

We would like to thank the referees for their useful comments.

References

[Birman 87] K.Birman, T.Joseph, "Reliable Communications in Presence of Failures", ACM Trans. on Computer Systems, Vol 5, No 1 (Feb 1987), pp 47- 76.

[Birman 88a] K.Birman et al., "ISIS - A Distributed Programming Environment", Cornell University, June 1988.

[Birman 88b] K.Birman, "Exploiting Replication", in Lectures Notes Arctic'88, Tromso, July 1988.

[Fidge 88] C.Fidge, "Timestamps in Message-Passing Systems That Preserve the Partial Ordering", Proc. of the 11th Australian Computer Science Conference, Univ of Queensland, Feb 1988.

[Joseph 86] T.Joseph, K.Birman, "Low Cost Management of Replicated Data in Fault-Tolerant Distributed Systems", ACM Trans. on Computer Systems, Vol 4, No 1 (Feb 1986), pp54-70.

[Lamport 78] L.Lamport, "Time, Clocks, and the Ordering of Events in a Distributed System", Communications of the ACM, Vol 21, No 7 (July 1978), pp 558-565.

[Mattern 89] F.Mattern, "Time and Global States of Distributed Systems", Proc. of the International Workshop on Parallel and Distributed Algorithms, Bonas, France, October 1988, North-Holland 1989.

[Peterson 87] L.Peterson, "Preserving Context Information in an IPC Abstraction", IEEE Proc. of the 6th Symp. on Reliability in Distributed Software and Database Systems, March 1987.

[Schiper 89] A.Schiper, J.Eggli, A.Sandoz, "A New Algorithm to Implement Causal Ordering", Rapport Interne 89/02, EPFL-Laboratoire de Systèmes d'Exploitation, April 1989.