



The causal ordering abstraction and a simple way to implement it

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THE CAUSAL ORDERING ABSTRACTION AND A SIMPLE WAY TO IMPLEMENT IT

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ABSTRACT

Control in distributed systems is mainly introduced to reduce non-determinism. This non-determinism is due on one hand to the asynchronous execution of the processes located on the various sites of the system, and on the other hand to the asynchronous nature of the communication channels. In order to get rid of part of the asynchronism due to the communication channels, a new ordering relation, known as causal ordering, has been introduced by Birman. After having shown the usefulness of causal ordering, we propose a natural implementation, based simply on counting the emitted messages. A proof of the correctness of the algorithm is also given.

LE CONCEPT D'ORDONNANCEMENT CAUSAL ET UNE MISE EN OEUVRE SIMPLE

RESUME

Une grande partie du contrôle réalisé dans les systèmes répartis a pour but de réduire le non-déterminisme de leurs comportements. Une cause de celui-ci est l'asynchronisme des processus placés sur les divers sites du système et l'asynchronisme des canaux de communication. Afin de s'affranchir en partie de ce dernier asynchronisme un nouvel ordre sur les réceptions de messages a été introduit par Birman : l'ordonnancement causal. Après avoir rappelé l'intérêt de cet ordre, une mise en oeuvre particulièrement simple en est proposée ; sa correction est également prouvée.

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ABSTRACT

Control in distributed systems is mainly introduced to reduce non-determinism. This non-determinism is due on one hand to the asynchronous execution of the processes located on the various sites of the system, and on the other hand to the asynchronous nature of the communication channels. In order to get rid of part of the asynchronism due to the communication channels, a new ordering relation, known as causal ordering, has been introduced by Birman. After having shown the usefulness of causal ordering, we propose a natural implementation, based simply on counting the emitted messages. A proof of the correctness of the algorithm is also given.

1. CONTROLLING NON-DETERMINISM

Controlling non-determinism is one of the essential tasks in computer systems. In centralized systems the non-determinism is caused by interrupts. In distributed systems the non-determinism is due to the asynchronous execution of the parallel processes together with the asynchronous nature of the communication channels linking them together; it is also due to the failures that can affect the different entities of the system.

In order to master the asynchronism of the processes and so solve the related problems (take for example the resource allocation problem) it is usual to introduce synchronization mechanisms [Raynal 86]. In order to master the asynchronism of the communication channels it is possible to build network synchronizers which force processes and channels to progress in synchronized steps [Awerbuch 85, Helary 90]. This corresponds to defining a virtual distributed machine in which the undesirable behaviour due to non-determinism has been suppressed. The same is true for communication protocols, whose objective is to get rid of the non-reliable channels: communication protocols define a "reliable channel" abstraction which is implemented on top of a non-reliable channel. The alternate bit protocol [Barlett 69] or Stenning's protocol [Stenning 76] are such examples: both build a channel without message loss, duplication or desequencing on top of a channel that can lose or duplicate messages, or even, in the case of Stenning's protocol, that can desequence them. The reliable channel abstraction, like the synchronization mechanisms, make it possible to get rid of the undesirable non-deterministic behaviours.

In this paper we consider a reliable distributed system, and are concerned by the realization of a communication scheme that make it possible to get rid of a particular non-deterministic behaviour. More precisely, we are concerned with the abstraction called "causal ordering", as proposed by the Isis system [Birman 87]. The paper is organized in the following way. In section 2 we define causal ordering and show its usefulness. In section 3 we show an easy and



natural way to implement causal ordering (which differs from the Isis implementation), and give in section 4 a proof of its correctness.

2. CAUSAL ORDERING

2.1 Definition

Causal ordering of events in a distributed system (an event corresponding to the emission of a message, the reception of a message, or an internal action) is based on the well known "happened before" relation, noted \rightarrow [Lamport 78]. If $E1$ and $E2$ are two events, then $A \rightarrow B$ iff one of the following conditions is true:

- i) A and B are two events occurring on the same site, A before B ;
- ii) A is the emission of a message, and B corresponds to the reception of the same message;
- iii) there exists an event C such that $A \rightarrow C$ and $C \rightarrow B$.

The delivery of a message depends in principle only on the fact that it has been sent; in other words, the delivery does not depend on the state of the system at reception time. In the case of FIFO channels, the reception of a message M partly depends on the state of the system: it depends on the state at emission time of the channel through which the message is received. So the FIFO channel abstraction reduces the non-determinism of a channel. The causal ordering corresponds to reducing the non-determinism globally on all of the channels: the delivery of a message is dependent on the state of the system as known by the sender at emission time. Consider two events $E1 = \text{SEND}(M1)$ and $E2 = \text{SEND}(M2)$. Causal ordering is respected if:

if $(E1 \rightarrow E2)$ and $(M1, M2 \text{ have same destination})$
then $\text{RECEIVE}(M1) \rightarrow \text{RECEIVE}(M2)$

In other words, in case of a "happened before" relation between two emissions to a same destination, there exists a "happened before" relation between the delivery of the messages. For example, on figure 1, message $M1$ must be delivered on site $S3$ before message $M3$.

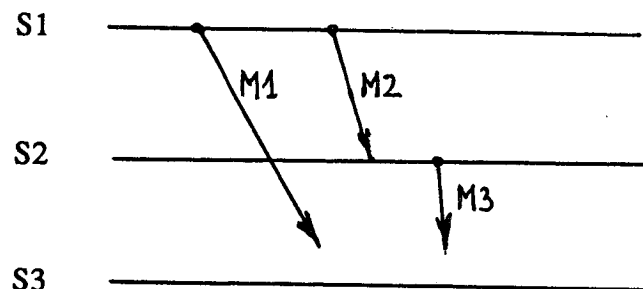


Fig. 1 Causal ordering ensures that $M1$ is received before $M3$.

2.2 Examples of the Usefulness of Causal Ordering

Management of a replicated data

Consider a data X replicated on various sites. In order to ensure mutual consistency of the various copies $x1, x2, \dots$, the updates to these copies must take place in the same order. In

particular this introduces the need for mutual exclusion on the updates done by two different sites. This can be solved using a token; when in possession of the token, a site can update his copy of X and broadcasts the update to all other sites having a copy of X (fig. 2). Causal ordering ensures that all sites will receive all the updates in the same order (the update W_i will not be delivered before the update W_j , for $i < j$), which ensures mutual consistency of the copies [Birman 88, Joseph 86]. The token ensures total ordering of the updates on X and causal ordering ensures that all the copies x_i are updated in this same order.

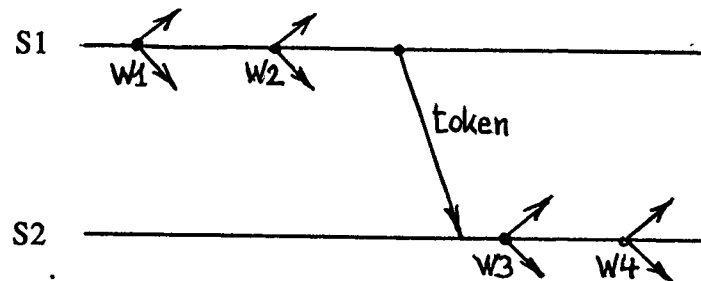


Fig. 2 Management of a replicated data

Consider now a second data Y, controlled by a second token, and two sites S1, S2 (with copies x_1, y_1 , resp. x_2, y_2). Both sites see the same sequence of updates on x_1, x_2 and on y_1, y_2 . The interleaving of these sequences can nevertheless be different on S1 and S2. In other words, causal ordering does not define a total order.

Monitoring a distributed system

Consistent observation of a distributed system is another example of the usefulness of causal ordering. Consider a number of sites monitoring events occurring locally, and suppose that all this information is of interest to an observer site OS. If the monitoring information collected by the sites is sent to OS respecting causal ordering, the information will be received in a coherent order (i.e. in an order not violating the events precedence order).

Resource allocation

Consider the mutual exclusion problem, or more generally a resource allocation problem. This can be solved by a resource allocator residing on a site, which receives allocation requests in a FIFO queue. With this scheme, the requests are honoured in the reception order. This might however be considered unsatisfactory in some cases: it might be desirable to honour requests not in their reception order, but in their emission order, i.e. if two requests R_1 and R_2 are such that $R_1 \rightarrow R_2$, then R_1 should be honoured before R_2 . This is again a causal ordering problem. Note that this example, in the particular case of mutual exclusion, was used by Lamport in his paper introducing logical clocks [Lamport 78]. Lamport's solution was to duplicate the resource allocator on each site (each site being concerned with all the requests and having to acknowledge them). This can be avoided using causal ordering!

3. IMPLEMENTATION OF CAUSAL ORDERING

3.1 Related Work

The Isis implementation of causal ordering [Birman 87] is straightforward: a message carries with it all the history of the communications that have preceded. Consider again figure 1. Message M3, sent by S2 to S3, carries the following information about the past: message M1, with the information that it was sent to S3, and message M2 with the information that it was sent to S3. When receiving M3, site S3 thus also receives a copy of M1: if not already delivered, M1 will be delivered at that time, i.e. before M3. To prevent unbounded growth of the information added to a message, a mechanism must be added to inform of messages that have been received and delivered: these messages need not be sent any more. This mechanism is however rather complex. Anyhow, the size of the information added to messages is unbounded.

Another implementation of causal ordering is given in [Schiper 89]. In this implementation, control information (and not messages as in Isis) is added to the messages. This control information allows the destination site of a message M to know if there are messages that have to be delivered before M, in order to respect causal ordering: if this is the case, M is not immediately delivered. The control information is composed of a bounded number of pairs (*destination site*, *vector time*), where "*vector time*" is a time defining a partial ordering of the events of a distributed system [Fidge 88, Mattern 88]. The implementation proposed in this paper has some similarities with this implementation. It does not however use vector times, and is thus much more easy to understand.

3.2 A Simple Implementation

To implement causal ordering we give every site control information representing the site's perception of the system state (more precisely, the site's perception of the communications). This information will allow each site to decide when a received message can be delivered. Moreover, information added to every message will allow the receiving site, when a message is delivered, to update its perception of the system state.

Local information of a site

Every site manages the following two variables (where n is equal to the number of sites in the system):

REC: array [1..n] of integer; (* initially set to 0 *)

SENT: array [1..n,1..n] of integer; (* initially set to 0 *)

We will use the notation REC_i and $SENT_i$ to refer to the variables managed by site S_i . So on site S_i , the variable $REC_i[j]$ represents the number of messages sent by S_j (and delivered); the variable $SENT_i[k,l]$ represents the knowledge of S_i of the number of messages sent (but not necessarily delivered) from S_k to S_l .

Behaviour of a site

The behaviour of a site S_i is expressed by the following two rules, governing the emission and the reception of a message.

i) *Emission of a message M from Si to Sj:*

$SENT_i[i,j] := SENT_i[i,j] + 1;$
send (M, $SENT_i$) to Sj;

Thus M is sent together with a copy of $SENT_i$, i.e. with site Si's view of the system state.

ii) *Reception of (M, ST_M) sent from Sj to Si (where ST_M represents the control information "SENT" carried by the message M):*

wait ($RECI[j]+1 = ST_M[j,i]$) and (for all $k \neq j$: $RECI[k] \geq ST_M[k,i]$);
delivery of M;
 $RECI[j] := RECI[j] + 1;$
for all k,l: $SENT_i[k,l] := \max (SENT_i[k,l], ST_M[k,l]);$

Thus a message M sent by Sj can be delivered only if:

- all the messages sent by Sj before M have been delivered. This is expressed by the first part of the wait condition: $RECI[j]+1 = ST_M[j,i]$. This condition ensures that the communication channels are perceived as FIFO;
- all other causally preceding messages, whose existence is revealed by ST_M , have been delivered. This is expressed by $RECI[k] \geq ST_M[k,i]$ for all $k \neq j$.

Once a message has been delivered, the site's perception of the system state is updated in an obvious way.

Before going further to prove the algorithm, let's notice that the algorithm is easy to adapt to the multicast case. The emission rule i) has simply to be replaced by the following rule i'):

i') *Emission of a message M from Si to the set of sites $S=[Sj1,...,Sjm]$:*

for all k in $[j1,...,jm]$: $SENT_i[i,k] := SENT_i[i,k] + 1;$
send (M, $SENT_i$) to every member of the set S;

4. PROOF OF CORRECTNESS

The correctness of the above algorithm will be proved in the usual two steps. We will first prove in 4.1 that causal ordering is not violated: this corresponds to the safety condition. In 4.2 we will then prove the liveness of the algorithm.

4.1 Safety

To prove the safety of the algorithm we need the following intermediate result:

Proposition 1. If neither a message M1, nor a message M such that $SEND(M1) \rightarrow SEND(M)$, has been delivered to a site Si, then $RECI[j] < ST_M1[j,i]$ (where j represents the sending site Sj, and ST_M1 the control information carried with message M1).

Proof. First notice that only the messages sent by Sj are to be considered, because only these messages can increment $RECI[j]$. So consider that M was sent by Sj. All the messages sent by Sj after message M1 are such that $SEND(M1) \rightarrow SEND(M)$. Thus if none of these messages has been delivered to Si, we have: the number of messages from Sj delivered to Si is less than

the number of messages sent to S_i by S_j up to the sending of M_1 , in other words $RECI[j] < ST_M1[j,i]$.

The safety condition is equivalent to the following assertion: as long as a message M_1 has not been delivered to S_i , no message M_2 such that $SEND(M_1) \rightarrow SEND(M_2)$ can be delivered. The proof will be made by induction on the number of messages delivered on the destination site S_i .

i) *Base step.*

The first message received by S_i cannot be M_2 . To prove this there are two cases to consider:

1) M_2 is sent from S_j to S_i (as message M_1). In this case $ST_M2[j,i] \geq 2$. Thus $RECI[j]+1 \neq ST_M2[j,i]$ (because $RECI[j]$ is initially 0), and M_2 cannot be delivered (first part of the wait condition not satisfied).

2) M_2 is sent from S_k ($k \neq j$). Here $ST_M2[j,i] > 0$, and thus on the destination site S_i , $RECI[j] < ST_M2[j,i]$. So M_2 cannot be delivered (second part of the wait condition not satisfied).

ii) *Induction step.*

We suppose that M_1 is not delivered on S_i , and that the n th message delivered is not a message M_2 such that $SEND(M_1) \rightarrow SEND(M_2)$. We will prove that the same is true for the $n+1$ st message. Again there are two cases to consider:

1) M_2 is sent from S_j to S_i (as message M_1). From the induction hypothesis and proposition 1, we have $RECI[j] < ST_M1[j,i]$. Further, we have $ST_M2[j,i] > ST_M1[j,i]$, as M_2 is also sent from S_j . So, after delivery of the n th message on S_i we have:

$$RECI[j] < ST_M1[j,i] < ST_M2[j,i]$$

This prevents M_2 from being the next message delivered on S_i (first part of the wait condition not satisfied).

2) M_2 is sent from S_k ($k \neq j$). Here we have the same inequalities as above, except that $ST_M1[j,i] \leq ST_M2[j,i]$ (because M_2 is not sent by S_j). Thus after delivery of the n th message on S_i we have:

$$RECI[j] < ST_M1[j,i] \leq ST_M2[j,i]$$

i.e. $RECI[j] < ST_M2[j,i]$, which again prevents M_2 from being the next message delivered on S_i (second part of the wait condition not satisfied).

4.2 Liveness

To prove liveness we will suppose that there exists a message M sent from S_j to S_i that is never delivered, and show that we end up with a contradiction. Message M comes with the control information $ST_M[x,y]$. For $x \neq j$, $ST_M[x,i]$ counts the number of messages sent by S_x to S_i that causally precede M , and $ST_M[j,i]-1$ counts the number of messages sent by S_j to S_i that causally precede M . The number of messages that causally precede M is thus bounded. In absence of failure, and after a finite time, all these messages will have arrived, and message M will be deliverable (see the wait conditions).

So, if M cannot be delivered, there exists a message M' , such that $SEND(M') \rightarrow SEND(M)$, which is never delivered. The same reasoning applied to M can again be applied to M' , and so on. As the number of messages causally preceding M is finite, we end up with a message $M(n)$

which has no message causally preceding it. So $M(n)$ will be delivered, which shows the contradiction.

5. CONCLUSION

In this paper, causal ordering has been justified as a means for reducing the non-determinism due to the asynchronism of communication channels. Its usefulness has been shown by various examples, and a simple implementation has been given. With this implementation, the destination site of a message can know, when receiving a message, if it can be immediately delivered, or if causally preceding messages are still underway. In contrast to the Isis implementation, the information added to messages to ensure causal ordering is here bounded, more precisely bounded by n^2 , where n is the number of sites. The same bound is obtained in [Schiper 89], but the given implementation is less easy to understand. In contrast, the proposed implementation is simply based on counting the messages emitted. In a certain sense, this implementation extends the concept of sequence numbers used in networks [Stenning 76]. More generally, the counting techniques are usual in many solution to synchronization problems, starting from semaphores in centralized systems (to solve competition or synchronization problems), up to counters in distributed systems used to obtain consistent global information (for example distributed termination [Helary 87, Mattern 87]) or to ensure coherent global decisions (e.g. distributed mutual exclusion [Raynal 86]).

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