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Checkpointing and Restarting Protocols on Object-based Systems

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In object-based systems, multiple objects cooperate with each other by exchanging messages. The objects may suffer from faults. If some object o is faulty, o is rolled back to the checkpoint c and objects which have received messages from o are also required to be rolled back to the checkpoints which is consistent with c. In this paper, we discuss how to take checkpoints in object-based systems. Object-based checkpoints are consistent in the object-based system but may be inconsistent according to the traditional message-based definition. We present a protocol for taking object-based checkpoints among objects. An object to take a checkpoint in the traditional message-based protocol does not take a checkpoint if the current checkpoint is object-based consistent with the other objects. The number of checkpoints can be reduced by the object-based protocol.

1. Introduction

Distributed applications are composed of multiple objects. An object is an encapsulation of data and methods for manipulating the data. A method is invoked by a message passing mechanism. On receipt of a request a message with a method *op*, *op* is performed on an object and a response message with the result of *op* is sent back. The method may invoke methods on other objects, i.e., invocation is assumed to be *nested*. A conflicting relation among the methods is defined based on the semantics of the object [4]. If a pair of methods op_1 and op_2 conflict, a state of the object obtained by performing op_1 and op_2 depends on the computation order of op_1 and op_2.

In order to increase the reliability and availability, an object takes a checkpoint where a state of an object is saved in the *log* at a checkpoint. A faulty object o is *rolled back* to the checkpoint and then is restarted. Here, objects which have received messages sent by objects rolled back also have to be rolled back. Papers [1),2),7),9)~11),13)] discuss how to take a globally consistent checkpoint of multiple objects.

The paper 7) presents synchronous protocols for taking checkpoints and rolling back objects. The paper 9) presents the concept of *significant* requests, i.e., the state of an object is changed by performing the request. If an object o is rolled back, only objects which have received significant requests sent by o are required to be rolled back. Thus, the number of objects to be rolled back can be reduced. However, in the object-based systems, types of messages, i.e., *request* and *response* messages are exchanged among objects and methods are invoked in various ways. In the paper 9), the transmissions of requests and responses and types of invocations are not considered. Since the traditional checkpoints are defined in terms of messages exchanged among objects, the definition is referred to as *message-based*.

We newly define *object-based consistent* (*O-consistent*) checkpoints which can be taken based on conflicting relations among methods in various types of invocations like synchronous and asynchronous ones. The O-consistent checkpoint may be inconsistent with the traditional message-based definition. In this paper, we present a protocol where O-consistent checkpoints are taken for objects without suspending the computation of methods. By taking only the O-consistent checkpoints, the number of checkpoints can be reduced.

In Section 2, we discuss the object-based checkpoints. In Sections 3 and 4, we show a checkpointing protocol and restarting protocol, respectively.

2. Object-based Checkpoints

In this section, we formalize a concept of objects, especially define a conflicting relation

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among methods. Then, based on conflicting relation, we discuss what types of checkpoints can be consistently taken in object-based systems.

2.1 Objects

A distributed system is composed of multiple objects $o_1, \ldots, o_n$. Each object o_i is an encapsulation of data and a set of methods for manipulating the data. In this paper, we assume methods are synchronously or asynchronously invoked by using the remote procedure call. On receipt of a *request op*, *op* is performed on the object o_i. Here, let op^i denote an instance of *op*, i.e., a thread of *op* on o_i. Then, a *response* message is sent back. *op* may furthermore invoke another method op_1, i.e., invocation is assumed to be *nested*. If op_1 is synchronously invoked, *op* blocks until receiving the response of op_1. In the asynchronously invocation, *op* is being performed without blocking. It is defined that a message m *participates* in a method *op* if m is a request or response of *op*. Let $Op(m)$ denote a method in which a message m participates.

Let $op(s)$ denote a state obtained by performing a method *op* on a state s of an object o_i. $op_1 \circ op_2$ shows that a method op_2 is performed after op_1 completes. op_1 and op_2 of an object o are defined to be *compatible* iff $op_1 \circ op_2(s)$ is equivalent with $op_2 \circ op_1(s)$ for every state s of o [4]. Otherwise, op_1 and op_2 *conflict*. It is assumed that an object supports two kinds of methods, i.e., *update* method which changes the state of the object and *non-update* one. The types of methods are assumed to be specified with the conflicting relation among the methods in the definition of the object.

2.2 Object-based Checkpoints

A local checkpoint c^i for an object o_i is taken where a state of o_i is stored in the log l_i. If o_i is faulty, o_i is rolled back to c^i by restoring the state stored in the log l_i. Then, other objects have to be rolled back to the checkpoints if they had received messages sent by o_i. A *global checkpoint* c is defined to be a tuple $\langle c^1, \ldots, c^n \rangle$ of the local checkpoints. From here, a term *checkpoint* means a *global* one.

Suppose an instance op_1^i invokes a method op_2 in o_j. **Figure 1** shows possible checkpoints for o_i and o_j. Here, c_3^i is not taken if op_2^j is synchronously invoked. Let $\pi_j(op^j, c^j)$ be a set

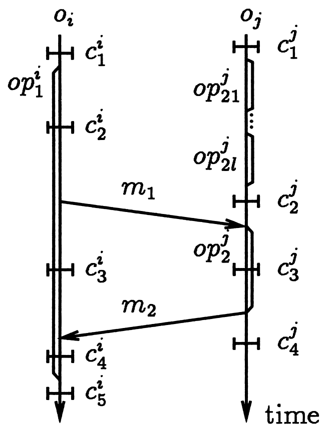

Fig. 1 Possible checkpoints.

Table 1 O-consistent checkpoints for Fig. 1.

o_i	o_j	Conditions
c_1^i	c_3^j*, c_4^j	op_2^j is a non-update type.
c_2^i	c_3^j*, c_4^j	op_2^j is a non-update type.
c_4^i c_5^i	c_1^j	op_2^j is a non-update type and no method in $\pi_j(op_2^j, c_1^j)$ conflicts with op_2^j.
	c_2^j, c_3^j*	op_2^j is a non-update type.

of instances performed on o_j, which precede op^j and succeed c^j or are being performed at c^j in o_j. For example, $\pi_j(op_2^j, c_1^j)$ is $\{op_{21}^j, \ldots, op_{2l}^j\}$ in Fig. 1.

We discuss whether or not each checkpoint $\langle c_k^i, c_h^j \rangle$ can be taken in the object-based system. For example, $\langle c_1^i, c_3^j \rangle$ is message-based inconsistent in Fig. 1 because a message m_1 is an orphan. If op_2^j is non-update, the state denoted by c_2^j is the same as c_3^j and c_4^j. That is, $\langle c_1^i, c_3^j \rangle$ and $\langle c_1^i, c_4^j \rangle$ show the same state as $\langle c_1^i, c_2^j \rangle$. $\langle c_1^i, c_2^j \rangle$ is message-based consistent. Hence, o_j can be restarted from any of c_3^j and c_4^j if o_j can be restarted from c_2^j. Here, $\langle c_1^i, c_3^j \rangle$ is consistent in the object-based system (O-consistent). $\langle c_1^i, c_4^j \rangle$ is also O-consistent. A local checkpoint c^i is defined to be *complete* if there is no method being performed at c^i. For example, c_3^i is incomplete in Fig. 1. **Table 1** summarizes the message-based inconsistent but O-consistent checkpoints, where checkpoints marked * are incomplete if op_2^j is being performed.

[Definition] A message m is *influential* iff a method instance op_2^j of an object o_j sends a message m to o_i and one of the following conditions is satisfied:

(1) op_1^i is an update type if m is a request message, i.e., op_2^j invokes op_1^i in o_i.

(2) If m is a response of op_2^j, op_2^j is an update type or conflicts with some instance in $\pi_j(op_2^j, c)$ where c is a local checkpoint most recently taken in o_j. □

If op^i is aborted, only instances receiving influential messages from op^i are required to be aborted. In Fig. 1, suppose op_1^i sends an asynchronous update request m_1. Here, m_1 is influential from the definition. If o_i is rolled back to c_2^i, o_j is also rolled back.

[Definition] A global checkpoint c ($= \langle c^1, \ldots, c^n \rangle$) is *object-based consistent* (*O-consistent*) iff there is no influential orphan message at c. □

3. Checkpointing Protocol

In this section, a communication-induced protocol used for taking O-consistent checkpoints is introduced. By the protocol, consistent global checkpoint can be taken without suspending the computation. First, a basic communication-induced protocol is presented. Then, we discuss how to take only O-consistent checkpoints in the protocol. Finally, we show how to solve the problems which may be occurred while taking the checkpoints, i.e., *cyclic checkpointing* and *cascading rollback.*

3.1 Communication-induced Protocol

We briefly present a basic communication-induced checkpointing protocol where objects are not suspended while checkpoints are being taken. First, each object o_i initially takes a local checkpoint c_0^i. An initial checkpoint $\langle c_0^1, \ldots, c_0^n \rangle$ is assumed to be consistent. After sending and receiving messages, a first local checkpoint c_1^i is taken for o_i. Thus, the t-th local checkpoint c_t^i is taken after c_{t-1}^i ($t > 0$). Here, t is defined to be a *checkpoint identifier* of c_t^i.

Suppose a local checkpoint c_t^i is taken for an object o_i after c_{t-1}^i. Then, only if o_i sends a message m to another object o_j, m is marked *checkpointed.* By sending m, o_i notifies the destination objects that o_i has taken c_t^i. Thus, o_i does not send any additional control message to take local checkpoints. Here, suppose c_{u-1}^j is taken for o_j and a checkpoint $\langle c_{t-1}^i, c_{u-1}^j \rangle$ is consistent. On receipt of the checkpointed message m from o_i, a local checkpoint c_u^j is taken for o_j at which o_j saves a state which is most recent before o_j receives m. The state saved here is referred to as *checkpoint* state. In fact, a current state and the operation $rec(m)$ for receiving m are stored in the log l_j. A compensating operation $\sim rec(m)$ to remove every effect done by $rec(m)$ is assumed to be supported for every object. If o_j is rolled back to c_u^j, the state saved in the log is first restored, and then $\sim rec(m)$ is performed (**Fig. 2**).

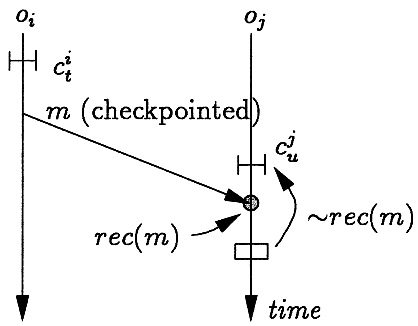

Fig. 2 Checkpoint state.

In the object-based system, o_j does not take c_u^j if $\langle c_t^i, c_{u-1}^j \rangle$ is O-consistent. We discuss how o_j decides if $\langle c_t^i, c_{u-1}^j \rangle$ is O-consistent.

3.2 O-consistent Checkpoints

A vector of checkpoint identifiers $\langle cp_1, \ldots, cp_n \rangle$ is manipulated for an object o_i to identify the t-th local checkpoint c_t^i of o_i. Each cp_k is initially 0. Each time a local checkpoint is taken for o_i, cp_i is increased by one. A message m which o_i sends to o_j after taking $c_{cp_i}^i$ carries a vector $m.cp$ which is equal to $\langle m.cp_1, \ldots, m.cp_n \rangle$, where $m.cp_k$ is cp_k of o_i ($k = 1, \ldots, n$).

On receipt of a message m from o_j, the value of $m.cp_j$ is stored in cp_j of o_i. cp_i shows a checkpoint identifier which o_i has most recently taken. Another variable cp_h shows a newest checkpoint identifier of an object o_h which o_i knows ($h = 1, \ldots, n$, $j \neq i$). That is, $\langle c_{cp_1}^i, \ldots, c_{cp_n}^i \rangle$ shows a current checkpoint which o_i knows. If $m.cp_j > cp_j$ in o_i, o_i finds that o_j has taken c_u^j following $c_{cp_j}^i$ where u is equal to $m.cp_j$. A local checkpoint c_t^i is identified by a vector $\langle c_t^i.cp_1, \cdots, c_t^i.cp_n \rangle$ where each $c_t^i.cp_j$ shows a value of cp_j when c_t^i is taken for

o_i.

A local checkpoint c_t^i has a bitmap $c_t^i.BM$ which is equal to $b_1 \cdots b_n$ where each h-th bit b_h is used for an object o_h ($h = 1, \ldots, n$). Suppose c_t^i is taken for o_i. Here, $c_t^i.b_i$ is 1 and $c_t^i.b_j$ is 0 for $j = 1, \ldots, n$, $j \neq i$. If $c_t^i.b_j$ is 0 and there is data to be sent to o_j, o_i sends a checkpointed message m with the data to o_j. Here, the value of $c_t^i.BM$ is stored in $m.BM$.

On receipt of m from o_i, o_j takes a local checkpoint c_u^j. Here, the value of $m.b_k$ is stored in $c_u^j.b_k$ ($k = 1, \ldots, n$, $k \neq j$) and $c_u^j.b_j$ is updated to 1 while the checkpoint identifier vector is updated as presented here. Thus, "$c_t^i.b_k = 1$" shows that o_i knows o_k takes a local checkpoint by the checkpointing protocol initiated by a same object.

[Definition] c_t^i and c_u^j are in the *same generation* if $c_t^i.BM \cap c_u^j.BM \neq \phi$ and $c_t^i.cp_k$ is equal to $c_u^j.cp_k$ for every object o_k such that $c_t^i.b_k = c_u^j.b_k = 1$. □

Each time an object o_i sends a message m to o_j, a message *sequence number sq* and a *subsequence number* ssq_j are incremented by one ($j = 1, \ldots, n$). The sequence number $m.sq$ and a vector of the subsequence numbers $m.ssq$ ($= \langle m.ssq_1, \ldots, m.ssq_n \rangle$) are carried by m. Variables $rsq_1, \ldots, rsq_n$ and $rssq_1, \ldots, rssq_n$ are manipulated in o_j. On receipt of m from o_i, o_j accepts m if $m.ssq_j$ is equal to $rssq_i + 1$. That is, o_j delivers messages from each object in the sending order. Then, $rssq_i$ is incremented by one and the value of $m.sq$ is stored in rsq_i. $rssq_i$ and rsq_i show subsequence and sequence numbers of message which o_j has most recently received from o_i. m also carries a vector $m.rq$ ($= \langle m.rq_1, \ldots, m.rq_n \rangle$) where $m.rq_k$ is equal to rsq_k ($k = 1, \ldots, n$). Here, $m.rq_k$ shows a sequence number of message which o_i has received from o_j just before c_t^i and t is equal to $m.cp_i$ ($k = 1, \ldots, n$).

On receipt of a message m from o_i, o_j collects a set M_j of messages $m_{j1}, \ldots, m_{jl_j}$ which o_j has sent to o_i after c_{u-1}^j and o_i has received before c_t^i. Here, $m_{jh}.sq \leq m.rq_j$ (**Fig. 3**). Messages which o_j sends after c_{u-1}^j are stored in the sending log of o_j. Suppose o_j receives a checkpointed message m from o_i. If $m.cp_i > cp_i$, o_j knows o_i takes c_t^i. o_j collects every message m' which o_j has sent after c_{u-1}^j and $m'.sq < m.rq_j$ in the set M_j.

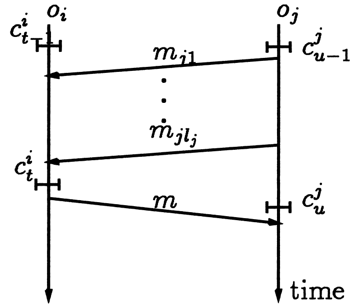

Fig. 3 Influential messages.

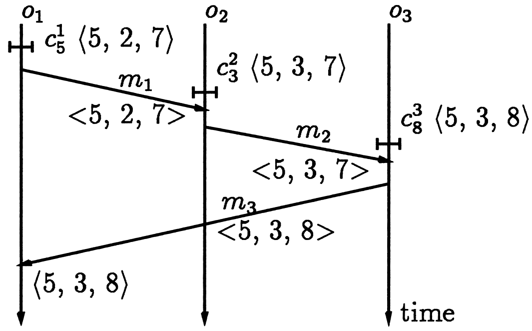

Fig. 4 Cyclic checkpointing.

It is clear for the following theorem to hold from the definition.

[Theorem] A message m_{jh} which o_j sends to o_h after taking a local checkpoint c_{u-1}^j before c_u^j is *influential* if m_{jh} is a request and $Op(m_{jh})$ is an update type, or m_{jh} is a response and $Op(m_{jh})$ is an update type or conflicts with some update method in $\pi_j(Op(m_{jh}), c_{u-1}^j)$. □

The condition of the theorem is referred to as *influential message* (*IM*) condition. Only if some message in M_j is decided to be influential by *IM* condition, o_j takes a local checkpoint.

3.3 Cyclic Checkpointing

We discuss how to resolve a *cyclic checkpointing* which occurred in the communication-induced protocol. Due to the *cyclic checkpointing*, the checkpointing procedure cannot be terminated as shown in Example 1.

[Example 1] Suppose each of three objects o_1, o_2, and o_3 has initially checkpoint identifier vector $cp = \langle cp_1, cp_2, cp_3 \rangle = \langle 4, 2, 7 \rangle$ (**Fig. 4**). First, a local checkpoint c_5^1 is taken for o_1. Here, cp is $\langle 5, 2, 7 \rangle$. o_1 sends m_1 with $\langle 5, 2, 7 \rangle$ to o_2 after taking c_5^1. o_2 takes c_3^2 on receipt of m_1

where $c_3^2.cp$ is $\langle 5, 3, 7\rangle$. Then, o_2 sends m_2 with $\langle 5, 3, 7\rangle$ to o_3. On receipt of m_2, o_3 takes c_8^3 and sends m_3 with $\langle 5, 3, 8\rangle$ to o_1. o_1 takes c_6^1. Then, o_2 and o_3 take new local checkpoints as presented here. Thus, the checkpointing procedure cannot be terminated in o_1, o_2, and o_3. This is *cyclic checkpointing.* □

Here, when o_1 receives m_3, o_1 is not required to take a local checkpoint because a checkpoint $\langle c_5^1, c_3^2, c_8^3\rangle$ taken already is consistent. A pair of checkpoints identified by $\langle 5, 2, 7\rangle$ and $\langle 5, 3, 8\rangle$ are in the same generation.

The cyclic checkpointing is resolved by using the bitmap BM as shown in Example 2.

[**Example 2**] Here, let a notation "$\langle cp_1, \ldots, cp_n\rangle_{b_1\ldots b_n}$" show cp is $\langle cp_1, \ldots, cp_n\rangle$ and BM is $b_1 \cdots b_n$. In Fig. 4, o_1 sends o_2 a message m_1 with $\langle 5, 2, 7\rangle_{100}$, i.e., $cp = \langle 5, 2, 7\rangle$ and $BM = 100$ after c_5^1. On receipt of m_1, cp is changed to $\langle 5, 2, 7\rangle$ in o_2. Then, o_2 sends m_2 with $\langle 5, 3, 7\rangle_{110}$ to o_3 after c_3^2. c_8^3 is taken for o_3 and then sends m_3 with $\langle 5, 3, 8\rangle_{111}$ to o_1. On receipt of m_3, o_1 knows the checkpointing procedure has been initiated by o_1 because $\langle 5, 2, 7\rangle$ and $\langle 5, 3, 8\rangle$ are in the same generation. □

The checkpoint identifier vector cp ($= \langle cp_1, \ldots, cp_n\rangle$) and the bitmap $BM = b_1 \cdots b_n$ are manipulated in o_i on receipt of m as follows:

- $cp_k := \max(cp_k, m.cp_k)$ if $m.b_k = 1$ for every k ($\neq i$).
- $BM := BM \cup m.BM$.

The checkpoint identifier vector cp and the bitmap BM are saved in the checkpoint log $c^i_{cp_i}$ of o_i only if they are changed. In Fig. 4, on receipt of m_3, $c_5^1.cp$ is updated to $\langle 5, 3, 8\rangle$. If $cp_1 > m.cp_1$, another object initiates the checkpointing procedure independently of o_1. A local checkpoint is taken for o_1 if there is some influential message in M_1.

3.4 Merge of Checkpoints

Next, we consider *a cascading rollback* problem which occurred while rolling back the objects as shown in the following example.

[**Example 3**] In **Fig. 5**, every object has a checkpoint identifier vector cp which is equal to $\langle 4, 3, 7, 2\rangle$. Suppose o_1 and o_4 independently take checkpoints. o_1 sends m_1 after c_5^1 with $\langle 5, 3, 7, 1\rangle_{1000}$, i.e., cp is $\langle 5, 3, 7, 1\rangle$ and BM is 1000. On receipt of m_1, o_2 takes c_4^2 and then sends m_2 with $\langle 5, 4, 7, 1\rangle_{1100}$. On the other hand, o_4 takes c_2^4 with $\langle 4, 3, 7, 2\rangle_{0001}$ and then sends m_4 to o_3. o_3 takes c_8^3 with $\langle 4, 3, 8, 2\rangle_{0011}$ and then sends m_3 to o_2. o_2 receives m_3 with $\langle 4, 3, 8, 2\rangle_{0011}$ from o_3 after c_4^2 with cp which is equal to $\langle 5, 4, 7, 1\rangle$. o_3 receives m_2 with $\langle 5, 4, 7, 1\rangle_{1100}$ after c_8^3 with cp which is equal to $\langle 4, 3, 8, 2\rangle$. One way is that o_2 and o_3 take c_5^2 with $\langle 4, 5, 8, 2\rangle_{0111}$ and c_9^3 with $\langle 5, 4, 9, 3\rangle_{1110}$, respectively. Here, $\langle c_5^1, c_4^2, c_9^3, c_3^4\rangle$ and $\langle c_6^1, c_5^2, c_8^3, c_2^4\rangle$ are taken for o_1, o_2, o_3, and o_4.

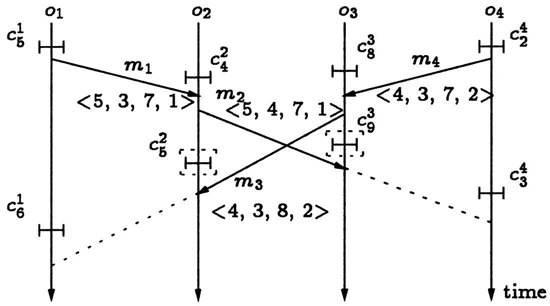

Fig. 5 Checkpoints.

Suppose o_4 is faulty and is rolled back to c_3^4. Then, o_3 is rolled back to c_9^3 and then o_2 is rolled back to c_4^2. Here, o_3 is required to be furthermore rolled back to c_8^3 and o_3 is also rolled back to c_2^4. In the worst case, each object is rolled back to the local checkpoints n times for the number n of objects [6]. □

In order to prevent such a *cascading* rollback, we take an approach to merging multiple checkpoints to one. In Fig. 5, o_2 receives m_3 after c_4^2. Here, $\langle c_5^1, c_4^2\rangle$ with BM which is equal to 1100 and $\langle c_8^3, c_2^4\rangle$ with BM which is equal to 0011 are merged into $\langle c_5^1, c_4^2, c_8^3, c_2^4\rangle$ with BM which is equal to 1111.

[**Merge of checkpoints**] After c_t^i, o_i receives a message m.

(1) If a checkpoint c_u^i denoted by $m.cp$ is not in the same generation as c_t^i, i.e., $c_u^i.BM \cap m.BM$ is not ϕ, the value of $m.cp_k$ is stored in $c_t^i.cp_k$ if $c_t^i.b_k$ is 0 and $m.b_k$ is 1 for every k ($\neq i$), and $c_t^i.BM$ is updated to $c_t^i.BM \cup m.BM$.

(2) Otherwise, $c_t^i.BM$ is updated to $c_t^i.BM \cup m.BM$ and $c_t^i.cp_k$ is changed to $\max(c_t^i.cp_k, m.cp_k)$ for every k ($\neq i$). □

[**Theorem**] A set of local checkpoints which belong to the same generation with the merge procedure are O-consistent. □

[Proof] We prove the theorem by contradiction. Assume there are a pair of local checkpoints c_t^i and c_u^j of the same generation, which are not O-consistent, i.e., there exists an influential message m which is sent after c_t^i and is received before c_i^j. Here, if o_i sends m to o_j, m is marked checkpointed. On receipt of m, o_j takes a local checkpoint c_{u-1}^j most recent before receiving m if m is influential. Otherwise, o_j does not take a local checkpoint. Thus, a pair of the local checkpoints c_t^i and c_u^j never belong to a same generation. This contradicts the assumption. □

By the merging procedure, a new local checkpoint is not taken for o_2 even if o_2 receives messages after m_3 in Fig. 5.

4. Rollback Recovery

If some object is faulty, objects which have received influential messages sent by the object are also required to be rolled back. In this session, we discuss how to restart the computation after some faulty object is rolled back.

4.1 Restarting Protocol

If an object o_i is faulty, o_i is rolled back to the local checkpoint c_t^i. Other objects which have received influential messages sent by o_i after c_t^i are also required to be rolled back. Messages which o_i sends are recorded in the sending log. o_i has to send a rollback request message *R-Req* to every object o_j which o_i has sent influential messages after c_t^i. In order to decide to which objects *R-Req* is sent, o_i manipulates a log SL_t^i as follows:

- When a local checkpoint c_t^i is taken for o_i, SL_t^i is initiated to be empty.
- If o_i sends an influential message m to o_j, SL_t^i is updated to $SL_t^i \cup \{o_j\}$.

If o_i is rolled back to c_t^i, o_i sends *R-Req* to every object o_j in SL_t^i. Here, *R-Req* contains the following information:

- A vector $cp = \langle cp_1, \ldots, cp_n \rangle$ of c_t^i to which o_i is rolled back.
- A bitmap $RB = rb_1 \ldots rb_n$ where each rb_k is 1 if o_i knows o_k is rolled back to a same generation checkpoint as c_t^i, otherwise, rv_b is 0.

Suppose an object o_i is faulty and is rolled back to c_t^i. o_i sends *R-Req* to every o_k in SL_u^j with $c_u^j.cp$ and RB where rb_i is updated to 1. Then, o_i is suspended. On receipt of *R-Req* from o_i, o_j is also suspended. o_j discards *R-Req* if *R-Req*.rv_j is 1 since o_j has been already rolled back in this generation. Otherwise, rb_j is changed to 1 and RB is updated to $RB \vee$ *R-Req*.RB. o_j looks for an oldest local checkpoint c_u^j where cp_i is equal to *R-Req*.cp_i. If o_j finds c_u^j, c_u^j is defined to be a *rollback point* of o_j. Otherwise, the most recent checkpoint where cp_i is smaller than *R-Req*.cp_i is a *rollback point*. Then, o_j collects a set RL^j of messages which o_j has received from o_i after c_u^j. If there is some influential message in RL^j, o_j is rolled back to the *rollback point* c_u^j. Then, o_j sends *R-Req* to every o_k in SL_u^j with RB and $c_u^j.cp$. If o_j received no influential message from o_i, o_j discards *R-Req* since o_j is not required to be rolled back. If o_j does not send *R-Req* to any objects, o_j sends the restart request message *Res-Req* to o_i. Otherwise, o_j waits for *Res-Req* from every object in SL_u^j. Then, o_j sends *Res-Req* to o_i.

[**Example 4**] In **Fig. 6**, if o_1 is faulty, o_1 is rolled back to c_1^1. o_1 is suspended and finds that o_1 has sent an influential message to o_2 by searching SL_1^1. Then, o_1 sends *R-Req* to o_2 with $cp = \langle 1, 0, 0 \rangle$ and $RB = 100$. On receipt of *R-Req* from o_1, o_2 finds an oldest local checkpoint c_1^2 where cp_1 is equal to 1 because *R-Req*.cp_1 is 1. Since m_1 in RL^1 is influential, o_2 is rolled back to c_1^2. *R-Req*.rb_2 is updated to 1. Then, o_2 sends *R-Req* to o_3 if m_2 is influential. On receipt of *R-Req* from o_2, o_3 is rolled back to c_2^3 if m_2 is influential. Otherwise, o_3 just discards *R-Req*, sends back the *Res-Req* to o_2, and then continues the computation. On receipt of *Res-Req* from o_3, o_2 sends *Res-Req* to o_1 and is

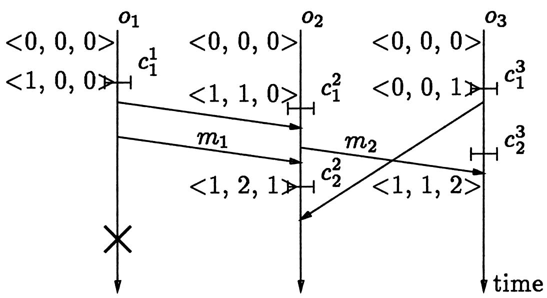

Fig. 6 Restarting procedure.

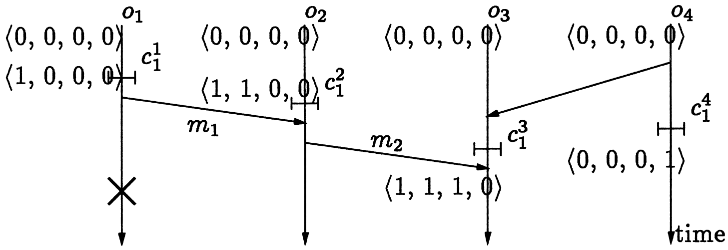

Fig. 7 Synchronous restarting procedure.

restarted. □

4.2 Synchronous Restarting Protocol

In the protocol, each object is not required to be restarted simultaneously with other objects. This protocol is effective if only a few number of objects are rolled back after some faulty object is rolled back. However, the more number of objects to be rolled back, the longer it takes to recover from the fault. In order to resolve the difficulty, we show a synchronous restarting protocol.

Suppose an object o_i is faulty and is rolled back to the local checkpoint c_t^i. o_i is suspended and broadcasts *R-Req* to all objects with $c_t^i.cp$. On receipt of *R-Req* from o_i, o_j is suspended. Then, the value $c_u^j.cp_i$ is compared with *R-Req*.cp_i where c_u^j is a most recent local checkpoint. Suppose *R-Req*.$cp_i \geq c_u^j.cp_i$. Since o_j has not taken a same generation checkpoint with c_t^i, o_j is not rolled back. o_j sends back a message *no* to o_i and then is restarted. Otherwise, o_j sends *yes* to o_i. o_i finds a group of objects to be rolled back by using a bitmap RB $(= rb_1, \ldots, rb_n)$. Each variable rb_k is initially 0 $(1 \geq k \geq n)$. On receipt of *yes* from o_k, rb_k is updated to 1. After receiving messages from all the objects, o_i sends *Rollback* with RB to o_k where rb_k is 1. On receipt of *Rollback* from o_i, o_j is rolled back to the *rollback point* if o_j had received any influential message from o_k where rb_k is 1. Then, o_j sends back *Done* to o_i. On receipt of *Done* from all the objects which o_i has sent *Rollback*, o_i sends *Res-Req* to the objects and then is restarted. On receipt of *Res-Req*, o_j is restarted.

[**Example 5**] Suppose there are four objects o_1, o_2, o_3 and o_4 as shown in **Fig. 7**. Here, suppose o_1 is faulty and is rolled back to the checkpoint c_1^1. o_1 broadcasts *R-Req*. On receipt of *R-Req* from o_1, o_2 and o_3 send *yes* and o_4 sends *no* to o_1 since $c_1^1.cp_1 = c_1^2.cp_1 = c_1^3.cp_1$. On receipt of the messages, rb is updated to 1110 in o_1. o_1 sends *Rollback* to o_2 and o_3. On receipt of *Rollback*, o_2 is rolled back to c_1^2 if m_1 is influential. Similarly, o_3 is rolled back to c_1^3 if m_2 is influential. □

5. Concluding Remarks

We discussed how to take *object-based consistent* (*O-consistent*) checkpoints which show consistent global checkpoints in object-based systems. *O-consistent* checkpoints may be inconsistent with the traditional message-based definition. We have defined *influential messages* on the basis of the conflicting relation of requests where the methods are synchronously or asynchronously invoked in the nested manner. Only objects receiving influential messages are rolled back if the senders of the influential messages are rolled back. As the result, the number of local checkpoints can be reduced by the O-checkpoints. At the *O-consistent checkpoint*, there is no orphan influential message. Also, we presented the protocol for taking O-consistent checkpoints where no object is suspended in taking checkpoints. We presented the restarting protocol after some faulty object is rolled back.

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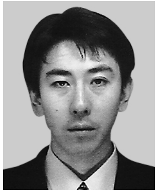

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