CONCURRENT RULE EXECUTION IN ACTIVE DATABASES

Yücel Saygın*, Özgür Ulusoy*[1], and Sharma Chakravarthy†

*Department of Computer Engineering and Information Science, Bilkent University, Turkey.

†Department of Computer and Information Science and Engineering, University of Florida, USA.

Abstract

An active DBMS is expected to support concurrent as well as sequential rule execution in an efficient manner. Nested transaction model is a suitable tool to implement rule execution as it can handle nested rule firing and concurrent rule execution well. In this paper, we describe a concurrent rule execution model based on parallel nested transactions. We discuss implementation details of how the flat transaction model of OpenOODB has been extended by using Solaris threads in order to support concurrent execution of rules. We also provide a formal specification of the rule execution model using the ACTA framework.

Key words: Active databases, nested transactions, execution model, Solaris threads, rule execution, ACTA.

1 Introduction

Conventional, passive databases execute queries or transactions only when explicitly requested to do so by a user or an application program. In contrast, an active database management system (ADBMS) allows users to specify actions to be executed when specific events are signaled [Day88]. The concept of active databases has been originated from the production rule paradigm of Artificial Intelligence (AI). The AI production rule concept has been modified for the active database context so that rules can respond to the state changes caused by the database operations [HW92]. An active database implements reactive behavior since it is able to detect situations, which may occur in and out of the database, and to perform necessary actions which were previously specified by the user. In the absence of such an active mechanism, either the database should be polled or situation monitoring should be embedded in the application code. Neither of these approaches is completely satisfactory. Frequent polling degrades performance of the system and infrequent polling may deteriorate the timeliness of system responses. Embedding situation monitoring in the application code is error prone and reduces the modularity of the application [Day88].

Applications supported by ADBMSs cover a wide range of areas like authorization, access logging, integrity constraint maintenance, alerting, network management, air traffic control, computer integrated manufacturing, engineering design, plant and reactor control, tracking, monitoring of toxic emissions, and any other application where large volumes of data must be analyzed to detect relevant situations [Day88], [BDZ95]. Active DBMSs are proposed for system level applications as well, like supporting different transaction models [CA95].

In a typical ADBMS, system responses are declaratively expressed using Event-Condition-Action (ECA) rules [Day88]. An ECA rule is composed of an *event* that triggers the rule, a

[1]Corresponding author who can be contacted via `oulusoy@cs.bilkent.edu.tr`.

condition describing a given situation, and an *action* to be performed if the condition is satisfied. One of the most important concerns in ADBMS research is *event*, *condition*, and *action* specification. Another significant issue that needs to be explored is event detection. Among typical events in an ADBMS are data modification operations (e.g., insertions and deletions), method invocations on objects, external events (e.g., application signals), temporal events, and transaction related events (e.g., begin, abort transaction) [BZBW95]. Basic events can also be combined to form composite events by using an event algebra. Efficient event detection is of particular importance especially when the number of events to be monitored is large. The occurrence of an event can lead to firing of some rules in the system. If the condition part of a fired rule is satisfied, then the action part of the rule is executed. Coupling modes between event and condition, and between condition and action determine when the condition should be executed relative to the occurrence of the event, and when the action should be executed relative to the satisfaction of the condition, respectively. Rule execution is also a significant research issue in ADBMSs. In Section 2 of this paper, we provide a detailed discussion of rule execution in ADBMSs.

An ADBMS should support both concurrent and sequential rule execution. Sequential rule execution is necessary when a certain execution order is enforced by priorities or when the rules have a predefined sequence of execution. Sequential execution may also be supported in levels; i.e., a certain number of groups of rules can be executed sequentially while the rules in each group are executed concurrently. Concurrent rule execution, on the other hand, is very important from the performance perspective of the system. Concurrency in rule execution can be achieved through either:

- inter-rule concurrency, or
- intra-rule concurrency, or
- both inter and intra-rule concurrency.

In the first case, rules are executed concurrently as if they are atomic transactions. In the second case, rules are divided into subcomponents and those subcomponents are executed concurrently. As another alternative, we may have both types of concurrency together, which is the most flexible concurrent rule execution model. Nested transaction model [Mos85] is considered as a suitable tool to implement rule execution since it provides us with a good model for concurrent rule execution and it can handle nested rule firing well. Nested rule firing occurs when the condition evaluation and action execution of a rule causes some other rules to be fired which may go on recursively. In the nested transaction model, some transactions can be started inside some other transactions forming a transaction hierarchy. The transaction at the top of the hierarchy is called a top-level transaction, and the other transactions are called subtransactions. Subtransactions can be executed concurrently which is a desirable situation if subtransactions are performing tasks that can be overlapped. Concurrency control of nested transactions is discussed in [HR93].

In this paper, we describe a rule execution model for ADBMSs based on parallel nested transactions. Our execution model supports concurrent rule execution through nested transactions, and sequential rule execution through user defined priorities. Rules with the same priority are executed concurrently which allows us to have sequential execution among rules with different priority levels and concurrent execution for the rules with the same priority. The rule execution model is formally specified using ACTA which is a framework proposed for extended transaction models [CR91]. We also discuss the implementation details of concurrent rule execution using parallel nested transactions. The locking protocol described in [HR93] has been implemented which allows us to control

the concurrency among all the transactions in a transaction hierarchy running in parallel. Implementation has been performed by extending the flat transaction semantics of OpenOODB using Solaris threads. OpenOODB is an open (i.e., extendible) object oriented database management system developed by Texas Instruments [WBT92]. In our implementation, all the transactions in a transaction hierarchy are allowed to run in parallel, therefore achieving the highest level of concurrency. Solaris threads are used for running the subtransactions in parallel which provides us with efficient handling of transactions executing concurrently [Sun94]. Our implementation of concurrent rule execution is currently being integrated into Sentinel [CAM93] which is an ADBMS developed at the University of Florida.

A detailed discussion of the issues introduced in this section is provided in the following sections. In Section 2 we provide a detailed description of rule execution in ADBMSs. Our execution model for ADBMSs is described in Section 3 together with its formal specification. Section 4 describes the implementation details of parallel nested transactions on OpenOODB using Solaris threads, and discusses the integration of our implementation into Sentinel. A brief discussion on the execution overhead of parallel nested transactions is provided in Section 5. We conclude the paper by outlining future directions of this work.

2 Rule Execution in ADBMSs

In this section, we provide an overview of rule execution in ADBMSs and discuss the basic issues in nested transactions that can be used in implementing rule execution.

2.1 Overview of ADBMS Rule Execution

A rule in an ADBMS consists of an *event*, a *condition* and an *action*. If the event is missing, then the rule is a *condition-action* (CA) rule or a *production rule*; if no condition is specified, then the resulting rule is an *event-action* (EA) rule or simply a *trigger* [PD95]. When an event is detected, the system searches for the corresponding rules. The condition part of the rule triggered by that event is evaluated and the action is taken if the condition is satisfied. An event may cause more than one rule to be fired. Handling of multiple rules fired by an event is also an important task of rule execution. New events may also occur during rule execution which may cause triggering of other rules. This is called nested (or cascaded) rule firing. Efficient handling of nested rule firing improves the performance of the whole system.

The action part of a rule may be executed in one transaction immediately as a linear extension of the triggering transaction. This is called *coupled execution* [HLM88]. In coupled execution, we do not have intra-rule concurrency. We can give Starburst as an example of coupled execution of rules [Wid96],[AWH92]. In Starburst, rules are based on the notion of transitions. A transition is a change in database state resulting from the execution of a sequence of data manipulation operations. Rules are activated at assertion points. There is an assertion point at the end of each transaction and users may specify other assertion points within a transaction. The state change resulting from the database operations issued by the user since the last assertion point creates the first relevant transition which triggers a set of rules. A rule r is chosen from the set of triggered rules such that no other triggered rule has precedence over it. Condition of r (if it has any) is evaluated. Action part of r is executed provided that its condition evaluates to true; otherwise another rule is chosen. After the execution of r's action, rules that are not considered up until now are triggered only if their transition predicates hold with respect to the predicate created by the composition of the initial transition and the execution of r's action. Rule processing terminates after all triggered rules are

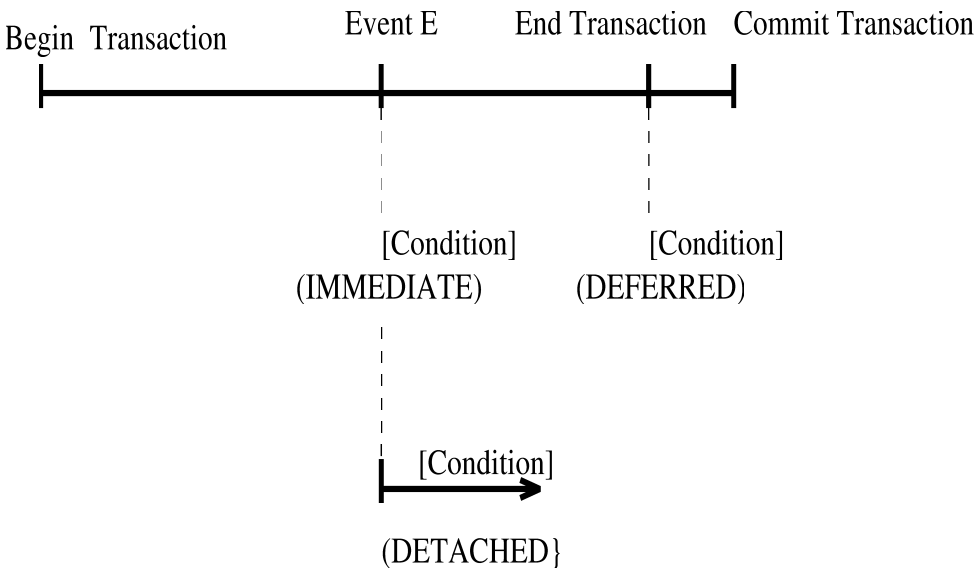


Figure 1: Basic coupling modes illustrated.

executed. Ariel is another ADBMS which uses coupled rule execution[Han96]. Rule instantiations in Ariel are set oriented and execution of rules is performed by recognize-act cycle as in production rules.

Although coupled execution is useful in some cases, it degrades the performance of the system by increasing the response time of transactions. If we allow actions to be executed in separate transactions, then the triggering transaction can finish more quickly and release resources earlier, and this way transaction response times can be improved. We may also want the condition part of the rule to be executed as a separate transaction since conditions which are queries on the database can be long and time consuming. Allowing conditions and actions to be executed in separate transactions is called *decoupled execution* [HLM88]. With decoupled execution we may have intra-rule concurrency.

It is also important to specify when the condition will be evaluated relative to the triggering event and when the action will be executed relative to the condition evaluation. This is achieved by defining *coupling mode*s for conditions and actions which are stated to be a functionality that an active database should provide [btANC96]. There are three basic coupling modes: *immediate*, *deferred*, and *detached* (or *decoupled*) [Day88]. Basic coupling modes between event and condition are illustrated in Figure 1. If the condition is specified to be evaluated in *immediate* mode, then it is executed right after the triggering operation that caused the event to be raised. If the action part is specified to be executed in immediate mode then it is executed immediately after the evaluation of the condition. In case the condition is specified to be in *deferred* mode, its evaluation is delayed until the commit point of the transaction, and similarly if the action is in deferred mode relative to the condition, again it is executed right before the transaction commits. Finally, in *detached mode*, condition is evaluated or action is executed in a separate transaction. Detached mode can further be classified into four subcategories: *detached coupling*, *detached causally dependent coupling*, *sequential causally dependent coupling*, and *exclusive causally dependent coupling* [Buc94]. In *detached coupling* there is no dependency between the triggering and triggered transactions. In *detached causally dependent coupling*, the triggered transaction can commit only if the triggering transaction commits. In *sequential causally dependent coupling*, the triggered transaction can

start executing only if the triggering transaction commits. Finally, in *exclusive causally dependent coupling*, triggered transaction commits only if the triggering transaction fails.

A deferred execution method proposed in [HLM88] involves the execution of transactions in cycles. In cycle-0, deferred transactions that have been fired up to that point are executed. Transactions spawned during cycle-0 in immediate mode are executed as a linear extension of their parents as usual. Execution of the deferred transactions that are fired during cycle-0 by another deferred transaction is postponed to the next cycle, which is cycle-1. Again deferred transactions that are fired in cycle-1 are postponed to the next cycle, which is cycle-2, and so on. This process continues until there are no deferred transactions left.

Intra-rule concurrency is achieved by dividing a rule into a condition and an action, and executing them concurrently. In our execution model, intra-rule concurrency is in the condition-action level, i.e. there are no subcomponents of conditions or actions executing concurrently. Inter-rule concurrency can be achieved by executing the rules concurrently. In the following subsection, nested transactions are explained as a concurrent rule execution model for ADBMSs.

2.2 Nested Transactions for Concurrent Rule Execution

Parallel nested transactions are accepted to be a suitable tool for concurrent rule execution in ADBMSs [HLM88]. In what follows, we will discuss nested transactions together with the concurrency control and recovery issues.

2.2.1 An Introduction to Nested Transactions

Traditional (i.e., flat) transactions have only one branch of execution. In the nested transaction model, transactions can have multiple branches of execution. A nested transaction forms a hierarchy which can be represented as a tree structure, and standard tree notions like parent, child, ancestor, descendant, superior, and inferior also apply to it. The root of the tree is called a root or a top-level transaction. The root may have one or more children, and similarly children of the root may also have their own children. By dividing transactions into smaller granules, we localize the failures into subtransactions. Subtransactions can abort independently without causing the abortion of the whole transaction hierarchy. When a transaction aborts, all of its descendants are also aborted, but other transactions are not affected. Nested transactions are also very useful in terms of system modularity. If we consider a transaction hierarchy as a big module, its subtransactions may be designed and implemented independently as submodules, also providing encapsulation and security [HR93].

2.2.2 Concurrency Control and Recovery Issues in Nested Transactions

Using nested transactions, we can exploit the parallelism among subtransactions since subtransactions can be executed in parallel. There can be four different kinds of parallelism:

1. only sibling,
2. only parent-child,
3. parent-child and sibling,
4. no parallelism (i.e., sequential execution).

In the first case, where only sibling parallelism is allowed, parent stops its execution while its children are running concurrently. In the second case, only parent-child parallelism is allowed where the parent and a child run concurrently while the other children wait. In the third case, all transactions in the hierarchy can run in parallel. In the fourth case, we have no parallelism at all (i.e., transactions in the hierarchy are executed sequentially) [HR93]. In our model, we will assume parent-child and sibling parallelism since it provides us with the most flexible model of parallelism.

When transactions are executed concurrently, serializability is used as the correctness criterion, and it is ensured by using a concurrency control protocol. A child transaction can potentially access any object in the database. When a subtransaction commits, the objects modified by it are delegated to its parent transaction. In our execution model, we used a locking protocol for concurrency control in nested transaction execution. The protocol is described in the next section.

In nested transactions, ACID properties (i.e., atomicity, consistency, isolation, and durability) are valid for top-level transactions, but only a subset of them holds for subtransactions [HR93]. A subtransaction may commit or abort independent of other transactions. Aborting a subtransaction does not affect other transactions outside of its hierarchy, hence they protect the outside world from internal failures. If we had packed all subtransactions into one big flat transaction then we would have to abort the whole transaction.

Recovery of nested transactions is similar to the recovery of flat transactions. Standard recovery algorithms like versioning or log-based recovery can be used. Log-based recovery for nested transactions is discussed in [Mos87] and [RM89]. [RM89] introduces a model called ARIES/NT and this has several advantages over the recovery model provided in [Mos87] . The biggest drawback of the recovery model of [Mos87] is that it does not use Compensation Log Records (CLRs) which are necessary for performance reasons. A detailed description of CLRs is provided in [RM89]. OpenOODB, on which our execution model has been built, uses Exodus as storage manager whose recovery component is implemented based on ARIES [MHL+92], and ARIES/NT is provided for nested transactions as an extension to ARIES.

3 Rule Execution Model

Our concurrent rule execution model is based on the nested transaction model. The nested transaction model implicitly assumes that subtransactions are spawned in immediate mode. In our execution model, transactions may spawn subtransactions in any coupling mode specified by the system. Each rule is encapsulated in a transaction. When a rule r_1 fires another rule r_2, then depending on the coupling mode, r_2 is encapsulated in another (sub)transaction and executed in the specified coupling mode. If the coupling mode is immediate or deferred, then r_2 is executed as a subtransaction of r_1. If the coupling mode is one of detached, sequential causally dependent, detached causally dependent, or exclusive causally dependent modes, then r_2 is executed as a top-level transaction. The overall structure of the currently executing rules in the system forms a forest consisting of trees whose roots are the rules fired in one of the detached coupling modes. As stated earlier, both parent-child and sibling parallelism are allowed which provides us with the maximum concurrency among subtransactions. Top-level transactions are executed in parallel. All nested transaction semantics applies among the individual rules in the nested transaction tree. Abort and commit dependencies among the top-level transactions are enforced by the transaction manager.

In addition to the coupling mode and the tuple- or set-oriented semantics, priority information also affects the order of rule execution. Typically, expert systems assumed a conflict resolution strategy which produced a sequential order for executing *eligible* rules one at a time. In contrast, DBMSs assume no priority among transactions/subtransactions and hence execute *eligible* trans-

actions in an interleaved order to maximize some metric (such as throughput). The correctness criteria is the serialization of transactions. Note that serial execution automatically satisfies the serializability criteria.

In fact, a combination of the above two alternatives is likely to meet the requirements of applications. This entails that the system be capable of supporting both serial execution using *a* conflict resolution strategy and concurrent execution based on the serialization criterion of correctness. In Sentinel, both of these are supported to provide maximum flexibility for the specification and execution of ECA rules [CAM93].

3.1 Concurrency Control

The concurrency control algorithm used in our execution model is based on the notion of nested concurrency control. Harder and Rothermel [HR93] have extended Moss's nested transaction model to contain downward as well as upward inheritance of locks. We have employed in our model the locking protocol provided in [HR93]. The protocol is composed of the following locking rules:

- Rule 1: Transaction T may acquire a lock in mode M or upgrade a lock it holds to mode M if:
  - no other transaction holds the lock in a mode that conflicts with M, and
  - all transactions that retain the lock in a mode conflicting with M are ancestors of T.

  A transaction *holds* a lock on an object if it has the right to access the locked object in the requested mode. In contrast, a transactions *retains* a lock on an object to control the access of the transactions outside the hierarchy of the retainer and cannot be accessed by the transaction retaining the lock.
- Rule 2: When subtransaction T commits, the parent of T inherits T's locks (held and retained). After that, the parent retains the locks in the same mode as T held or retained them before.
- Rule 3: When a top-level transaction commits, it releases all the locks it holds or retains.
- Rule 4: When a transaction aborts, it releases all the locks it holds or retains. If any of its superiors hold or retain any of these locks, they continue to do so.
- Rule 5: Transaction T, holding a lock in mode M, can downgrade the lock to a less restrictive mode, M′. After downgrading the lock, T retains it in mode M.

These locking rules can be used with different types of coupling modes. A transaction spawned in detached causally dependent mode should be able to use its parent's locks in the same way as a subtransaction spawned in immediate or deferred mode. Since the transaction spawned in detached causally dependent mode should abort if its parent aborts, it can use its parent's locks without causing any problem in the recovery. Both shared and exclusive lock modes are available to transactions in our execution model as described in Section4.2.1 .

3.2 Rule Priorities

Rules, in our execution model, are associated with priorities. Several rules can have the same priority value. Rule scheduler uses the priority information to either schedule them sequentially

(the rule priority is converted into thread priority in which the rule is executed as a subtransaction), or concurrently by assigning the same priority to several threads. Correctness of rule execution is guaranteed by the semantics of nested transactions. For nested rule execution, the determination of the order of execution can be based on whether depth-first, breadth-first, or a combined control strategy is used. In fact, depending upon the preferred control strategy, the priorities can be determined by the system to create a total order of thread priorities that will satisfy the control strategy. Currently, depth-first execution has been implemented. Priorities are used to allow sequential execution of rules. There are some points that should be taken into account since the semantics of coupling modes makes some priority assignment schemes meaningless. In case of immediate mode, priority of the child transaction should be higher then the priority of the parent transaction, since parent cannot commit before its children commits. The same argument holds for deferred coupling mode. In detached causally dependent mode, child cannot commit if its parent aborts. So it should wait for the commit of its parent implying that a lower priority given to the child would be more meaningful. In sequential causally dependent mode, child cannot start its execution until its parent commits and in exclusive causally dependent mode, the child transaction commits only if the parent aborts. So, transactions spawned in sequential causally dependent or exclusive causally dependent modes should have a lower priority then their parent. Dependencies among subtransactions can be viewed as implicit priorities and they should be taken into account in priority assignment. Priorities are important when a group of transactions are spawned by the same transaction in immediate, deferred, or detached coupling modes. The execution of transactions that are spawned in deferred mode is delayed until the end of the parent transaction, for that reason they should be considered as a separate group. During the cycling execution of deferred transactions, priorities should be taken into account. Transactions spawned in immediate mode and detached mode should be considered as a separate group and should be executed in sequence with respect to their priorities. Transactions with same priority are executed concurrently. In case a transaction does not posses a priority, we should assign the lowest priority among the group of transactions in concern.

3.3 A Formal Description of Our Rule Execution Model Using ACTA

ACTA is a transaction framework that can be used to formally describe extended transaction models [CR94]. Using ACTA, we can specify the interactions and dependencies between the transactions in a model. ACTA characterizes the semantics of interactions (1) in terms of different types of dependencies between transactions (e.g., commit dependency and abort dependency) and (2) in terms of transactions effects on objects (their state and concurrency status, i.e., synchronization state) [CR94]. Effects of transactions on objects are specified using two sets associated with each transaction: a *view set* which contains the state of objects visible to that transaction and a *conflict set* which contains operations for which conflicts need to be considered. ACTA framework consists of four basic blocks which are *history*, *dependencies* between transactions, *view* and *conflict sets* of transactions, and finally *delegation*. *History* represents the concurrent execution of a set of transactions and contains all the events invoked by those transactions, also indicating the partial order in which these events occur. Invocation of an event ϵ by a transaction t is denoted by ϵ_t. There are three possibilities that can affect the occurrence of an event:

1. an event ϵ can occur only after the occurrence of another event ϵ' (denoted as $\epsilon' \rightarrow \epsilon$),
2. an event ϵ can occur only if a condition c is true (denoted as $c \Rightarrow \epsilon$),
3. a condition c can require the occurrence of an event ϵ (denoted as $\epsilon \Rightarrow c$).

Standard dependencies defined in ACTA which we have used for specifying our execution model are:

- Commit Dependency (denoted as $t_j\ CD\ t_i$). If transactions t_i and t_j both commit then t_i should commit before t_j. This can be shown axiomatically as:

  $Commit_{t_j} \in H \Rightarrow (Commit_{t_i} \in H \Rightarrow (Commit_{t_i} \rightarrow Commit_{t_j}))$.

- Abort Dependency (denoted as $t_j\ AD\ t_i$). If t_i aborts then t_j should also abort:

  $Abort_{t_i} \in H \Rightarrow Abort_{t_j} \in H$

- Weak-Abort Dependency (denoted as $t_j\ WD\ t_i$). If t_i aborts and t_j has not yet committed, then t_j aborts:

  $Abort_{t_i} \in H \Rightarrow (\neg(Commit_{t_j} \rightarrow Abort_{t_i}) \Rightarrow (Abort_{t_j} \in H))$

- *Exclusion Dependency* is denoted by $t_j\ ED\ t_i$, and ensures that if t_i commits , then t_j must abort. We can state this formally as:
  $Commit_{t_i} \in H \Rightarrow Abort_{t_j} \in H$.

These dependencies may be the result of the structural properties of transactions. For example, in nested transactions child transactions are related to their parent by commit and weak-abort dependencies.

Standard ACTA terms *Delegate* and $ResponsibleTr$ are defined as:

> $Delegate_{t_i}[t_j, p_{t_i}[ob]]$ denotes that transaction t_i delegated the responsibility of committing or aborting the operation $p_{t_i}[ob]$ to transaction t_j. A set of operations may be delegated by $Delegate_{t_i}[t_j, DelegateSet]$. Initially, the responsibility of committing or aborting an operation belongs to the transaction that invoked the operation, unless it is delegated to another transaction.
>
> $ResponsibleTr(p_{t_i}[ob])$ identifies the transaction that is responsible for committing or aborting the operation $p_{t_i}[ob]$ with respect to the current history.

Axiomatic definition of the standard nested transaction model is provided in [CR94]. Since the nested transaction model we use is different from the standard nested transaction model of [Mos85], we need to modify the axiomatic definitions provided for nested transactions. First of all, the standard ACTA term $ResponsibleTr$ is separated into two notions, namely $Responsible\_retainTr$ and $Responsible\_selfTr$. With respect to this modification, $Responsible\_selfTr(p_{t_i}[ob])$ identifies the transaction which actually invoked an operation on the object *ob*. The transaction identified by $Responsible\_selfTr(p_{t_i}[ob])$ is also responsible for the commit or abort of this operation. $Responsible\_retainTr(p_{t_i}[ob])$, on the other hand, identifies the transaction to which the responsibility of committing or aborting this operation is delegated.

Since our notion of responsible transaction is different, the semantics of delegation should also be modified. According to this modification,

> $Delegate_{t_i}[t_j, p_{t_i}[ob]]$ denotes that transaction t_i delegated the retain or self responsibility of committing or aborting the operation $p_{t_i}[ob]]$ to transaction t_j as retain responsibility.

Finally, the access set of a transaction is modified as:

$AccessSet_t = \{p_{t_i}[ob] | Responsible\_selfTr(p_{t_i}[ob]) = t$
$\vee \ Responsible\_retainTr(p_{t_i}[ob]) = t\}$

In the next subsection, we provide the axiomatic definition of the extended parallel nested transaction model which allows all the transactions in a transaction hierarchy to run in parallel. These definitions have been obtained by making appropriate modifications on the axiomatic definitions of standard nested transactions provided in [CR94].

3.3.1 Axiomatic Definition of Parallel Nested Transactions in ACTA

Assume that t_0 is the root transaction, t_p is a root or a subtransaction, and t_c is a subtransaction of t_p. $Ancestors(t)$ is the set of all ancestors of transaction t, $Descendants(t)$ is the set of all descendants of transaction t, and $Parent(t)$ is the parent of t.

1. $SE_{t_0} = \{Begin, Spawn, Commit, Abort\}$
2. $IE_{t_0} = \{Begin\}$
3. $TE_{t_0} = \{Commit, Abort\}$
4. $SE_{t_c} = \{Spawn, Commit, Abort\}$
5. $IE_{t_c} = \{Spawn\}$
6. $TE_{t_c} = \{Commit, Abort\}$
7. t_p satisfies the fundamental axioms of transactions that are listed in [CR94].
8. $View_{t_p} = H_{ct}$
   That is, t_p sees the current state of objects in the database.
9. $ConflictSet_{t_0} = \{p_t[ob] | Responsible\_selfTr(p_t[ob]) \neq t_0, Inprogress(p_t[ob])\}$
   Conflict set of t_0 consists of all operations performed by different transactions for which it is not self-responsible (i.e., t_0 did not actually invoked the operation).
10. $\forall ob \, \exists p \, p_{t_p}[ob] \in H \Rightarrow (ob \ is \ atomic)$
    All objects on which t_p invokes an operation are atomic objects.
11. $Commit_{t_p} \in H \Rightarrow \neg(t_p b_N^* t_p)$
    Transaction t_p can commit only if it is not part of a cycle of b relations
    that are results of conflicting operations.
12. $\exists ob, p, t \, (Commit_{t_p}[p_t[ob]] \in H \Rightarrow Commit_{t_p} \in H \wedge Parent(t_p) = \phi)$
    If an operation p invoked on an object ob is committed by transaction t_p, then t_p should also commit and it should be a top-level transaction.
13. $(Commit_{t_p} \in H \wedge Parent(t_p) = \phi) \Rightarrow \forall ob, p, t (p_t[ob] \in AccessSet_{t_p}$
    $\Rightarrow Commit_t[p_t[ob]] \in H)$
    If a top-level transaction commits then all the operations for which it is responsible must also be committed.
14. $\exists ob, p, t \, (Abort_{t_p}[p_t[ob]] \in H \Rightarrow Abort_{t_p} \in H)$
    If an operation p invoked on an object ob in transaction t is aborted by transaction t_p, then t_p must also abort.

15. $Abort_{t_p} \in H \Rightarrow \forall ob, p, t(p_t[ob] \in AccessSet_{t_p} \Rightarrow Abort_{t_p}[p_t[ob]] \in H)$
If t_p aborts then all the operations for which it is responsible must abort.

16. $Begin_{t_p} \in H \Rightarrow (Parent(t_p) = \phi \wedge Ancestor(t_p) = \phi)$
Begin operation implies that a top-level transaction starts its execution.

17. $ConflictSet_{t_c} = \{p_t[ob] | Responsible\_selfTr(p_t[ob]) \neq t_c, Inprogress(p_t[ob])\}$
Conflict set of a child transaction t_c consists of those operations for which t_c is not self responsible, since the operations on the object *ob* for which t_c has the retain responsibility may be conflicting with another transaction which is not an ancestor of t_c. This is due to the fact that subtransactions are executing in parallel with their parent transaction.

18. $Spawn_{t_p}[t_c] \in H \Rightarrow Parent(t_c) = t_p$
If transaction t_c is spawned by transaction t_p then t_p is the parent of t_c.

19. $Spawn_{t_p}[t_c] \in H \Rightarrow (t_c WDt_p) \wedge (t_p CDt_c)$
If transaction t_c is spawned by transaction t_p then t_p cannot commit until t_c terminates, and if t_p aborts then t_c must also abort.

20. $Commit_{t_c} \in H \Leftrightarrow Delegate_{t_c}[Parent(t_c), AccessSet_{t_c}] \in H$
If a child transaction t_c commits, then it should delegate the objects in its access set to its parent.

21. $\forall t \in Descendants(t_p) \forall ob, p, q(p_t[ob] \rightarrow q_{t_p}[ob]) Conflict(p_t[ob], q_{t_p}[ob])$
$\Rightarrow \exists t_c ((Delegate_{t_c}[t_p, AccessSet_{t_c}] \rightarrow q_{t_p}[ob]) \wedge p_t[ob] \in AccessSet_{t_c})$
Given a transaction t and its ancestor t_p and operations p and q, t_p can invoke q after t invokes p if t_p is responsible for the operation p.

22. $(Ancestor(t_c) = Ancestor(t_p) \cup \{t_p\}) \wedge \forall t(t_p \in Descendants(t)$
$\Rightarrow t_c \in Descendants(t))$
Ancestor set of t_c consists of its parent plus ancestors of its parent, and for all transactions t of which t_p is a descendant, t_c is also a descendant of t.

3.3.2 Formalization of the Rule Execution Model

A formal specification of rule execution in ADBMSs using ACTA can be provided without significant changes to the standard ACTA primitives. The *Spawn* primitive can be extended to the primitives *Spawn_Imm*, *Spawn_Def*, *Spawn_Detached*, *Spawn_Caus*, *Spawn_Seq*, and *Spawn_Exc*, which specify the coupling modes in which the subtransactions are spawned. All coupling modes except the *deferred mode* and *sequential causally dependent mode* can be specified easily using the standard dependencies of ACTA (i.e., commit dependency, abort dependency, weak abort dependency, and exclusion dependency [CR94]). For the deferred mode, we need to specify a *cycling execution method*, which can be stated as follows:

> Deferred transactions are executed in cycles at the end, but just before the commit of the transaction that spawned them. Cycling execution can start only in a top-level transaction or a subtransaction spawned in immediate mode since deferred subtransactions spawned by another deferred transaction are executed in the next cycle after the commitment of their parent. Subtransactions spawned by a deferred transaction in immediate mode are executed immediately, which deviates from the standard specification of the "deferred execution in cycles".

The specification of all the coupling modes we considered, including the deferred mode and sequential causally dependent mode is provided in the following.

Coupling Modes

The coupling modes we considered in our execution model are listed below:

- *immediate mode*: It has the same semantics as the creation of a subtransaction in standard nested transaction model. Spawning of an immediate subtransaction is denoted by the primitive $Spawn\_Imm$.

- *detached mode*:It has the same semantics as the creation of top-level transactions in the standard nested transaction model. There are no dependencies between the spawning and spawned transaction. Spawning of a detached transaction is denoted by the primitive $Spawn\_Detached$.

- *detached causally dependent mode*: In this mode, spawned transaction aborts if the parent aborts, therefore there is an abort dependency between the spawning transaction and spawned transaction. Spawning of a transaction in this mode is specified by the primitive $Spawn\_Caus$.

- *sequential causally dependent mode*: It specifies that a child transaction cannot start its execution until its parent commits. This can be enforced by a $Sequential\_Dependency(SQD)$ which is provided as an extension to the standard ACTA dependency set and can be stated formally as:

  $$t_i SQD t_j \Leftrightarrow ((Begin_{t_j} \in H) \Rightarrow (Commit_{t_i} \rightarrow Begin_{t_j}))$$

  The primitive $Spawn\_Seq$ indicates that a subtransaction is spawned in this mode.

- *exclusive causally dependent mode*: It is denoted by the primitive *Spawn_Exc* and it ensures that the spawned transaction commits only if the spawning transaction aborts. This can be enforced by using a standard ACTA dependency, namely the *Exclusion Dependency* between the spawning and spawned transactions.

- *deferred mode*: It is denoted by the primitive *Spawn_Def*, and a bit more effort is required to specify it in ACTA framework due to the cycling execution method. Assume that t_0 is a top-level transaction, t_p is a top-level or subtransaction, and t_c is a child transaction spawned by t_p in deferred mode.

  Case 1: t_p is a top-level transaction or a subtransaction spawned in immediate mode, i.e., t_c is going to be executed in cycle-0. In this case, t_c is executed just before the commit of t_p after all other operations of t_p are completed; i.e., all operations of t_p precede all operations of t_c.
  Case 2: t_p is a transaction spawned in deferred mode. This means that t_c is spawned during a cycle. Then, every operation performed by t_c should succeed all the operations of t_p and the operations of siblings of t_p that are spawned in deferred mode (i.e., executed in the same cycle).

There is an ambiguity in the method described in [HLM88] for the cycling execution of rules fired in deferred coupling mode. If a rule is fired in deferred mode by a transaction during the execution of a cycle, it is executed in the next cycle; but if a rule is fired in deferred mode by a transaction which has been fired in immediate mode then the fate of this transaction, i.e., whether it will be deferred to the next cycle or it will be executed in another execution cycle is left unspecified.

We chose to execute these kinds of rules in another cycle before the commit point of the immediate rule.

In our execution model, we consider the coupling modes between the event and condition, and also the condition and action. We can give the option of defining the coupling mode between the condition and action to the user, where the user can select immediate or sequential causally dependent coupling mode. Other coupling modes would not make sense due to the semantics of the relation between the condition and action. In immediate mode, condition evaluation is followed by execution of the action only if the condition evaluates to true. In sequential causally dependent mode, action execution starts before condition evaluation is completed. This improves the concurrency in a system in case there exist abundant resources in the system, which is a reasonable assumption due to the continuous decrease in the prices of system resources. The transaction in which the action is executed can commit only if the condition commits and returns true. The performance impact of the sequential causally dependent coupling mode between condition and action needs further investigation.

Priorities

In order to provide priorities in ACTA primitives, we define $priority(t)$ to specify the priority of transaction t. Priorities are assumed to be assigned by the user. Our priority scheme assumes that priorities are taken into consideration only for the transactions which do not have any dependencies among each other since dependencies are considered as implicit priorities. As we stated earlier, deferred transactions spawned by the same transaction are independent of each other. So we can use priorities to schedule them by enforcing the operations of a deferred transaction with a higher priority to precede the operations of a lower priority transaction spawned in deferred mode by the same transaction. Similarly, we can use priorities in scheduling subtransactions spawned in immediate mode by the same transaction by enforcing that the operations of a high priority transaction are scheduled before the operations of a lower priority transaction.

A Formal Rule Execution Model

Assume that the definitions provided at the beginning of Section 3.3.1 for the following notations also hold in this section: t_0, t_p, t_c, $Ancestors(t)$, $Decendants(t)$, $Parent(t)$.

Notice that, as one deviation from the standard nested transaction model, there are various spawn events in axioms (1),(4), and (5) corresponding to different coupling modes. Some of the axioms used for the nested transaction model directly apply to our execution model. For example, axioms (7) through (17) which define the semantics of a top-level or a subtransaction which spawns another transaction are the same for both models, therefore we did not include their explanations here. Readers who need more information about those axioms are referred to Section 3.3.1.

1. $SE_{t_0} = \{Begin, Spawn\_Imm, Spawn\_Def, Spawn\_Detach, Spawn\_Caus, Spawn\_Seq, Spawn\_Exc, Commit, Abort\}$
2. $IE_{t_0} = \{Begin\}$
3. $TE_{t_0} = \{Commit, Abort\}$
4. $SE_{t_c} = \{Spawn\_Imm, Spawn\_Def, Spawn\_Detach, Spawn\_Caus, Spawn\_Seq, Spawn\_Exc, Commit, Abort\}$
5. $IE_{t_c} = \{Spawn\_Imm, Spawn\_Def, Spawn\_Detach, Spawn\_Caus, Spawn\_Seq, Spawn\_Exc\}$

6. $TE_{t_c} = \{Commit, Abort\}$

7. t_p satisfies the fundamental axioms of transactions that are listed in [CR94].

8. $View_{t_p} = H_{ct}$

9. $ConflictSet_{t_0} = \{p_t[ob] | responsible\_selfTr(p_t[ob]) \neq t_0, Inprogress(p_t[ob])\}$

10. $\forall ob \exists pp_{t_p}[ob] \in H \Rightarrow (ob\ is\ atomic)$

11. $Commit_{t_p} \in H \Rightarrow \neg(t_p b_N^* t_p)$

12. $\exists ob, p, tCommit_{t_p}[p_t[ob]] \in H \Rightarrow Commit_{t_p} \in H \wedge Parent(t_p) = \phi$

13. $Commit_{t_p} \in H \wedge Parent(t_p) = \phi \Rightarrow (\forall ob, p, t(p_t[ob] \in AccessSet_{t_p}$
$\Rightarrow Commit_t[p_t[ob]] \in H))$

14. $\exists ob, p, t\ Abort_{t_p}[p_t[ob]] \in H \Rightarrow Abort_{t_p} \in H$

15. $Abort_{t_p} \in H \Rightarrow (\forall ob, p, t(p_t[ob] \in AccessSet_{t_p} \Rightarrow Abort_{t_p}[p_t[ob]] \in H))$

16. $Begin_{t_p} \in H \Rightarrow Parent(t_p) = \phi \wedge Ancestor(t_p) = \phi$

17. $ConflictSet_{t_c} = \{p_t[ob] | Responsible\_selfTr(p_t[ob]) \neq t_c, Inprogress(p_t[ob])\}$

18. $(Spawn\_Imm_{t_p}[t_c] \in H \vee Spawn\_def_{t_p}[t_c] \in H) \Rightarrow Parent(t_c) = t_p$
If a transaction t_p spawns a child transaction t_c in immediate or deferred mode then t_p is the parent of t_c.

19. $(Spawn\_Imm_{t_p}[t_c] \in H \vee Spawn\_def_{t_p}[t_c] \in H) \Rightarrow (t_c W D t_p) \wedge (t_p C D t_c)$
If a transaction t_c is spawned in immediate or deferred mode by a transaction t_p, then t_c aborts when t_p aborts and t_p cannot commit until t_c terminates.

20. $(Spawn\_Caus_{t_p}[t_c] \in H \vee Spawn\_Detach_{t_p}[t_c] \in H$
$\vee\ Spawn\_Seq_{t_p}[t_c] \in H \vee Spawn\_Exc_{t_p}[t_c] \in H) \Rightarrow Parent(t_c) = \phi$
$\wedge\ Ancesstor(t_c) = \phi$
A transaction spawned with detached, detached causally dependent, sequential causally dependent, or exclusive causally dependent mode is a top-level transaction, therefore has no parent or ancestor.

21. $Spawn\_Caus_{t_p}[t_c] \in H \Rightarrow t_c A D t_p$
If a subtransaction t_c is spawned in causally dependent mode by transaction t_p then t_c must abort if t_p aborts.

22. $Spawn\_Seq_{t_p}[t_c] \in H \Rightarrow t_c SQD t_p$
If a subtransaction t_c is spawned in sequential causally dependent mode by transaction t_p then t_c can start its execution only if t_p commits.

23. $Spawn\_Exc_{t_p}[t_c] \in H \Rightarrow t_c E D t_p$
If a subtransaction t_c is spawned in exclusive causally dependent mode by transaction t_p then t_c can start its execution only if t_p aborts.

24. $(Spawn\_Imm_{t_p}[t_c] \vee Spawn\_def_{t_p}[t_c]) \in H \wedge Commit_{t_c} \in H$
$\Leftrightarrow Delegate_{t_c}[Parent(t_c), AccessSet_{t_c}] \in H$
If a subtransaction t_c is spawned in immediate or deferred mode by transaction t_p then t_c must delegate all the operations in its access set to its parent t_p.

25. $\forall t, ob, p, q(t \in Descendants(t_p) \wedge (p_t[ob] \rightarrow q_{t_p}[ob]) \wedge Conflict(p_t[ob], q_{t_p}[ob])$
$\Rightarrow \exists t_c((Delegate_{t_c}[t_p, AccessSet_{t_c}] \rightarrow q_{t_p}[ob] \wedge p_t[ob] \in AccessSet_{t_c})))$
Given a transaction t and its ancestor t_p and operations p and q, t_p can invoke q after t invokes p if t_p is responsible for the operation p.

26. $(Spawn\_Imm_{t_p}[t_c] \vee Spawn\_Def_{t_p}[t_c]) \in H$
$\Leftrightarrow (Ancestor(t_c) = Ancestor(t_p) \cup \{t_p\}) \wedge \forall t(t_p \in Descendants(t)$
$\Rightarrow t_c \in Descendants(t))$
Ancestor set of a transaction spawned in immediate or deferred mode is defined similar to that with the standard nested transactions.

27. $(Spawn\_Def_{t_p}[t_c] \in H \wedge (Parent(t_p) = \phi \vee \exists t(Spawn\_Imm_t[t_p] \in H))$
$\Rightarrow \forall p, ob_1, q, ob_2(p \neq Commit \wedge p_{t_p}[ob_1] \in H \wedge q_{t_c}[ob_2] \in H$
$\Rightarrow (p_{t_p}[ob1] \rightarrow p_{t_c}[ob_2])))$
This axiom corresponds to Case-1 of the deferred coupling mode execution described in Section 3.3.2.

28. $(Spawn\_Def_{t_p}[t_c] \in H \wedge \exists t(Spawn\_Def_t[t_p] \in H)$
$\Rightarrow \forall p, q, r, ob_1, ob_2, ob_3, t_1, t_2(p_{t_p}[ob1] \in H \wedge q_{t_c}[ob2] \in H$
$\wedge Spawn\_Def_t[t_2] \in H \Rightarrow (p_{t_p}[ob1] \rightarrow q_{t_c}[ob2] \wedge r_{t_2}[ob3] \rightarrow q_{t_c}[ob3])$
This axiom corresponds to Case-2 of the deferred mode execution.

29. $(Spawn\_Def_{t_p}[t_{c_1}] \in H \wedge Spawn\_Def_{t_p}[t_{c_2}] \in H \wedge priority(t_{c_1}) > priority(t_{c_2})$
$\Rightarrow \forall p, q, ob_1, ob_2(q_{t_{c_1}}[ob1] \rightarrow q_{t_{c_2}}[ob2])$
Among the deferred transactions spawned by the same transaction, operations are executed in the order of priorities of the corresponding transactions.

30. $(Spawn\_Imm_{t_p}[t_{c_1}] \in H \wedge Spawn\_Imm_{t_p}[t_{c_2}] \in H \wedge priority(t_{c_1}) > priority(t_{c_2})$
$\Rightarrow \forall p, q, ob_1, ob_2((Spawn\_Imm_{t_p}[t_{c_1}]) \rightarrow q_{t_{c_2}}[ob2] \Rightarrow (q_{t_{c_1}}[ob1] \rightarrow q_{t_{c_2}}[ob2]))$
Among the immediate transactions spawned by the same transaction, operations of the lower priority transaction which are issued after the start of a higher priority transaction are executed after the operations of the higher priority transaction.

4 Implementation of Nested Transactions for Rule Execution

4.1 Previous Work

Although various implementations of the nested transaction model have been provided to date, to the best of our knowledge, implementation of concurrent rule execution through nested transactions has not been attempted for any ADBMS.

One implementation of nested transactions has been performed on the Eden Resource Management System (ERMS) [PN87]. In ERMS, transaction managers are composed hierarchically; i.e., for each subtransaction there is a corresponding transaction manager. For ensuring the serializability, two-phase locking is used, and a version-based recovery is used for the recovery of

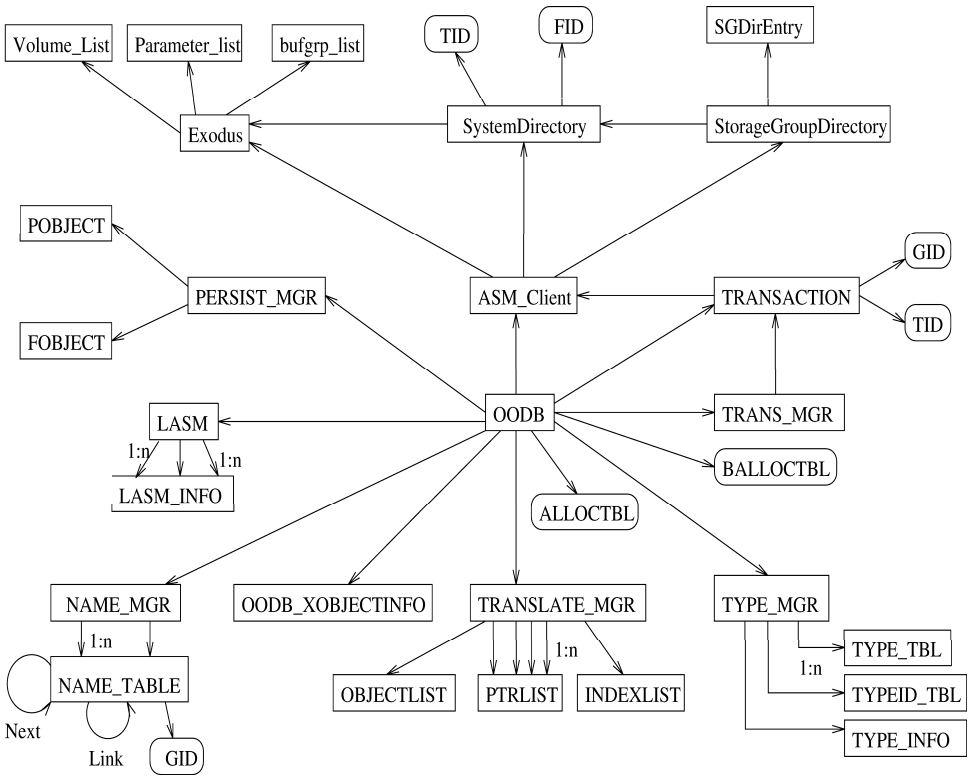


Figure 2: OpenOODB object relationship diagram.

sub-transactions. In [DGRV95], the implementation described focuses on nested transactions for client workstations of an object oriented DBMS(OODBMS).

Nested transactions have also been implemented for supporting parallelism in engineering databases [HPS92]. That particular implementation supports both parent-child and sibling parallelism as in our implementation.

4.2 Implementation

We implement nested transactions by extending the flat-transaction semantics of OpenOODB [WBT92]. OpenOODB is an open object oriented DBMS that can be extended by special constructs called *sentries*. In our implementation, a component architecture method is used instead of sentries; i.e., a new component is added without significantly modifying the existing ones. Our first task was to construct the object relationships of OpenOODB by examining the class declarations. In Figure 2, the whole OpenOODB object relationships diagram is given. Among the components illustrated in this diagram, the ones that need to be considered for our implementation are isolated. These isolated components are shown in Figure 3. In this figure, we see that the main OpenOODB object $OODB$ has a pointer to each of four objects namely $PERSIST\_MGR$, $TRANS\_MGR$, $TRANSACTION$, and ASM_CLIENT which means that whenever an instance of an object of type $OODB$ is created, its constructor creates instances of $PERSIST\_MGR$, $TRANS\_MGR$, $TRANSACTION$, and ASM_CLIENT objects. Furthermore, the constructor of $TRANS\_MGR$ object creates an instance of $TRANSACTION$ object which is also used directly by $OODB$.

To give a flavor of how a transaction is started and objects are fetched from the database, we give a sample application of OpenOODB in Figure 4. As can be seen from the figure, an OpenOODB

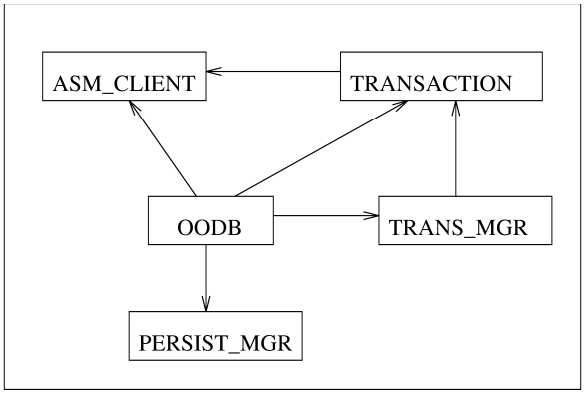


Figure 3: Related object relationships

```
OODB *p_oodb;
My_Class *my_obj = new My_Class;
My_Class *tmp_obj;
char *obj_name = "obj1";
main()
{
        p_oodb →beginTransaction();
        /* make the object persistent and give a name to it */
        my_obj →persist(obj_name);
        p_oodb →commitTransaction();

        p_oodb →beginTransaction();
        /* fetch the object with the given name */
        p_oodb →fetch(obj_name);
        p_oodb →commitTransaction();
}
```

Figure 4: A simple OpenOODB application.

main object *p_oodb* is created which provides us with an interface to OpenOODB. A transaction is started by using $p\_oodb \rightarrow beginTransaction$ and committed by $p\_oodb \rightarrow commitTransaction$. Abortion of a transaction is achieved by $p\_oodb \rightarrow abortTransaction$. Objects are made persistent by $my\_obj \rightarrow persist()$ and are fetched from the database by the $p\_oodb \rightarrow fetch(...)$. OpenOODB fetch operation does not give the flexibility of specifying the lock mode but acquires a default *READ* lock from EXODUS storage manager. To provide the application programmer with more flexibility, we decided to modify the fetch operator of OpenOODB so that it takes the locking mode as a parameter. As a second stage, nested transaction primitives:

- *spawn_sub_transaction*
- *commit_sub_transaction*
- *abort_sub_transaction*

are added to the transaction manager of OpenOODB (i.e., $TRANS\_MGR$ in Figure 3). Finally, a Lock Manager is implemented to support the nested transaction primitives that are added to the transaction manager. Among the nested transaction primitives, only the *spawn_sub_transaction* takes parameters. The first parameter of it is the name of the function where the subtransaction is written in, the second one is the spawn-mode. Spawn-mode specifies the coupling mode between the parent and child. For our nested transaction component, we implemented the immediate and deferred coupling modes. Detached coupling modes are handled by the rule manager of the ADBMS.

Using Figure 3 we can describe where our lock manager fits in the object relationships diagram. In that figure, the main object of OpenOODB (i.e., $OODB$), points to a $TRANS\_MGR$ object which has a $TRANSACTION$ object. And the $TRANSACTION$ object has a $LOCK\_MANAGER$ object; i.e., the constructor of the transaction object creates the $LOCK\_MANAGER$ object which can be accessed by $OODB$. This way the constructs implemented in $LOCK\_MANAGER$ and $TRANS\_MGR$ can be used by the application via the OpenOODB interface object, $OODB$.

$LOCK\_MANAGER$ has two main data structures, namely the *Lock_Table* and the *Transaction_Table*. *Lock_Table* is a hash table that is used to keep the lock information of objects that have previously been fetched by a transaction in the transaction hierarchy. *Lock_Table* is hashed by the object name, and given an object, we can reach all the transactions that have a lock on this object with any mode. *Transaction_Table* keeps the transaction hierarchy, wait-for graph and the lock information of the subtransactions. These data structures are shown in Figure 5. We can see from the figure that those hash tables are interconnected, that is, we can reach the objects that are held by a transaction given its transaction identifier. This provides us with efficient abort and commit of subtransactions. *Transaction_Table* is hashed by transaction identifiers(tid). Given the tid of a transaction [2]:

- We can reach all the objects held by that transaction in any hold and lock mode. The hold mode of a lock can be either *hold* or *retain*, and the lock mode can be either *READ* or *WRITE*.
- We can reach the transactions for which the transaction with tid is waiting.
- We can reach the transactions waiting for the transaction with tid.
- We can reach all the children and ancestors of the transaction with tid.

[2] In the remaining part of this section, we use the term transaction to denote both top-level transactions and subtransactions.

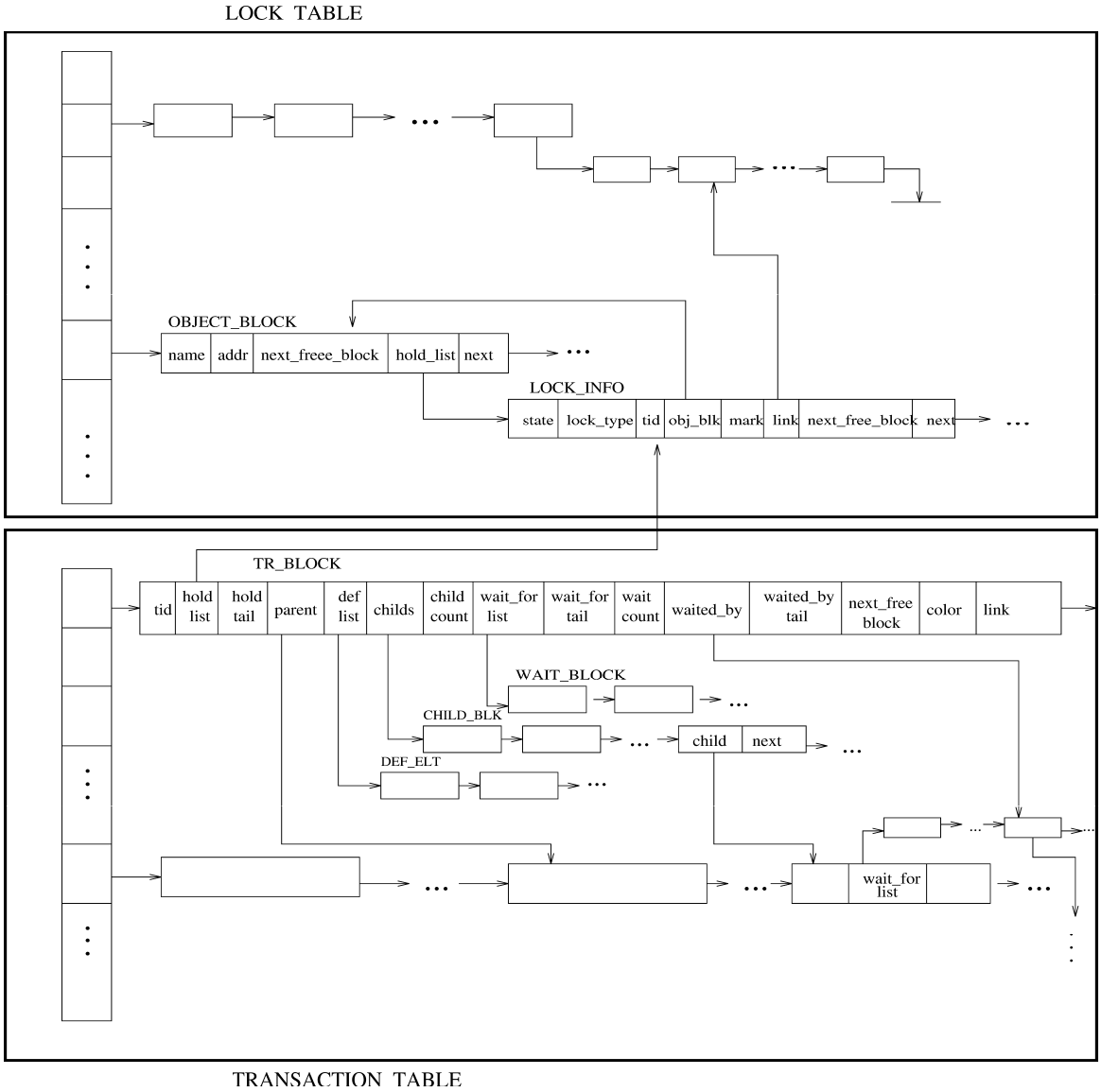


Figure 5: Data structures.

Primitive	Explanation
thr_create()	create a thread
thr_self()	return the thread identifier of the calling thread
thr_suspend()	block the execution of a thread
thr_continue()	unblock a thread
thr_kill()	send a signal to a thread
thr_exit()	terminate a thread
thr_join()	wait for the termination of a thread

Table 1: Thread primitives used.

For the parallel execution of subtransactions, Solaris threads are used [Sun94]. Solaris is a fully functional distributed operating and windowing environment [Sun92]. Thread is a sequence of instructions executed within the context of a process. Traditional Unix process contains a single thread of control. Solaris provides us with Multi-threaded Programming. Multi-threading separates a process into many execution threads each of which runs independently.

Advantages of Multi-threading can be listed as:

- overlap in time, logically separating tasks that use different resources,
- sharing the same address space,
- providing cheap switching among threads.

Mutual exclusive locks are used to control the concurrent access of different threads to the shared data structures.

Thread primitives used in our implementation are listed in Table 1. Using *thr_create*() we execute a given function in a thread. In our implementation, subtransactions are defined as functions in a specified format and are executed concurrently using the *spawn_sub_transaction* primitive provided by our implementation of nested transactions. In Figure 6, the *spawn_sub_transaction* primitive executes the transaction, embedded inside a function, in a thread using *thr_create*(). Threads are created in suspended mode so that the necessary information is inserted into the *Transaction_Table*. Since the *tid*s are unique within a Unix process, and top-level transaction boundaries do not exceed the process boundaries, it was very convenient for us to define the *tid*s as the transaction identifiers. This way we do not need to pass the transaction identifier to the subtransaction as a parameter. Subtransactions can access their *tid*s by calling the thread library function *thr_self*(). This function returns the thread identifier of the calling thread, i.e., the *tid*. When an OpenOODB top-level transaction is created, the *tid* is also inserted into the transaction table for the sake of completeness of the transaction hierarchy.

Since all the subtransactions in the transaction hierarchy can access the data structures in the *LOCK_MANAGER*, we define a global mutex variable. This way, the critical sections of the methods modifying the *Lock_Table* and *Transaction_Table* are wrapped by *mutex_lock* and *mutex – unlock*.

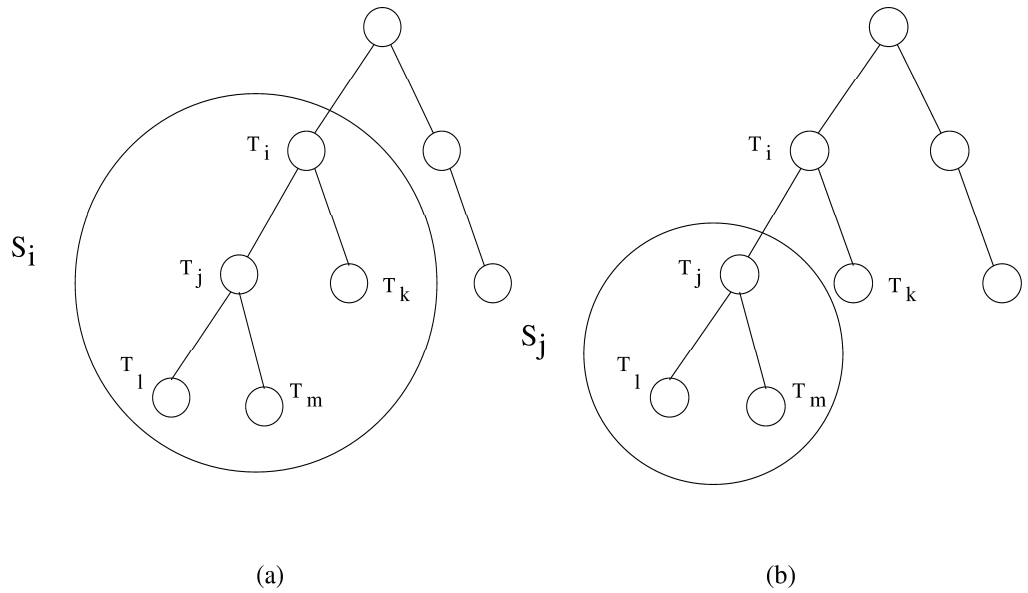
When we look at the data structures, we observe that there are linked lists belonging to both *Transaction_Table* and *Lock_Table* which means that deletions and insertions of new blocks to those lists take a long time. At this point, we made an optimization by implementing our own memory management via keeping lists of deleted blocks so that they can be used efficiently whenever they

```
// create an OpenOODB main object
OODB *p_oodb;
void *sub2(void *res)
{
    // lock the object with name obj3 in WRITE mode
    int rc = p_oodb →fetch_object("obj3",WRITE);
    // in case of an error, abort the subtransaction
    // otherwise, commit the subtransactions
    if ( rc == ERROR )
      p_oodb → sub_abort();
    else
      p_oodb →sub_commit();
}


void *sub1(void *res)
{
    // lock the object with name obj1 in READ mode
    p_oodb →fetch_object("obj1",READ);
    // create a subtransaction in IMMEDIATE mode
    p_oodb →spawn_sub_tr(sub2,IMMEDIATE);
    // commit the subtransaction
    p_oodb →sub_commit();
}


main()
{
    // start an OpenOODB transaction
    p_oodb →beginTransaction();
    // spawn a subtransaction in IMMEDIATE mode
    p_oodb →spawn_sub_tr(sub1,IMMEDIATE);
    // commit the OpenOODB transaction
    p_oodb →commitTransaction();
}
```

Figure 6: Sample OpenOODB application using nested transactions.



(a) (b)

Figure 7: (a)Control sphere of T_i, (b) Control sphere of T_j.

are needed. Another optimization was to extend our component with a sort of garbage collection; i.e., when we want to delete a block from the *Lock_Table* or *Transaction_Table*, we do not delete it physically but mark it as deleted. This technique makes the usage of doubly linked lists unnecessary. Garbage collection is performed during the searches in the *Lock_Table*.

4.2.1 Implementation of the Locking Protocol for Nested Transactions

When a transaction requests a lock on an object it specifies the locking mode as well by providing the *fetch_object* method with the *lock_type* parameter. Allowed lock-modes are *READ* and *WRITE*.

We implemented the locking protocol described in Section 3.1 considering both *READ* and *WRITE* locks (i.e., *shared* and *exclusive* locks respectively).

As an example, consider the nested transaction structure in Figure 7(a). If T_i retains a *WRITE* lock on an object O_i and no other transaction inside the sphere S_i (i.e., T_j, T_k, T_l and T_m) has any lock on O_i, then all the transactions inside S_i can acquire a *READ* or a *WRITE* lock on O_i. If T_j acquires a *WRITE* lock on O_i, then no other transaction (including the ones inside the sphere S_j in Figure 7(b)) can acquire a *READ* or a *WRITE* lock on O_i.

In handling an object access request, the *fetch_object* method first checks whether the requested object is in the *Lock_Table*. If not, it just requests the object from OpenOODB and returns a pointer to it. If the requested object is in the *Lock_Table* then the nested transaction concurrency control protocol is put into action. If the lock can be granted, then a pointer to the object is returned as in the previous case. If the lock cannot be granted with the requested *lock_type*, then for each transaction that has a lock on the object that conflicts with the requested *lock_type*, a node is inserted to the *wait_for_list* of the lock requesting transaction and a corresponding node is also appended to the *waited_by_list* of the conflicting transaction. Additionally, the *wait_for_count* (i.e., the number of transactions for which the transaction in concern is waiting for) is incremented for each node appended to the *wait_for_list*. Deadlock detection is performed each time a node is appended to *wait_for_list*. If no deadlock is detected after appending all the nodes, then the transaction that requested the lock is suspended using *thr_suspend()*, otherwise it is aborted. Transactions

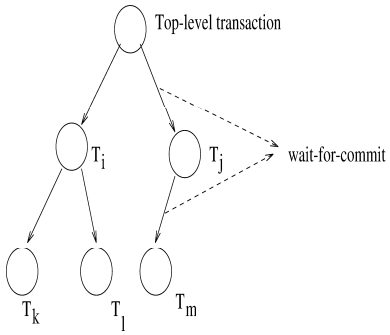


Figure 8: Wait-for-commit relations.

are unblocked using the *thr_continue()* function provided by the thread library. Unblocking of a transaction may occur due to the commit or abort of another transaction. When a transaction is aborted, all its locks are released, and all the nodes in the *waited_by_list* of that transaction are deleted; while doing the deletions, *wait_for_count*s of the corresponding (blocked) transactions are decremented by one. Blocked transactions whose *wait_for_count*s become zero, are unblocked, and their lock requests are reconsidered. When a subtransaction commits, all the locks held or retained by that transaction are inherited by the parent transaction which may cause some transaction(s) to be unblocked. Those transactions are identified by checking the *waited_by_list* of the committing transaction, and decrementing the *wait_for_count*s of the transactions which are descendants of the transaction inheriting the locks. The transactions whose *wait_for_count*s become zero are unblocked and their lock requests are reconsidered as in the previous case.

4.2.2 Deadlock Detection

Deadlocks may arise among subtransactions in the same transaction hierarchy as well as among subtransactions belonging to different transaction hierarchies. OpenOODB views a transaction hierarchy as one flat transaction; i.e., it is not aware of subtransactions. Lock requests made by a subtransaction is treated by OpenOODB as if the top-level transaction made the request. If there exists a deadlock cycle involving subtransactions belonging to different transaction hierarchies, then, from the OpenOODB viewpoint, it means that there is a deadlock cycle involving the top-level transactions as well. Therefore, deadlocks that can occur among transactions belonging to different transaction hierarchies are resolved by OpenOODB via EXODUS storage manager. Deadlocks among the transactions belonging to the same transaction hierarchy are detected and resolved by the new component we added to OpenOODB for managing nested transactions. To detect deadlocks, we use the *wait-for-graph* data structure. Deadlock detection for nested transactions is different from the one for flat transactions in that, there are some other *wait-for* relations besides the *wait-for-lock* relation. One possible *wait-for* relation associated with nested transactions is *wait-for-commit*; i.e., a parent transaction should wait for all its children to finish their execution. A *wait-for-commit* graph is illustrated in Figure 8 for a transaction hierarchy where the top-level transaction spawns subtransactions T_i and T_j, T_i spawns subtransactions T_k and T_l, and finally T_j spawns subtransaction T_m.

Another possible *wait-for* relation for nested transactions is *wait-for-lock* relation. There are two types of *wait-for-lock* relation; *wait-for-retained-lock* and *wait-for-held-lock*. In flat transaction model, when a transaction commits, all the locks it holds are released, and transactions waiting for one or more of those locks can be unblocked immediately provided that they are not waiting for

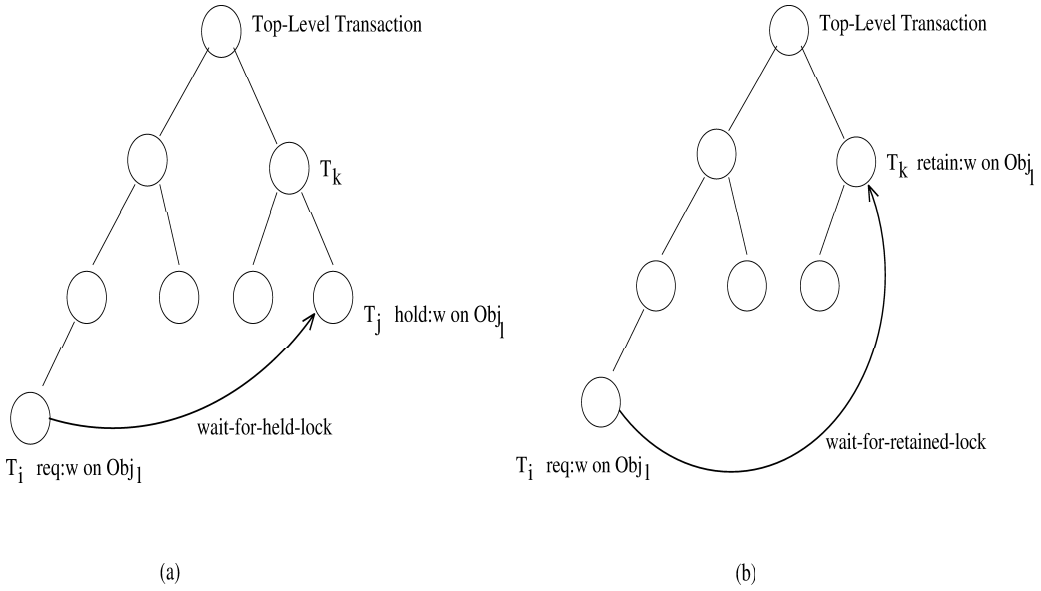


Figure 9: Wait-for-lock relations; (a) before the commit of T_j, (b) after the commit of T_j.

any other transaction. In nested transaction model, locks held by a subtransaction are not released immediately after it commits, but they are inherited by the parent transaction and kept in *retain* mode which causes *wait-for-retained-lock* relations to occur. Examples of *wait-for-held-lock* and *wait-for-retained-lock* relations are illustrated in Figures 9(a) and 9(b).

In Figure 9(a) we see that transaction T_j is holding a write lock on object Obj_i at the time when transaction T_i requests a $WRITE$ lock on the same object. The arc labeled as *wait-for-held-lock* depicts this waiting situation. Following the commit of transaction T_j, all the locks that belong to T_j are inherited by the parent transaction, namely T_k, in retain mode. Transaction T_i still have to wait until the commit of T_k. T_i should wait until the first common ancestor of T_i and T_j inherits the lock on object Obj_l, which is the top-level transaction in this case.

Both *wait-for-commit* and *wait-for-retained-lock* relations should be taken into consideration in addition to the classical *wait-for* relation, for deadlock detection in nested transactions. Whenever a sub-transaction is spawned, a node is appended to the *child-list* of the parent transaction. The union of those linked lists is also used as the *wait-for-commit* graph. When a transaction is blocked on a lock request, all the transactions that cause this transaction to be blocked are kept as a linked list (*wait-for* list) to be used for unblocking the transaction later on. Those lists also represent the *wait-for-retained-lock* or *wait-for-held-lock* relationship. During the commit of a transaction, *wait-for* list of the committing transaction is inherited by its parent.

Deadlock detection is performed before each insertion to a *wait-for-graph* and just before lock inheritance using the graph coloring technique. If a *wait-for* arc (T_i,T_j) is going to be inserted to the *wait-for-graph* or for any of the locks being inherited, if the inheriting transaction is not an ancestor of a transaction waiting for that lock, deadlock detection algorithm is started assuming that the new link or the inherited link is added. Initially all the nodes of the graph are colored $BLACK$. Deadlock detection algorithm colors T_i as $WHITE$, and marks all the nodes on its way recursively till there are no remaining nodes or a $WHITE$ node is reached. Deadlock detection algorithm uses the child and *wait-for* lists of the transactions during its traversal. Since all the nodes are initially $BLACK$, a $WHITE$ node reached means that there is a cycle in the graph, implying a deadlock situation. Deadlock algorithm recursively restores the colors of all the nodes

```
class Rule:Notifiable // Rule class made notifiable
{
    char *name; // Rule name
    Event *event-id; //
    PMF *condition, *action; // PMF is a pointer
                             // to a member function
    Coupling mode; // Coupling Mode
    int enabled; // Rule Enabled or not

    public:
        virtual int Enable();
        virtual int Disable();
        virtual Update(Event* eventid);
        virtual int Condition();
        virtual int Action();
        Rule(Event* eventid, PMF condition, PMF action, Coupling mode);
        ~Rule();
```

Figure 10: Rule class of Sentinel.

it traversed back to $BLACK$.

If the insertion of the arc (T_i, T_j) to the *wait-for-graph* leads to a deadlock, we can abort either of T_i and T_j, or any other transaction in the deadlock cycle. Deciding which transaction to abort is not a trivial task. The simplest solution is to abort T_i (i.e., the transaction that requests the lock). Another possibility would be to abort the transaction that caused the lock-requesting transaction to block. Other possibilities for deciding which transaction to abort require the involvement of some information such as the arrival time or the number of subtransactions of the transactions in concern. We can choose the transaction that has the smallest transaction hierarchy, or we can choose the youngest transaction. As a future work, these alternative techniques could be implemented and their effects on the performance could be observed. We have chosen the simplest solution in our implementation, i.e., aborting the lock requesting transaction.

4.3 Integration of Our Implementation to Sentinel

Our implementation of concurrent rule execution is currently being integrated into Sentinel [CAM93] which is an ADBMS built on OpenOODB. In Sentinel, rules are treated as objects which means that they can be created, modified, and deleted in the same way as other objects. Subscription mechanism is used to reduce the checking overhead of rules; i.e., when an object generates an event, during rule execution, the rules that are checked are the ones which have previously been subscribed to the object that has generated the event.

In Sentinel, there is a *rule class* and all the rules in the system are instances of that class. The condition and action parts of a rule are implemented as functions. The rule class is shown in Figure 10. The rule class is a subclass of the *notifiable class* which means that it can receive and record primitive events generated by reactive (i.e., event generating) objects. Each rule has a *name*, *event-id*, *condition*, *action*, *mode* and *enabled*. The *event-id* denotes the identity of the

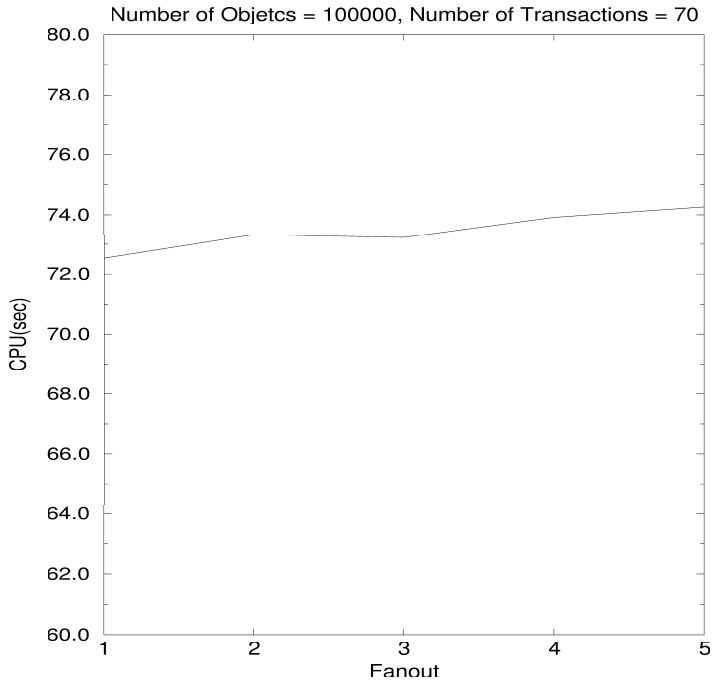


Figure 11: Impact of fanout on CPU-time used by a transaction hierarchy.

event object associated with the rule. *Condition*, and *action* are pointers to the condition and action member functions, respectively. The attribute *mode* denotes the coupling mode, and *enabled* indicates whether the rule is enabled or disabled.

In integrating our implementation to Sentinel, declaration of the condition and action functions are modified so that they can be executed in subtransactions. The modified function declarations look like the sample subtransactions provided in Figure 6. Furthermore, the rule execution component of Sentinel is modified so that conditions and actions of rules can be executed in parallel inside the subtransactions.

5 Execution Overhead of Parallel Nested Transactions

To have an idea about how the performance of the system can be affected by the overhead of the implementation of parallel nested transactions, we simulated the fetch operation of OpenOODB using a dummy method in case the object is not in the *Lock_Table*. Once an object is inserted to the *Lock_Table*, fetch requests for that object is considered by the nested transaction component. Fanout (i.e., the maximum number of subtransactions that can be spawned by a transaction) and the total number of transactions in a transaction hierarchy are two important parameters that indicate the complexity of the transaction hierarchy.

We conducted two experiments to evaluate the impact of the parameters fanout and the total number of transactions in a transactions hierarchy on the performance in terms of the total CPU time used by all the transactions in a transaction hierarchy. In both experiments, total number of objects accessed by all the transactions in the hierarchy was kept constant. Approximately 20% of the fetch requests are done with a WRITE lock, and the rest are done with a READ lock. There are no hot spots in the object space. The number of objects that a transaction requests is calculated by the total number of objects divided by the total number of transactions in the hierarchy. Therefore as the total number of transactions increases, the number of objects accessed by a transaction becomes less but the total number of objects accessed by the hierarchy remains constant. The

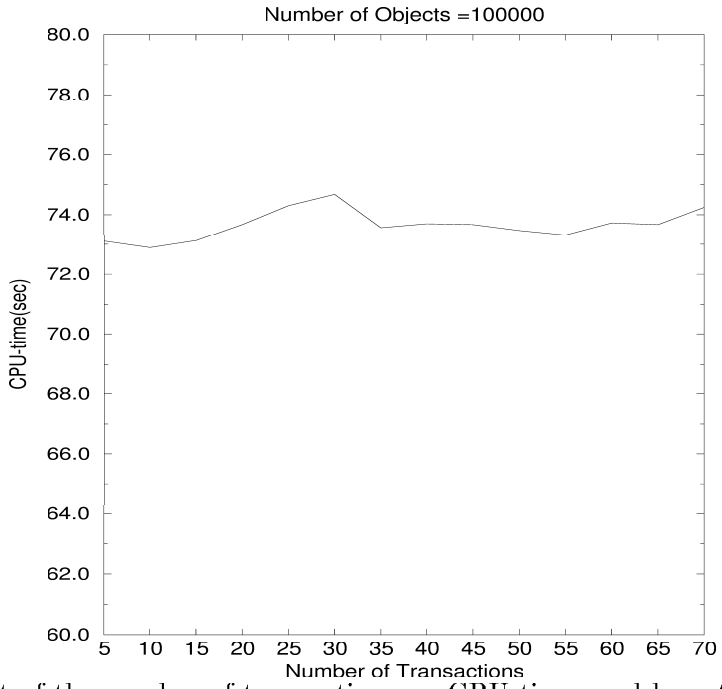


Figure 12: Impact of the number of transactions on CPU-time used by a transaction hierarchy.

OpenOODB operations are not involved in the CPU time measurements as they are just simulated rather then being actually implemented. Therefore, the measured CPU times correspond to the execution overhead introduced by the implementation of parallel nested transactions. Transactions used in the experiments are actual transactions generated automatically by a transaction generator program. The total number of objects accessed by the whole transaction hierarchy is 100000 and the object size is 100 bytes.

In the first experiment, the number of transactions was kept constant and the performance impact of increasing the fanout value was evaluated. Total number of the transactions in the hierarchy is 70 and the fanout value ranges between 1 and 5. As illustrated in Figure 11, the CPU time used by the overall transaction hierarchy increases slightly with increasing fanout. In the second experiment, we kept the fanout constant at 3 and increased the number of transactions from 5 to 70. By keeping the fanout value constant, we eliminated the impact of fanout. The change in the CPU time as a result of increasing the number of transactions is negligible as in the previous case. The results of this experiment leading to that observation are illustrated in Figure 12. Both experiments that we have briefly discussed show that the overhead induced by the implementation of our parallel nested transaction model is not considerable.

6 Discussion and Future Work

In this paper, we described a rule execution model for active database management systems (ADBMSs). We used nested transactions for concurrent rule execution and covered some aspects of nested transactions like concurrency control and deadlock detection. Although we implemented nested transactions on OpenOODB, our rule execution module was designed in such a way that it can easily be ported to other systems as well.

Some of the highlights of our implementation of rule execution can be listed as follows:

- Previous implementations for rule execution assume only sibling parallelism. We implement, on the other hand, both sibling and parent-child parallelism which is the most flexible kind

of parallelism.

- We support deferred and detached modes of rule execution as well as immediate mode.
- In previous implementations, triggered rules are executed in distinct processes. We execute triggered rules in threads which is more efficient than forking processes.

It was shown through experiments that the execution overhead of nested transactions that were used in the implementation of concurrent rule execution is negligible and is not significantly affected by the number of transactions in the transaction hierarchy.

Implementation of the recovery of nested transactions is left as a future work. A log based recovery method, ARIES/NT [RM89], was proposed for nested transaction recovery which is an extension of the ARIES recovery method. Version based recovery techniques can also be applied which are easier to implement but have some major drawbacks against log-based recovery techniques [MHL+92]. Since our implementation was built on top of Exodus, implementation of recovery for nested transactions should involve some modifications to Exodus which is a difficult task. There is also no consensus on the abort semantics of rules. One way to think is that only the rule is aborted but not the triggering rule which is compatible with the nested transaction abort semantics. Another way is to abort the triggering rule as well in which case the nested transaction model should further be modified to support the abortion of the parent in case the child aborts. Same problems arise when a rule should be aborted as a result of a deadlock.

Our implementation of concurrent rule execution through parallel nested transactions is currently being integrated into Sentinel which is an ADBMS developed at the University of Florida. Following the completion of the integration, we are planning to investigate the impact of concurrent rule execution on the performance of Sentinel.

Acknowledgment

The authors wish to thank Prof. Alejandro Buchmann and the database research group of the Technical University of Darmstadt for their help during the initial phases of our work.

References

[AWH92] Alexander Aiken, Jennifer Widom, and Joseph M. Hellerstein. Behavior of Database Production Rules: Termination, Confluence, and Observable Determinism. In *Proceedings of ACM-SIGMOD Conference on Management of Data*, pages 59–68, San Diego, California, June 1992.

[BDZ95] Alejandro P. Buchmann, Alin Deutsch, and Juergen Zimmermann. The REACH Active OODBMS. Technical report, Technical University Darmstadt, 1995.

[btANC96] A Joint Report by the ACT-NET Consortium. The active database management system manifesto: A rulebase of adbms features. *ACM SIGMOD Record*, 25(3):40–49, September 1996.

[Buc94] Alejandro Buchmann. Active Object Systems. In Asuman Dogac, M. Tamer Ozsu, Alex Biliris, and Timos Sellis, editors, *Advances in Object-Oriented Database Systems*, pages 201–224. Springer-Verlag, 1994.

[BZBW95] A.P. Buchmann, J. Zimmermann, J.A. Blakeley, and D.L. Wells. Building an Integrated Active OODBMS: Requirements, Architecture, and Design Decisions. In *Proceedings of the 11th International Conference on Data Engineering*, pages 117–128, Taipei, Taiwan, 1995.

[CA95] A. Chakravarthy and E. Anwar. Exploiting Active Database Paradigm For Supporting Flexible Transaction Models. Technical report, University of Florida, Computer and Information Science and Engineering Department, 1995.

[CAM93] S. Chakravarthy, E. Anwar, and L. Maugis. Design and Implementation of Active Capability for an Object-Oriented Database. Technical Report UF-CIS-TR-93-001, University of Florida, Department of Computer and Information Sciences, 1993.

[CR91] Panos K. Chrysanthis and Krithi Ramamritham. A Formalism For Extended Transaction Models. In *Proceedings of the 17th International Conference on Very Large Databases*, pages 103–112, Barcelona, Spain, September 1991.

[CR94] Panos K. Chrysanthis and Krithi Ramamritham. Synthesis of Extended Transaction Models Using ACTA. *ACM Transactions on Database Systems*, 19(3):450–491, September 1994.

[Day88] Umeshwar Dayal. Active Database Management Systems. In *Proceedings of the Third International Conference on Data and Knowledge Bases*, pages 150–169, Jerusalem, June 1988.

[DGRV95] Laurent Daynes, Olivier Gruber, Projet Rodin, and Patrick Valduriez. Locking in OODBMS Client Supporting Nested Transactions. In *Proceedings of the 11th International Conference on Data Engineering*, pages 316–322, Tai-pei(Taiwan), March 1995.

[Han96] Eric N. Hanson. Design and implementation of the ariel active database rule system. *IEEE Transactions on Knowledge and Data Engineering*, 8(1):157–173, February 1996.

[HLM88] Meichun Hsu, Rivka Ladin, and Dennis R. McCarthy. An Execution Model For Active Database Management Systems. In *Proceedings of the Third International Conference on Data and Knowledge Bases*, pages 171–179, Jerusalem, June 1988.

[HPS92] T. Harder, M. Profit, and H. Schonning. Supporting Parallelism in Engineering Databases by Nested Transactions. Technical Report 34/92, University of Kaiserslautern, Computer Science Department, 1992.

[HR93] Theo Harder and Kurt Rothermel. Concurrency Control Issues in Nested Transactions. *VLDB Journal*, 2(1):39–74, 1993.

[HW92] Eric N. Hanson and Jennifer Widom. An Overview of Production Rules in Database Systems. Technical report, University of Florida, Department of Computer and Information Sciences, October 1992.

[MHL+92] C. Mohan, Don Haderle, Bruce Lindsay, Hamid Pirahesh, and Peter Schwartz. ARIES: A transaction recovery method supporting fine-granularity locking and partial rollbacks using write-ahead logging. *ACM Transactions on Database Systems*, 17(1):94–162, March 1992.

[Mos85] E. Moss. *Nested Transactions.* M.I.T. Press, Cambridge, Mass., 1985.

[Mos87] J. Eliot B. Moss. Log-Based Recovery for Nested Transactions. In *Proceedings of the 13th VLDB Conference*, pages 427–432, Brighton, 1987.

[PD95] Norman W. Paton and Oscar Diaz. Active Database Systems. Technical report, University of Manchester, Department of Computer Science, 1995.

[PN87] Calton Pu and Jerre D. Noe. Design and Implementation of Nested Transactions in Eden. In *Proceedings of Sixth International Symposium on Reliability in Distributed Software and Database Systems*, pages 126–136, Kingsmill-Williamsburg, VA, March 1987.

[RM89] K. Rothermel and C. Mohan. ARIES/NT: A recovery method based on write-ahead logging for nested transactions. In *Proceedings of the Fifteenth International Conference on Very Large Data Bases*, pages 337–346, Amsterdam, 1989.

[Sun92] Sun Microsystems, Inc., 2550 Garcia Avenue, Mountain View, California 94043-1100 U.S.A. *Getting Started with Solaris*, 1992.

[Sun94] Sun Microsystems, Inc., 2550 Garcia Avenue, Mountain View, California 94043-1100 U.S.A. *Multithreaded Programming Guide*, 1994.

[WBT92] David L. Wells, Jose A. Blakeley, and Craig W. Thompson. Architecture of and Open Object-Oriented Database Management System. *IEEE COMPUTER*, pages 74–81, October 1992.

[Wid96] Jennifer Widom. The starburst active database rule system. *IEEE Transactions on Knowledge and Data Engineering*, 8(4):583–595, August 1996.