SAGAS

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CS-TR-070-87

January 1987

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ABSTRACT

Long lived transactions (LLTS) hold on to database resources for relatively long periods of time, significantly delaying the termination of shorter and more common transactions. To alleviate these problems we propose the notion of a saga. A LLT is a saga if it can be written as a sequence of transactions that can be interleaved with other transactions. The database management system guarantees that either all the transactions in a saga are successfully completed or compensating transactions are run to amend a partial execution. Both the concept of saga and its implementation are relatively simple but they have the potential to improve performance significantly. We analyze the various implementation issues related to sagas, including how they can be run on an existing system that does not directly support them. We also discuss techniques for database and LLT design that make it feasible to break up LLTs into sagas.

January 7, 1987

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### 1 INTRODUCTION

顾名思义，一个执行长生命周期的事务，即使没有其他事务的干扰，也需要大量的时间，可能需要数小时或数天。一个长生命周期事务，或者说 LLT，与大多数其他事务相比, 持续时间较长, 因为它访问了许多数据库对象，它有很长的计算过程，

As its name indicates, a long lived transaction is a transaction whose execution, even without interference from other transactions, takes a substantial amount of time, possibly on the order of hours or days. A long lived transaction, or LLT, has a long duration compared to the majority of other transactions either because it accesses many database objects, it has lengthy computations, it pauses for inputs from the users, or a combination of these factors. Examples of LLTs are transactions to produce monthly account statements at a bank transactions to process claims at an insurance company, and transactions to collect statistics over an entire database [Gray81a].

In most cases, LLTs present serious performance problems. Since they are transactions, the system must execute them as atomic actions, thus preserving the consistency of the database Date81a, Ullm82a. To make a transaction atomic, the system usually locks the objects accessed by the transaction until it commits, and this typically occurs at the end of the transaction. As a consequence, other transactions wishing to access the LLT's objects are delayed for a substantial amount of time.

Furthermore, the transaction abort rate can also be increased by LLTS. As dis-

cussed in [Gray81b], the frequency of deadlock is very sensitive to the"size"of transac-

tions, that is, to how many objects transactions access. (In the analysis of [Gray81b]

the deadlock frequency grows with the fourth power of the transaction size.) Hence,

since LLTS access many objects, they may cause many deadlocks, and correspondingly,

many abortions. From the point of view of system crashes, LLTS have a higher proba-

bility of encountering a failure (because of their duration), and are thus more likely to

encounter yet more delays and more likely to be aborted themselves.

In general there is no solution that eliminates the problems of LLTS. Even if we

use a mechanism different from locking to ensure atomicity of the LLTS, the long delays

and/or the high abort rate will remain: No matter how the mechanism operates, a

transaction that needs to access the objects that were accessed by a LLT cannot

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commit until the LLT commits.

However, for specific applications it may be possible to alleviate the problems by

relaxing the requirement that an LLT be executed as an atomic action. In other words,

without sacrificing the consistency of the database, it may be possible for certain LLTs

to release their resources before they complete, thus permitting other waiting transac-

tions to proceed.

To illustrate this idea, consider an airline reservation application. The database

(or actually a collection of databases from different airlines) contains reservations for

fights, and a transaction T wishes to make a number of reservations. For this discus-

sion, let us assume that T is a LLT (say it pauses for customer input after each reserva-

tion). In this application it may not be necessary for T to hold on to all of its resources

until it completes. For instance, after T reserves a seat on fight F1, it could immedi-

ately allow other transactions to reserve seats on the same Alight. In other words, we

can view T as a collection of sub-transactions"T1,T2,, T, that reserve the indivi-

dual seats.

However, we do not wish to submit T to the database management system

(DBMS) simply as a collection of independent transactions because we still want Tto be

a unit that is either successfully completed or not done at all. We would not be

satisfied with a DBMS that would allow T to reserve three out of five seats and then

(due to a crash)do nothing more. On the other hand, we would be satisfied with a

DBMS that guaranteed that T would make all of its reservations, or would cancel any

reservations made if T had to be suspended.

This example shows that a control mechanism that is less rigid than the conven-

tional atomic-transaction ones but still offers some guarantees regarding the execution

of the components of an LLT would be useful. In this paper we will present such a

mechanism.

Let us use the term saga to refer to a LLT that can be broken up into a collection

of sub-transactions that can be interleaved in any way with other transactions. Each

sub-transaction in this case is a real transaction in the sense that it preserves database

consistency. However, unlike other transactions, the transactions in a saga are related

to each other and should be executed as a (non-atomic unit: any partial executions of

the saga are undesirable, and if they occur, must be compensated for.

To amend partial executions, each saga transaction Ti should be provided with a

compensating transaction C:. The compensating transaction undoes, from a semantic

point of view, any of the actions performed by Ti, but does not necessarily return the

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database to the state that existed when the execution of T: began. In our airline exam-

ple, if T, reserves a seat on a fight, then C; can cancel the reservation (say by subtract-

ing one from the number of reservations and performing some other checks). But C;

cannot simply store in the database the number of seats that existed when T:ran

because other transactions could have run between the time T: reserved the seat and C;

canceled the reservation, and could have changed the number of reservations for this

flight.

Once compensating transactions C1, C2...Cn-1 are defined for saga T1, T2,.Ta,

then the system can make the following guarantee. Either the sequence

T1,T2,…Tn

(which is the preferable one)or the sequence

T1,T2,…T3,C3,C2,C1

for some 0 i< n will be executed.

Sagas appear to be a relatively common type of LLT. They occur when a LLT

consists of a sequence of relatively independent steps, where each step does not have to

observe the same consistent database state. For instance, in a bank it is common to

perform a fixed operation (e.g, compute interest) on all accounts, and there is very lit-

tle interaction between the computations for one account and the next. In an office

information system, it is also common to have LLTs with independent steps that can be

interleaved with those of other transactions For example, receiving a purchase order

involves entering the information into the database, updating the inventory, notifying

accounting, printing a shipping order, and so on. Such office LLTs mimic real pro-

cedures and hence can cope with interleaved transactions. In reality, one does not phy-

sically lock the warehouse until a purchase order is fully processed. Thus there is no

need for the computerized procedures to lock out the inventory database until they

complete

Once again, the bank and office LLTs we have presented are not just collections of

normal transactions, they are sagas. There is an application. constraint"(not

representable by the database consistency constraints) that the steps of these activities

should not be left unfinished. The applications demand that all accounts be processed

or that the purchase order is fully processed. If the purchase order is not successfully

completed, then the records must be straightened(e.g, inventory should not reflect the

departure of the item). In the bank example it may always be possible to move for-

ward and finish the LLT. In this case, it may not be necessary to ever compensate for

an unfinished LLT.

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Note that the notion of a saga is related to that of a nested

transaction Mossa, Lync83a]. However there are two important differences:

(a) A saga only permits two levels of nesting the top level saga and simple transac-

tions,and

(b)At the outer level full atomicity is not provided. That is, sagas may view the par-

tial results of other sagas.

Sagas can also be viewed as special types of transactions running under the mechanisms

described in Garc83a, Lync83a]. The restrictions we have placed on the more general

mechanisms make it much simpler to implement (and understand) sagas, in consequence

making it more likely that they be used in practice.

Two ingredients are necessary to make the ideas we have presented feasible: a

DBMS that supports sagas, and LLTs that are broken into sequences of transactions.

In the rest of this paper we study these ingredients in more detail. In Sections 2

through 7 we study the implementation of a saga processing mechanism. We start by

discussing how an application programmer can define sagas, and then how the system.

can support them. We initially assume that compensating transactions can only

encounter system failures. Later on, in Section 6, we study the effects of other failures

(e.g. program bugs) in compensating transactions.

In Sections 8 and 9 we address the design of LLTs. We first show that our model

of sequential transaction execution for a saga can be generalized to include parallel

transaction execution and hence a wider range of LLTs. Then we discuss some stra-

tegies that an application programmer may follow in order to write LLTs that are

indeed sagas and can take advantage of our proposed mechanism.

2. USER FACILITIES

From the point of view of an application programmer, a mechanism is required for

informing the system of the beginning and end of a saga, the beginning and end of each

transaction, and the compensating transactions. This mechanism could be similar to

the one used in conventional systems to manage transactions [Gray78a].

In particular, when an application program wishes to initiate a saga it issues a

begin-saga command to the system. This is followed by a series of begin-transaction,

end-transaction commands that indicate the boundaries of each transaction. In between

these commands the application program would issue conventional database access

commands. From within a transaction, the program can optionally start a user-

initiated abort by issuing an abort-transaction command. This terminates the current

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transaction, but not the saga. Similarly, there is an abort-saga command to abort first

the currently executing transaction and second the entire saga(by running compensat-

ing transactions). Finally, there is an end-saga command to commit the currently exe-

cuting transaction(if any) and to complete the saga.

Most of these commands will include various parameters. The begin-saga com-

mand can return a saga identifier to the program. This identifier can then be passed to

the system on subsequent calls made by the saga. An abort-transaction command will

include as a parameter the address where saga execution is to continue after the abor-

tion. Each end-transaction call includes the identification of the compensating transac-

tion that must be executed in case the currently ending transaction must be rolled

back. The identification includes the name and entry point of the compensating pro-

gram, plus any parameters that the compensating transaction may need. (We assume

that each compensating program includes its own begin-transaction and end-

transaction calls. Abort-transaction and abort-saga commands are not allowed within

a compensating transaction.) Finally, the abort-saga command may include as a

parameter a save-point identifier, as described below.

Note that it is possible to have each transaction store in the database the param-

eters that its compensating transaction may need in the future. In this case,the

parameters do not have to be passed by the system they can be read by the compen-

sating transaction when it starts. Also note that if an end-saga command ends both

the last transaction and the saga, there is no need to have a compensating transaction

for the last transaction. If instead a separate end-transaction is used, then it will have

to include the identification of a compensating transaction.

In some cases it may be desirable to let the application programmer indicate

through the save-point command where saga check points should be taken. This com-

mand can be issued between transactions. It forces the system to save the state of the

running application program and returns a save-point identifier for future reference.

The save points could then be useful in reducing the amount of work after a saga

failure or a system crash: instead of compensating for all of the outstanding transac-

tions, the system could compensate for transactions executed since the last save point,

and then restart the saga.

Of course, this means that we can now have executions of the type Tu, T2, C2, T2,

T3, T4, T5, C5, C4,T4, T5, Te. (After successfully executing T2 the first time, the system

crashed. A save-point had been taken after Ti, but to restart here, the system first

undoes T2 by running C2. Then the saga can be restarted and T2 reexecuted. A second

failure occurred after the execution of T.)This means that our definition of valid

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execution sequences given above must be modified to include such sequences. If these

partial recovery sequences are not valid then the system should either not take save-

points, or it should take them automatically at the beginning (or end)of every transac-

tion

The model we have described up to now is the quite general, but in some cases it

may be easier to have a more restrictive one. We will discuss such a restrictive model

later on in Section 5.

3. SAVING CODE RELIABLY

In a conventional transaction processing system, application code is not needed to

restore the database to a consistent state after a crash. If a failure destroys the code

of a running transaction, the system logs contains enough information to undo the

effects of the transaction. In a saga processing system, the situation is different.To

complete a running saga after a crash it is necessary to either complete the missing

transactions or to run compensating transactions to abort the saga. In either case it is

essential to have the required application code.

There are various possible solutions to this problem. One is to handle application

code as system code is handled in conventional systems. Note that even though a con-

ventional DBMS need not save application code reliably, it must save system code.

That is, a conventional DBMS cannot restart if a failure destroys the code required to

run the system. Thus, conventional systems have manual or automatic procedures, out-

side the DBMS itself, for updating and storing backup copies of the system.

In a saga processing system we could then require that application code for sagas

be defined and updated in the same fashion. Each new version of a program created

would be stored in the current system area, as well as in one or more backup areas.

Since the updates would not be under the control of the DBMS, they would not be

atomic operations and would probably require manual intervention in case a crash

occurs during the update. When a saga starts running, it would assume that all its

transactions and compensating transactions have been predefined, and it would simply

make the appropriate calls

Such an approach may be acceptable if sagas are written by trusted application

programmers and not updated frequently. If this is not the case, it may be best to han-

dle saga code as part of the database. If saga code is simply stored as one or more

database objects, then its recovery would be automatic. The only drawback is that the

DBMS must be able to handle large objectsi.e, the code. Some systems would not be

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able to do this, because their data model does not permit large" unstructured"" objects,

the buffer manager cannot manage objects that span more than one buffer, or some

other reason.

If the DBMS can manage code, then reliable code storage for sagas becomes quite

simple. The first transaction of the saga, T1, enters into the database all further tran-

sactions( compensating or not)that may be needed in the future. When Ti commits,

the rest of the saga is ready to start. The compensating transaction for Ti, Ci would

simply remove these objects from the database It is also possible to define transactions

incrementally. For example, a compensating transaction C: need not be entered into

the data base until its corresponding transaction T: is ready to commit. This approach

is slightly more complicated but saves unnecessary database operations.

4. BACKWARD RECOVERY

When a failure interrupts a saga, there are two choices: compensate for the exe-

cuted transactions, backward recovery or execute the missing transactions, forward

recovery.(Of course, forward recovery may not be an option in all situations.).For

backward recovery the system needs compensating transactions, for forward recovery it

needs sa. ve-points. In this section we will describe how pure backward recovery can be

implemented, the next will discuss mixed backwardforward and pure forward recovery.

Within the DBMS, a saga execution component(SEC) manages sagas. This com-

ponent calls on the conventional transaction execution component(TEC), which manages

the execution of the individual transactions. The operation of the SEC is similar to

that of the TEC: the SEC executes a series of transactions as a unit, while the TEC

executes a series of actions as an (atomic) unit. Both components require a log to

record the activities of sagas and transactions As a matter of fact, it is convenient to

merge both logs into a single one, and we will assume that this is the case here. We

will also assume that the log is duplexed for reliability. Note that the SEC needs no

concurrency control because the transactions it controls can be interleaved with other

transactions.

All saga commands and database actions are channeled through the SEC. Each

saga command (e-8, begin-saga) is recorded in the log before any action is taken. Any

parameters contained in the commands (e.g, the compensating transaction

identification in an end-transaction command are also recorded in the log. The begin-

transaction and end-transaction commands as well as all database actions, are for-

warded to the TEC, which handles them in a conventional way [Gray78a]

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When the SEC receives an abort-saga command it initiates backward recovery.

To illustrate, let us consider a saga that has executed transactions TI and T2, and that

halfway through the execution of T3 issues an abort-saga command to the SEC.The

SEC records the command in the log (to protect against a crash during roll back)and

then instructs the TEC to abort the current transaction T3. This transaction is rolled

back using conventional techniques, e.g., by storing the before"" values (found in the

log) back into the database.

Next the SEC consults the log and orders the execution of compensating transac-

tions C2 and C1. If the parameters for these transactions are in the log, they are

extracted and passed in the call. The two transactions are executed just like other

transactions, and of course, the information as to when they begin and commit is

recorded in the log by the TEC. (If there is a crash during this time, the system will

then be able to know what work remains to be done. When Cr commits, the saga ter-

minates. An entry is made in the log, sim ilar to the one created by the er

end-saga. com-

mand.

The log is also used to recover from crashes. After a crash, the TEC is first

invoked to clean up pending transactions. Once all transactions are either aborted or.

committed, the SEC evaluates the status of each saga. If a saga has corresponding

begin-saga and end-saga entries in the log then the saga completed and no further

action is necessary. If there is a missing end-saga entry, then the saga is aborted. By

scanning the log the SEC discovers the identity of the last successfully executed and

uncompensated transaction. Compensating transactions are run for this transaction

and all preceeding ones.

5. FORWARD RECOVERY

For forward recovery, the SEC requires a reliable copy of the code for all missing

transactions plus a save-point. The save point to be used may be specified by the appli-

cation or by the system, depending on which aborted the saga. (Recall that a save-

point identifer can be included as a parameter to the abort-saga command.)In the

case of a system crash, the recovery component can specify the most recent save point

for each active saga.

To illustrate the operation of the SEC in this case, consider a saga that executes

transactions Ti, T2, a save-point command, and transaction T3. Then during the exe-

cution of transaction T4 the system crashes Upon recovery, the system must first per-

form a back ward recovery to the save-point (aborting T4 and running C3). After ensur-

ing that the code for running T3, T4,.. is available, the SEC records in the log it

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decision to restart and restarts the saga. We call this backward /forward recovery.

As mentioned in Section 2, if save-points are automatically taken at the beginning

of every transaction, then pure forward recovery is feasible. If we in addition prohibit

the use of abort-saga commands, then it becomes unnecessary to ever perform back-

ward recovery. (Abort-transaction commands would still be acceptable.)This has the

advantage of eliminating the need for compensating transactions, which may be difficult

to write in some applications (see Section 9).

In this case the SEC becomes a simplepersistent"transaction executor, similar

to persistent message transmission mechanisms (Hamm80a]. After every crash, for

every active saga, the SEC instructs the TEC to abort the last executing transaction,

and then restarts the saga at the point where this transaction had started

We can simplify this further if we simply view a saga as a file containing a

sequence of calls to individual transaction programs. Here there is no need for explicit

begin or end saga nor begin or end transaction commands. The saga begins with the

first call in the file and ends with the last one. Furthermore, each call is a transaction.

The state of a running saga is simply the number of the transaction that is executing.

This means that the system can take save-points after each transaction with very little

cost.

Such pure forward recovery methods would be useful for simple LLTs that always

succeed. The LLT that computes interest payments for back accounts may be an

example of such a LLT. The interest computation on an individual account may fail

(through an abort-transaction command, but the rest of the computations would

proceed unaffected.

Using operating systems terminology, the transaction file model described above

could be called a simple EXEC or SCRIPT. The idea of a persistent SCRIPT would

also be useful in an operating system to ensure that a collection of commands were suc-

cessfully executed (assuming that each command executed as a transaction). For exam-

ple, a typical text processing and printing job consists of several steps(e.g, in UNIX,

equation processing, troffing, printing). Each step produces one or more files that are

used by the following steps. A persistent SCRIPT would allow a user to start a long

text processing job and go home, confident that the system would complete it.

t In this case we must also assume that every sub-transaction in the saga will eventually succeed if it

is retried enough times.

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6. OTHER ERRORS

Up to this point we have assumed that the user-provided code in compensating

can

transactions does not have bugs. But what happens if a compensating transaction can-

not be successfully completed due to errors(e.g, it tries to read a file that does not

exist, or there is a bug in the code)? The transaction could be aborted, but if it were

run again it would probably encounter the same error. In this case, the system is stuck:

it cannot abort the transaction nor can it complete it. A similar situation occurs if in a

pure forward scenario a transaction has an error.

One possible solution is to make use of software fault tolerant techniques along the

lines of recovery blocks [Ande81a, Horn74a]. A recovery block is an alternate or secon-

dary block of code that is provided in case a failure is detected in the primary block.If

a failure is detected the system is reset to its pre-primary state and the secondary

block is executed. The secondary block is designed to achieve the same end as the pri-

mary using a different algorithm or technique, hopefully avoiding the primary's failure.

The recovery block idea translates very easily into the framework of sagas. Tran-

sactions are natural program blocks, and rollback capability for failed transactions is

provided by the TEC. The saga application can control recovery block execution.After

it aborts a transaction (or is notified that its transaction has been aborted), the appli-

cation either aborts the saga, tries an alternative transaction, or retries the primary.

Note that compensating transactions can be given alternates as well to make aborting

sagas more reliable.

The other possible solution to this problem is manual intervention. The erroneous

transaction is first aborted. Then it is given to an application programmer who, given

a description of the error, can correct it. The SEC (or the application) then reruns the

transaction and continues processing the saga.

Fortunately, while the transaction is being manually repaired the saga does not

hold any database resources(i.e, locks). Hence, the fact that an already long saga will

take even longer will not significantly affect performance of other transactions.

Relying on manual intervention is definitely not an elegant solution, but it is a

practical one. The remaining alternative is to run the saga as a long transaction

When this LLT encounters an error it will be aborted in its entirety, potentially wast-

ing much more effort. Furthermore, the bug will still have to be corrected manually

and the LLT resubmitted. The only advantage is that during the repair, the LLT will

be unknown to the system. In the case of a saga, saga will continue to be pending in

the system until the repaired transaction is installed.

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7. IMPLEMENTING SAGAS ON TOP OF AN EXISTING DBMS

In our discussion of saga management we have assumed that the SEC is part of

the DBMS and has direct access to the log. However, in some cases it may be desirable

to run sagas on an existing DBMS that does not directly support them. This is possible

as long as the database can store large unstructured objects(i.., code and save-points).

However, it involves giving the application programmer more responsibilities and possi-

bly hurting performance.

There are basically two things to do. First, the saga commands embedded in the

application code become subroutine calls(as opposed to system calls). (The subroutines

are loaded together with the application code. Each subroutine stores within the data-

base all the information that the SEC would have stored in the log. For example, the

begin-saga subroutine would enter an identification for the saga in a database table of

active sagas. The save-point subroutine would cause the application to save its state

(or a key portion of its state) in a similar database table. Similarly, the end-

transaction subroutine enters into some other table(s), the identification of the ending

transaction and its compensating transaction before executing an end-transaction sys-

tem call( to be processed by the TEC).

The commands to store saga information(except save-point)in the database must

always be performed within a transaction else the information may be lost in a crash

Thus, the saga subroutines must keep track of whether the saga is currently executing

a transaction or not. This can easily be achieved if the begin-transaction subroutine

sets a flag that is reset by the end-transaction one. All database storage actions would

be disallowed if the flag is not set. Note that the subroutine approach only works if the

application code never makes system calls on its own. For instance, if a transaction is

terminated by an end-transaction system call (and not a subroutine call), then the com-

pensating information will not be recorded and the transaction flag will not be reset.

Second, a special process must exist to implement the rest of the SEC functions.

This process, the saga daemon(SD) would always be active. It would be restarted after

a crash by the operating system. After a crash it would scan the saga tables to dis-

cover the status of pending sagas. This scan would be performed by submitting a data-

base transaction. The TEC will only execute this transaction after transaction

recovery is complete; hence the SD will read consistent data. Once the SD knows the

status of the pending sagas, it issues the necessary compensating or normal transac-

tions, just as the SEC would have after recovery. Care must be taken not to interfere

with sagas that started right after the crash, but before the SD submitted its database

query.

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After the TEC aborts a transaction(e-g, because of a deadlock or a user initiated

abort), it may simply kill the process that initiated the transaction. In a conventional

system this may be fine, but with sagas this leaves the saga unfinished. If the TEC can-

not signal the SD when this occurs, then the SD will have to periodically scan the saga

table searching for such a situation. If found, the corrective action is immediately

taken.

A running saga can also directly request services from the SD. For instance, to

perform an abort-saga, the abort-saga subroutine sends the request to the SD and then

(if necessary) executes an abort-transaction.

8. PARALLEL SAGAS

Our model for sequential transaction execution within a saga can be extended to

include parallel transactions. This could be useful in an application where the transac-

tions of a saga are naturally executed concurrently. For example, when processing a

purchase order, it may be best to generate the shipping order and update accounts

receivable at the same time.

We will assume that a saga process(the parent) can create new processes(chil-

dren)with which it will run in parallel, with a request similar to a fork request in

UNIX. The system may also provide a join capability to combine processes within a

saga.

Backward crash recovery for parallel sagas is similar to that for sequential sagas.

Within each process of the parallel saga, transactions are compensated for (or undone)

in reverse order just as with sequential sagas. In addition all compensations in a child

process must occur before any compensations for transactions in the parent that were

executed before the child was created (forked. (Note that only transaction execution

order within a process and fork and join information constrain the order of compensa-

tion. If Ti and T2 have executed in parallel processes and T2 has read data written by

T1, compensating for Ti does not force us to compensate for T2 first.

Unlike backward crash recovery, backward recovery from a saga failure is more

complicated with parallel sagas because the saga may consist of several processes, all of

which must be terminated. For this, it is convenient to route all process fork and join

operations through the SEC so it can keep track of the process structure of the saga.

When one of the saga processes requests an abort-saga, the SEC kills all processes

involved in the saga. It then aborts all pending transactions and compensates all com-

mitted ones.

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Forward recovery is even more complicated due to the possibility of inconsistent??

save-points. To illustrate, consider the saga of Figure 8.1. Each box represents a pro-

cess; within each box is the sequence of transactions and save-points(sp)executed by

the process. The lower process was forked after T, committed. Suppose that T3 and

Ts are the currently executing transactions and that save-points were executed before

Ti and Ts.

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lo-->sp-->T1-->T2-->T3

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---->t4-->sp-->T5

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Figure 8.1

At this point the system fails. The top process will have to be restarted before Ti.

Therefore, the save-point made by the second process is not useful. It depends on the

execution of Ti which is being compensated for.

This problem is known as cascading roll backs. It problem has been analyzed in a

scenario where processes communicate via messages Rand78a]. There it is possible to

analyze save-point dependencies to arrive at a consistent set of save-points (if it exists).

The consistent set can then be used to restart the processes. With parallel sagas, the

situation is even simpler since save-point dependencies arise only through forks and

joins, and transaction and save-point order within a process.

To arrive at a consistent set of sa.ve-points the SEC must again be informed of

process forking and joining. The information must be stored on the log and analyzed at

recovery time. The SEC chooses the latest save-point within each process of the saga

such that no earlier transaction has been compensated for. (A transaction is earlier

than a save-point if it would have to be compensated for after a transaction that had

executed in place of that save-point). If there is no such save-point in a process, that

entire process must be rolled back. For those processes with save-points, the necessary

backward recoveries can be conducted and the processes restarted.

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9. DESIGNING SAGAS

The saga processing mechanisms we have described will only be of use if applica-

tion programmers write their LLTs as sagas. Thus the following questions immediately

arise: How can a programmer know if a given LLT can be safely broken up into a

sequence of transactions? How does the programmer select the break points? How

difficult is it to write compensating transactions?In this section we will address some

of these issues.

To identify potential sub-transactions within a LLT, one must search for natural

divisions of the work being performed. In many cases, the LLT models a series of real

world actions, and each of these actions is a candidate for a saga transaction.For

example, when a university student graduates several actions must be performed before

his or her diploma can be issued: the library must check that no book are out, the con-

troller must check that all housing bills and tuition bills are checked; the students new

address must be recorded; and so on. Clearly each of these real world actions can be

modeled by a transaction.

In other cases, it is the database itself that is naturally partitioned into relatively

independent components, and the actions on each component can be grouped into a

saga transaction. For example, consider the source code for a large operating system.

Usually the operating system and its programs can be divided into components like the

scheduler, the memory manager, the interrupt handlers, etc. A LLT to add a tracing

facility to the operating system can be broken up so that each transaction adds the

tracing code to one of the components. Similarly if the data on employees can be split

by plant location, then a Ll to give a cost-of-living raise to all employees can be bro-

ken up by plant location.

Designing compensating transactions for LLTs is a difficult problem in general.

tion.

(For instance, if a transaction fires a missile, it may not be possible to undo this action.

However, for many practical applications it may be as simple (or difficult) as writing

the transactions themselves. In fact, Gray notes in [Gray8la] that, transactions often

have corresponding compensating transactions within the application transaction set.

This is especially true when the transaction models a real world action that can be

undone, like reserving a rental car or issuing a shipping order. In such cases, writing

either a compensating or a normal transaction is very similar: the programmer must

write code that performs the action and preserves the database consistency constraints.

It may even be possible to compensate for actions that are harder to undo, like

sending a letter or printing a check. For example, to compensate for the letter, send a

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second letter explaining the problem. To compensate for the check, send a stop-

payment message to the bank. Of course, it would be desirable not to have to compen-

sate for such actions. However, the price of running LLTs as regular transactions may

be so high that one is forced to write sagas and their compensating transactions.

Also recall that pure forward recovery does not require compensating transactions

(see Section 5). So if compensating transactions are hard to write, then one has the

choice of tailoring the application so that LLTs do not have user initiated aborts.

Without these aborts, pure forward recovery is feasible and compensation is never

needed.

As has become clear from our discussion, the structure of the database plays an

important role in the design of sagas. Thus, it is best not to study each LLT in isola-

tion, but to design the entire database with LLTs and sagas in mind. That is, if the

database can be laid out into a set of loosely-coupled components (with few and simple

inter-component consistency constraints, then it is likely that the LLT will naturally

break up into sub-transactions that can be interleaved.

Another technique that could be useful for converting LLTs into sagas involves

storing the temporary data of an LLT in the database itself. To illustrate, consider a

LLT L with three sub-transactions Ti, T2, and T3. In Ti, L performs some actions and

then withdraws a certain amount of money from an account stored in the database.

This amount is stored in a temporary, local variable until during T3 the funds are

placed in some other account(s). After Ti completes, the database is left in an incon-

sistent state because some money is"missing,"i.e, it cannot be found in the database.

Therefore, L cannot be run as a saga. If it were, a transaction that needed to see all

the money (say an audit transaction) could run sometime between Ti and T3 and would

not find all the funds, If L is run as a regular transaction, then the audit is delayed

until L completes. This guarantees consistency but hurts performance.

However, if instead of storing the missing money in local storage L stores it in the

database, then the database would be consistent, and other transactions could be inter-

leaved. To achieve this we must incorporate into the database schema the < tem-

porary"storage (e.g, we add a relation for funds in transit or for pending insurance

claims). Also, transactions that need to see all the money must be aware of this new

storage. Hence it is best if this storage is defined when the database is first designed

and not added as an afterthought.

Even if L had no T2 transaction, writing the missing funds in the database may be

convenient. Notice that in this case L would release the locks on the temporary storage

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after Ti, only to immediately request them again in T3. This may add some overhead

to L, but in return for this transactions that are waiting to see the funds will be able to

proceed sooner, after T1. This is analogous to having a person with a huge photocoping

job periodically step aside and let shorter jobs through. For this the coveted resources,

i.e., the coping machine or the funds, must be temporarily released.

We believe that what we have stated in terms of money and LLT L holds in gen-

eral. The database and the LLTs should be designed so that data passed from one

sub-transaction to the next via local storage is minimized. This technique, together

with a well structured database, can make it possible to write LLT's as sagas.

10.CONCLUSIONS

We have presented the notion of saga, a long lived transaction that can be broken

up into transactions, but still executed as a unit. Both the concept and its implementa-

tion are relatively simple, but in its simplicity lies its usefulness. We believe that a

saga processing mechanism can be implemented with relatively little effort, either as

part of the DBMS or as an added-on facility. The mechanism can then be used by the

large number of LLTs that are sagas to improve performance significantly.

ACKNOWLEDGMENTS

Bruce Lindsay provided several useful suggestions including the name "saga.

Rafael Alonso and Ricardo Cordon also contributed a number of ideas.

This research was supported by the Defense Advanced Research Projects Agency

of the Department of Defense and by the Office of Naval Research under Contracts

Nos. NO0014-85-C-0456 and NOO014-85-K-0465 and by the National Science Foundation

under Cooperative Agreement No. DCR-842094. The views and conclusions contained

in this document are those of the authors and should not be interpreted as necessarily

representing the official policies, either expressed or implied, of the Defense Advanced

Research Projects Agency or the U.S. Government.

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