Safe Generic Data Synchronizer

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Abstract

Reconciliating divergent data is an important issue in concurrent engineering, mobile computing and software configuration management. Actually, a lot of synchronizers or merge tools perform reconciliations, however, which strategy they apply ? is it correct ? In this paper, we propose to use a transformational approach to build a safe generic data synchronizer.

1 Introduction

Generally, users involved in mobile computing, collaborative computing, concurrent engineering work on replicates of shared data. They can make updates while working disconnected or insulated. This generates divergence on replicates that has to be reconciliated later.

Many systems exist today for reconciliating divergent data: file synchronizers, tools for PDAs, configuration management tools with merge tools, optimistic replication algorithms in databases, groupware algorithms in CSCW and distributed systems algorithms. However, an important issue is still open: what is a *correct* synchronization ? How to write a safe synchronizer ? In this paper, we propose to use the transformational approach[6, 23, 19, 22] as a theoretical foundation for a safe generic data synchronizer. This approach allows to define general correctness criteria for synchronizing any kind of data. To validate this approach, we developed a prototype that allows to synchronize *with the same algorithm* a file system and *file's contents* for text files and XML files. The same correctness properties are ensured at all levels of synchronization. Of course, we can extend the prototype for more data types. I this paper, we present the transformational model and how we can use it for building a safe generic data synchronizer.

The paper is organized as follows: Section 2 details problems with actual synchronizers. Section 3 gives an overview of the transformational approach. Section 4 presents the generic integration algorithm. Section 5 and 6 details transformation functions for a file system and text files. Section 7 presents an example of integration on file system and Section 8 describes the S_5 prototype. Section 9 presents related works. The last section concludes with some points to future works.

2 Why a Safe Generic Synchronizer ?

Synchronization is a critical application. If safety is not ensured, users can loose data, or read inconsistent data and propagate inconsistencies. This can be dramatic in the context of distributed software engineering or mobile computing. What warranties are ensured by actual synchronizers ? Often, we can read simple slogans like "non-conflicting updates are propagated to other replicates" [1]. So, what is precisely a conflict and what happens to conflicting updates ? For example, in a file system, if two users create concurrently a file with the same name, is it considered as a conflict or not ? If it is, the system will ask the user, to keep the old one or the new one. What is the good choice ? To be more general, what is the correct synchronization in this case ? What general properties should be ensured during a synchronization ?

If we investigate distributed systems like Coda[11], Bayou[13], Ficus[15], these systems allow users to work disconnected and use reconciliation procedures when people reconnect. Nice epidemic algorithms[13]

have been developed to propagate changes among replicates. Replicates are consistent if they all converge towards the same state. This means that a correct synchronization is a synchronization that ensures convergence. However, if we look carefully on how things work, conflicting updates are treated with *ad-hoc* merge procedures. If these procedures fail, then the conflict is delegated to an administrator in charge to solve the conflict. In this case, convergence in not reached until the administrator solves the conflict. We find similar approach in database systems [8]. If we use replication facilities of database systems, conflicts occur if two transactions working on two different replicates, update the same row at the same time. In this case, database systems [5] can use pre-defined merge procedures to achieve convergence. If convergence cannot be reached, conflicting updates are delegated to the database administrator. Is it really impossible to build a synchronizer that achieves convergence in all cases?

In configuration management[4, 7], divergence on data occurs when users work insulated in their workspaces. Reconciliation is performed when users update their workspaces. If conflicts occur on the file system, the system delegates conflict resolution to users. If conflicts are detected on files, the system calls specific merge tools associated to file types with all versions needed. If the merge tool detects more fine grained conflicts, it represents the conflict within the file and flags the file with a conflict tag.

The main objective of reconciliation in CM is more to avoid lost updates rather than to converge among workspaces. However, this tight cooperation between the CM systems and merge tools raises others problems. Is it really different to merge a file system, a text file and a XML file ? If several merge tools are used each with its own policy of conflict resolution, what is the correctness of the whole synchronization ? The first question raises the problem of the existence of a generic synchronizer. The second question illustrates that if a generic synchronizer exists, then it will be easier to prove the correctness of a generic synchronizer rather than a set of specific synchronizers. Finally, if we make the hypothesis that a safe generic synchronizer exists, then it will give a framework to build the specific part dedicated to specific data.

In this paper, we propose to use the transformational approach as a theoretical foundation for building a safe generic synchronizer.

1. The transformational model gives a correctness criterion for synchronizing data.
2. The transformational algorithms can be adapted for building a generic synchronizer.
3. Transformation functions are developed for handling specific data types.

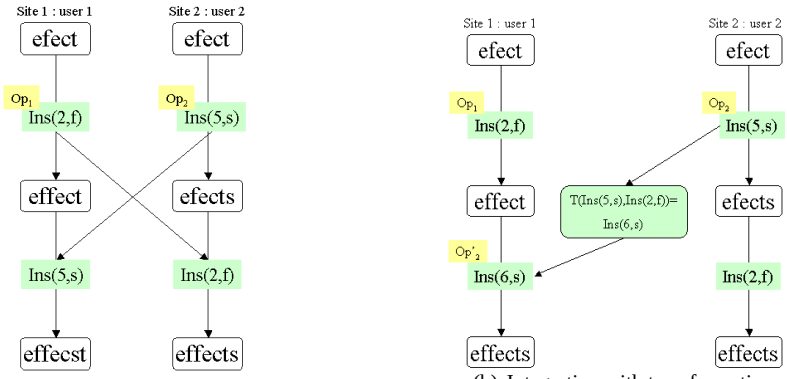
3 Transformational Approach

The model of transformational approach considers n sites. Each site has a copy of the shared objects. When an object is modified on one site, the operation is executed immediately and sent to others sites to be executed again. So every operation is processed in four steps: (a) generation on one site, (b) broadcast to others sites, (c) reception by others sites, (d) execution on other sites.

The execution context of a received operation op_i may be different from its generation context. In this case, the integration of op_i by others sites may leads to inconsistencies between replicates. We illustrate this behavior in figure 1(a). There are two sites $site_1$ and $site_2$ working on a shared data of type $String$. We consider that a $String$ object can be modified with the operation $Ins(p, c)$ for inserting a character c at position p in the string. We suppose the position of the first character in string is 0. $user_1$ and $user_2$ generate two concurrent operations: $op_1 = Ins(2, f)$ and $op_2 = Ins(5, s)$. When op_1 is received and executed on $site_2$, it produces the expected string "effects". But, when op_2 is received on $site_1$, it does not take into account that op_1 has been executed before it. So, we obtain a divergence between $site_1$ and $site_2$.

In the operational transformation approach, received operations are transformed according to local concurrent operations and then executed. This transformation is done by calling transformation functions. A transformation function T takes two concurrent operations op_1 and op_2 defined on the same state s and returns op'_1. op'_1 is equivalent to op_1 but defined on a state where op_2 has been applied. We illustrate the effect of a transformation function in figure 1(b). When op_2 is received on $site_1$, op_2 needs to be transformed according to op_1. The integration algorithm calls the transformation function as follows:

$$T(\overbrace{Ins(5, s)}^{op_2}, \overbrace{Ins(2, f)}^{op_1}) = \overbrace{Ins(6, s)}^{op'_2}$$



(a) Incorrect integration (b) Integration with transformation

Figure 1: Integration of two concurrent operations

The insertion position of op_2 is incremented because op_1 has inserted an f before s in state $efect$. Next, op'_2 is executed on $site_1$. In the same way, when op_1 is received on $site_2$, the transformation algorithm calls:

$$T(\overbrace{Ins(2, f)}^{op_1}, \overbrace{Ins(5, s)}^{op_2}) = \overbrace{Ins(2, f)}^{op'_1}$$

In this case the transformation function returns $op'_1 = op_1$ because, f is inserted before s. Intuitively we can write the transformation function as follows

```
T(Ins(p1,c1),Ins(p2,c2):-
  if p1 < p2 then                                    2
    return Ins(p1, c1)
  else                                               4
    return Ins(p1 + 1, c1)
  endif                                              6
```

This example makes it clear that the transformational approach defines two main components: the *integration algorithm* and the *transformation functions*. The Integration algorithm is responsible of receiving, broadcasting and executing operations. It is independent of the type of shared data, it calls transformation functions when needed. The transformation functions are responsible for merging two concurrent operations defined on the same state. They are specific to the type of shared data ($String$ in our example).

A more theoretical model is defined in [23, 19, 22, 21]. To be correct, an integration algorithm has to ensure three general properties:

Convergence When the system is idle (no operation in pipes), all copies are identical.

Causality If on one site, an operation op_2 has been executed after op_1, then op_2 must be executed after op_1 in all sites.

Intention preservation If an operation op_i has to be transformed into op'_i, then the effects of op'_i have to be equivalent to op_i.

To ensure these properties, it has been proved [23, 19] that the underlying transformation functions must satisfy two conditions:

1. The condition C_1 defines a *state equivalence*. The state generated by the execution op_1 followed by $T(op_2, op_1)$ must be the same as the state generated by op_2 followed by $T(op_1, op_2)$:

$$C_1 : op_1 \circ T(op_2, op_1) \equiv op_2 \circ T(op_1, op_2)$$

2. The condition C_2 ensures that the transformation of an operation according to a sequence of concurrent operations does not depend on the order in which operations of the sequence are transformed:

$$C_2 : T(op_3, op_1 \circ T(op_2, op_1)) = T(op_3, op_2 \circ T(op_1, op_2))$$

In order to use the transformational model, we must follow these steps:

1. Choose a integration algorithm. Depending of the algorithm, C_2 maybe required or not on underlying transformation functions.
2. Define shared data types with their operations
3. Write transformation functions for all combination of operations. For example, on a string object with *Ins*(*p*, *c*), *Del*(*p*), we define T(Ins(p_1,c_1),Ins(p_2,c_2)), T(Ins(p_1,c_1),Del(p_2)), T(Del(p_1),Ins(p_2,c_2)), T(Del(p_1),Del(p_2))
4. Prove the required conditions on these transformation functions.

4 An Integration Algorithm For Synchronization

In order to use the transformational model, we adapt one existing integration algorithm and we write transformation functions for typed objects we want to synchronize.

```
Sync(log,Ns) :-
  while ((opr = getOp(Ns+1))!=∅)                    2
    for (i=0;i<log.size();i++)
      opl=log[i];                                   4
      log[i]=T(opl,opi)
      op'i=T(opi,opl);                              6
    endfor
    execute(op'i)                                   8
    Ns=Ns+1
  endwhile                                          10

  for (i=0;i<log.size();i++)                        12
    op'l=log[i];
    if send(op'l,Ns+1) then                         14
      Ns=Ns+1
    else                                            16
      error 'need to synchronize'
    endif                                           18
  endfor
```

Figure 2: Generic synchronization algorithm

In the transformational approach, the integration algorithm has the responsibility of receiving, integrating, broadcasting and executing operations. Among existing algorithms, SOCT4[26] with its deferred broadcast, is the more suitable algorithm for our synchronization needs. SOCT4 is based on a continuous global order of operations and requires only C_1 to be verified by transformation functions. Each operation is sent with an unique global timestamp. An operation on a site S with a timestamp cannot be sent if all operations that precede it according to the timestamp order have been received and executed.

Synchronization algorithm is presented in figure 2. Synchronizing a site S takes two parameters: *log* and N_s. *log* is the sequence of operations executed locally since the last synchronization. N_s is an integer. It contains the timestamp of the last operation received or sent by site *s*. We define two functions:

1. getOp(int ticket) →op: retrieves the operation identified by the timestamp *ticket*. If no operation is available, *getOp* return ∅

2. send(Operation op, int ticket) →boolean: sends a local operation with the timestamp *ticket*. If *ticket* already exists, it means that a concurrent synchronization is in progress. In this case, the operation *send* returns false. The current state is not corrupted, it requires just to start again another synchronization.

$site_1$	$site_2$
op_1	op_3
op_2	op_4
s_1 = *synchronize*	
	s_2 = *synchronize*
s_3 = *synchronize*	

Figure 3: Scenario of integrations

Suppose we want to synchronize two sites as illustrated in figure 3. At the beginning, each site has $N_s = 0$. $site_1$ performed two local operations op_1, op_2, and $site_2$ performed two concurrent local operations op_3, op_4.

1. At point s_1, $site_1$ synchronizes. It calls $sync([op_1, op_2], 0)$. There is no concurrent operation available, so we just send op_1, op_2 as is to $site_2$. Now, $N_s = 2$ on $site_1$.

2. At point s_2, $site_2$ synchronizes by calling $sync([op_3, op_4], 0)$. The following transformation functions are called:

$op'_1 = T(op_1, op_3)$
$op'_3 = T(op_3, op_1)$
$op''_1 = T(op'_1, op_4)$
$op'_4 = T(op_4, op'_1)$
$op'_2 = T(op_2, op'_3)$
$op''_3 = T(op'_3, op_2)$
$op''_2 = T(op'_2, op'_4)$
$op''_4 = T(op'_4, op'_2)$

op''_1, op''_2 are executed on $site_2$. op''_1, op''_2 are sent to others sites. Now $N_s = 4$ on $site_2$.

3. At point S_3, $site_1$ synchronizes again by calling $sync([], 2)$. There is no more local concurrent operations, so remote operations are executed without transformation on $site_2$ and $N_s = 4$.

4. After point s_3, $site_1$ has executed the following sequence:

op_1
op_2
$op''_3 = T(T(op_3, op_1), op_2)$
$op''_4 = T(T(op_4, op'_1), op'_2)$

and $site_2$ has executed the following equivalent sequence:

op_3
op_4
$op''_1 = T(T(op_1, op_3), op_4)$
$op''_2 = T(T(op_2, op'_3), op'_4)$

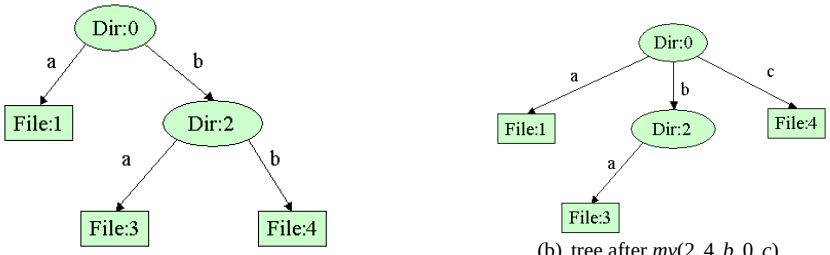
This equivalence is ensured if transformation functions verify C_1. It is clear in this example that conflicts detection and conflicts resolution are delegated to transformation functions. However, the problem is now simpler. A transformation function detects and resolves conflicts for *one combination* of *two concurrent operations* defined on the *same state*. If one transformed operation has an effect on the next operation, the cascading effect is handled by the integration algorithm.

This algorithm is a safe generic synchronizer if underlying transformation functions verify condition C_1. It preserves convergence, causality and intention.

5 Transformation functions for a File System

The transformation functions are responsible for merging two concurrent operations defined on the same state. They are specific to the type of shared data. A transformation function T takes two concurrent operations op_1 and op_2 defined on the same state s and returns op'_1. op'_1 is equivalent to op_1 but defined on a state where op_2 was applied. A transformation function detects and resolves all possibles conflicts between two concurrent operations. Condition C_1 ensures that all conflicts are resolved in the same way

in all sites. We define transformation functions for a file system and for each type of files. We limit our description to text files.



(a) Initial tree

(b) tree after $mv(2, 4, b, 0, c)$

Figure 4: File System representation

We consider a file system like a tree where nodes are directories and leafs are files. We define the following operations:

1. mf(int id, int pid, String name). *mf* stands for mkfile. It creates a file identified with a unique *id* . *pid* is the parent identifier. *id* is referenced with the name *name* in *pid*. *mf* has the following preconditions: *id* does not exist, *pid* exists and *name* is not used by *pid*.

2. md(int id, int pid, String name). *md* stands for mkdir. It creates a directory. In order to represent the root of the tree, we consider that a unique identifier 0 exists and represents the root.
The sequence $mf(1, 0, a)$; $md(2, 0, b)$; $mf(3, 2, a)$; $mf(4, 2, b)$ builds the tree illustrated in figure 4(a):

3. mv(int pid1, int id1, String name1,int pid2, String name2). Moves the object identified by id_1 referenced in pid_1 with name $name_1$ under node identified by pid_2 with $name_2$. *mv* has the following preconditions: pid_1, id_1, pid_2 exist. id_1 is referenced with the name $name_1$ by pid_1. $name_2$ is not used in pid_2. If we apply $mv(2, 4, b, 0, c)$ on the tree illustrated in 4(a), we obtain the state described in figure 4(b). We do not define the remove operation, we consider that removing is equivalent to moving a subtree to a directory representing the garbage.

```
T(mf(id1,idp1,n1,s1),mf(id2,idp2,n2,s2))=
if (idp1==idp2) then                                          2
 if (n1==n2) then
  if (id1<id2) then return                                    4
  mf(id1,idp1,max(s1)⊙id1,
          s1 ∪ {max(s1)⊙id1})                                 6
  else return
   mv(idp2,id2,n2,idp2,max(s2)⊙id2,                           8
         s2 \ {n2} ∪ {max(s2)⊙id2})
   ⊞ mf(id1,idp1,n1,s2 ∪ {max(s2)⊙id2})                       10
  endif
 else                                                         12
 return mf(id1,idp1,n1,s2 ∪ {n1})
 endif                                                        14
else
 return mf(id1,idp1,n1,s1)                                    16
endif;
```

Figure 5: transformation function for mkfile-mkfile

Writing *correct* transformation functions is complex. We have to preserve convergence by verifying condition C_1 and intention by computing equivalent operations. Our general strategy when writing transformation functions is to *converge to a state in which conflicts are represented*. A merge tool does the same

thing when it merges two files. For example, rcsmerge [24] handles an update conflict by producing the following output:

```
<<<<<<< testfile.txt
std::string LineReader::readLine()
{
  return std::read_line( cin );
}=======
CString LineReader::ReadLine()
{
  CString line;
  m_archive >> line;
  return line;
}>>>>>>> 1.1.1.1.2.1
```

Users resolve the conflict by just editing the file. We apply the same principle for the file system. We handle conflicts on a file system by renaming files or directories involved in this conflict. For example, if two users create concurrently the same file in the same directory , we converge to a state where we have renamed one file. Users resolve the conflict by using the *move* operation.

$$
\begin{array}{l}
\mathrm{T}(\underline{\mathrm{mf}}(id_1, idp_1, n_1, s_1), \\
\quad \underline{\mathrm{mv}}(opid_2, id_2, \mathrm{nb}, idp_2, n_2, s_2)) = \\
\textbf{if } (idp_1 == idp_2) \textbf{ then} \\
\quad \textbf{if } (n_1 == n_2) \textbf{ then} \\
\quad\quad \textbf{if } (id_1 < id_2) \textbf{ then return} \\
\quad\quad\quad \underline{\mathrm{mf}}(id_1, idp_1, max(s_1) \odot id_1, \\
\quad\quad\quad s2 \cup \{max(s_1) \odot id_1\}) \\
\quad\quad \textbf{else return} \\
\quad\quad\quad \underline{\mathrm{mv}}(idp_2, id_2, n_2, idp_2, max(s_1) \odot id_2, \\
\quad\quad\quad\quad s_2 \setminus \{n_2\} \cup \{max(s_1) \odot id_2\}) \\
\quad\quad\quad \boxplus\ \underline{\mathrm{mf}}(id_1, idp_1, n_1, s_2 \cup \{max(s_1) \odot id_2) \\
\quad\quad \textbf{endif} \\
\quad \textbf{else return} \\
\quad\quad \underline{\mathrm{mf}}(id_1, idp_1, n_1, s_2 \odot n_1) \\
\quad \textbf{endif} \\
\textbf{else return} \\
\quad \underline{\mathrm{mf}}(id_1, idp_1, n_1, s_1) \\
\textbf{endif}
\end{array}
$$

Figure 6: transformation function for mkfile-move

Figure 5 represents the transformation function for mkfile-mkfile. Renaming entries in a file system is a little tricky:

1. How to compute a new unique name in a directory ? In order to represent conflicts by renaming files or directories, we need to compute unique names within transformation function. This must be done using only the state informations where both concurrent operations are defined. Every operation modifying a directory provides the set of names contained in the directory after the execution of the operation. For example, on a directory identified by 1 and containing names $\{a, b, c\}$, the operation $mf(2, 1, d)$ is created with a fourth parameter s containing the set $\{a, b, c, d\}$. On this set, we define an extra operation $max(s)$. It returns the name with higher lexicographical value. If we append id of the renamed object to $max(s)$, we obtain a new unique name $max(s) \odot id$. $\odot$ as the append operator.

2. which entry to rename ? In order to converge, we must make the same deterministic choice on all sites. We choose to rename the file with the least id. Thus, if we integrate two concurrent operations

```
T(mv(opid1 ,id1 , na , idp1 ,n1 , s1 ) ,
   mf(id2 ,idp2 ,n2 , s2 ) ) =                                          2
if (idp1==idp2) then
 if (n1==n2) then                                                       4
  if (id1<id2) then return
  mv(opid1 ,id1 , na , idp1 , max(s2) ⊙ id1 ,                           6
       s2 ∪ {max(s2) ⊙ id1} \ {na})
  else return                                                           8
  mv(idp2 ,id2 ,n2 ,idp2 ,max(s2) ⊙ id2 ,
       s2 ∪ {max(s2) ⊙ id2} \ {n2})                                     10
  ⊎ mv(opid1 ,id1 , na , idp1 ,n1 ,
        s2 ∪ {max(s2) ⊙ id2} \ {na})                                    12
  endif
 else return                                                            14
  mv(opid1 ,id1 , na , idp1 ,n1 , s2 ∪ {n1} \ {na})
 endif                                                                  16
else return
 mv(opid1 ,id1 , na , idp1 ,n1 , s1 )                                   18
endif ;
```

Figure 7: transformation function for move-mkfile

creating the same file in the same directory, there are two cases: (a) we are transforming the operation with the least id (cf line 5 in figure 5). In this case, we just rename the file with $max(s_1) \odot id_1$. (b) we are transforming the file with greatest id (cf line 8 in figure 5). In this case, we rename the least, and create the greatest without modifications. By this way, the transformation function returns a sequence of two operations. ⊎ is the sequence constructor.

Figures 6 and 7 describes transformation function for mkfile-move and move-mkfile. We use these functions in section 7.

The safety of the transformational approach relies on correctness of transformation functions. If transformation functions don't verify C_1 then the integration algorithm ensures nothing. Proving condition C_1 is error prone, time consuming and part of an iterative process. It is nearly impossible to do this by hand. We made the proof using the automatic SPIKE theorem prover [18]. The input of SPIKE is exactly the transformation functions written in this paper.

6 Transformation functions for text files

On a text file; we define the following operations:

1. ab(id_1,s_1,os_1,v_1). Adds a block of text v_1 on the file identified by id_1 at the insert point s_1. os_1 parameter is used to solve some false ambiguous conflicting situation [20]. It is the original insert point. when an operation *ab* is created, $os_1 = s_1$. If the operation is transformed, os_1 remains identical. In order to simplify the transformation functions, we use l_1 to represent the number of lines of block v_1. id_1 and s_1 have to exist.

2. db(id_1,s_1,ov_1). Deletes the block of text ov_1 on file identified by id_1 at the delete point s_1. l_1 is used to represent the number of lines of block ov_1. id_1 and s_1 have to exist.

Figure 8 presents the transformation function for addblock-addblock. As for the file system, our general strategy for writing transformation function is to converge towards a state where conflicts are represented. In case of conflict, we will produce a block of text containing the effects of both operations like rcsmerge[24]. Conflicts occur when the effects of two concurrent operations are overlapping. For example, a *db* operation can delete lines added concurrently by a *ab* operation. The overlapping between these two concurrent operations can be partial or complete.

```
T(ab(id1,s1,os1,v1) ,
  ab(id2,s2,os2,v2)) :-                                          2
if (id1!=id2) then
 return ab(id1,s1,os1,v1)                                        4
 else
  if (s1<s2) then                                                6
   return ab(id1,s1,os1,v1)
  elseif (s1 > s2) then                                          8
   return ab(id1,s1+l2,os1,v1)
  else                                                           10
  if (os1 < os2) then
   return ab(id1,s1,os1,v1)                                      12
  elseif (os1 > os2) then
   return ab(id1,s1 + l2,os1,v1)                                 14
  else
   if (v1 == v2) then                                            16
    return Id(ab(id1,s1,os1,v1)
   else                                                          18
    return db(id2,s2,l2,v2)
           ⊞ ab(id1,s1,os1,v1 ⊙ v2)                              20
   endif
  endif                                                          22
 endif
endif                                                            24
```

Figure 8: Transformation function for addblock-addblock

For addblock-addblock, a conflict occurs only if both operations insert at the same line two different texts. In this case, we delete the block previously inserted and insert a new block containing both texts. If there is no overlapping, we just manage the insert point. The same strategy is applied for addblock-delblock in figure 9 and for delblock-addblock 10.

For space reasons, we don't define transformation functions for delblock-delblock and move-move. All others transformation functions $T(op_1, op_2)$ (for example $T(op_1 = move, op_2 = addblock)$) return op_1.

7 Example

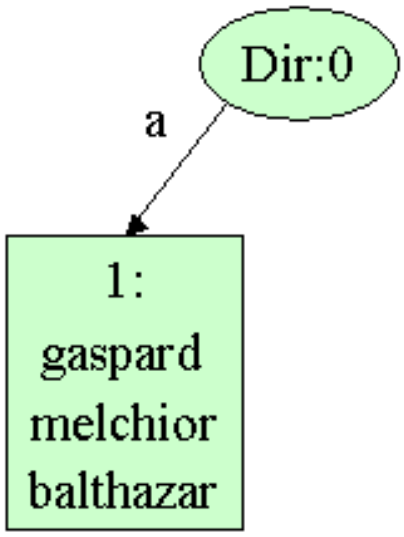
We suppose three users working concurrently on the same initial state: mf(1,0,a,{a}) , ab (1,0,0,{" gaspard "," melchior "," balthazar "}).

```
T(ab(id1,s1,os1,v1), db(id2,s2,ov2)):-
if (id1 != id2) then                                          2
 return ab(id1,s1,os1,v1)
else                                                          4
 if (s1 < s2) then
  return ab(id1,s1,os1,v1)                                    6
 elseif (s1 > s2 + l2 − 1) then
  return ab(id1,s1 − l2,os1,v1)                               8
 else
  return ab(id1,s2,s2,ov2 ⊙ v1)                               10
 endif
endif                                                         12
```

Figure 9: Transformation function for addblock-delblock

```
T(db(id1,s1,ov1), ab(id2,s2,os2,v2)):-
if (id1 != id2) then                                          2
 return db(id1,s1,ov1)
else                                                          4
 if (s1 > s2) then
  return db(id1,s1 + l2,ov1)                                  6
 elseif (s1 + l1 − 1 < s2) then
  return db(id1,s1,ov1)                                       8
 else
  return db(id2,s2,v2)                                        10
         ⊎ db(id1,s1,ov1)
         ⊎ ab(id1,s1,s1,ov1 ⊙ v2)                             12
 endif
endif                                                         14
```

Figure 10: Transformation function for delblock-addblock



u_1	u_2	u_3
$op_1 = mv(0,1,a,0,b,\{b\})$	$op_3 = mf(2,0,b,\{a,b\})$	$op_5 = ab(1,3,3,\{"abdou"\})$
$op_2 = db(1,2,\{"melchior","balthazar"\})$	$op_4 = ab(2,0,0,\{"zidane"\})$	
$s_1 = synchronize$		
	$s_2 = synchronize$	
		$s_3 = synchronize$
	$s_4 = synchronize$	
$s_5 = synchronize$		

Figure 11: Integration scenario

On this state, users produce concurrent operations described in figure 11. After the synchronization s_5, all users observe the same state.

This scenario illustrates how the synchronizer handles conflicts between op_1 and op_3 and between op_2 and op_5. We describe now what happens for each synchronize command.

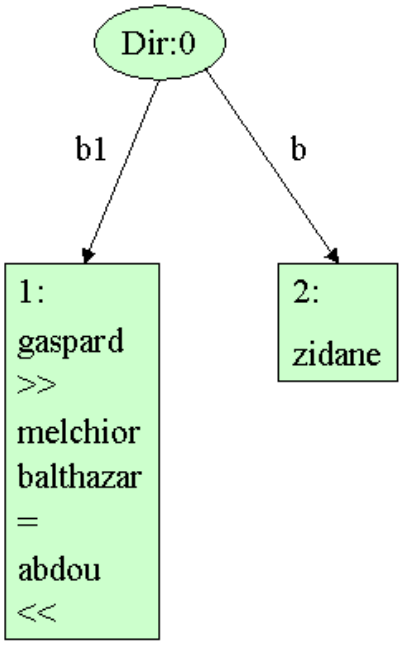
1. s_1. At this point, there is no concurrent operation. Merge is straightforward. op_1 and op_2 are just sent to the others sites.

2. s_2. The synchronizer merges the sequence $op_1; op_2$ to the local log $op_3; op_4$. If we execute the integration algorithm described in figure 2, we obtain the following calls to transformation functions.

Operations	*Result*
$op_1^1 = T(op_1, op_3)$	$mv(0,1,a,0,b1,\{b,b1\})$
$op_3^1 = T(op_3, op_1)$	$mv(0,1,b,0,b1,\{b1\})$ $\boxplus mf(2,0,b,\{b,b1\})$
$op_1^2 = T(op_1', op_4)$	$mv(0,1,a,0,b1,\{b,b1\})$
$op_4^1 = T(op_4, op_1')$	$ab(2,0,0,\{"zidane"\})$
$op_2^1 = T(op_2, op_3')$	$db(1,2,\{"melchior","balthazar"\})$
$op_3^2 = T(op_3', op_2)$	$mv(0,1,b,0,b1,\{b1\})$ $\boxplus mf(2,0,b,\{b,b1\})$
$op_2^2 = T(op_2', op_4')$	$db(1,2,\{"melchior","balthazar"\})$
$op_4^2 = T(op_4', op_2')$	$ab(2,0,0,\{"zidane"\})$

3. For s_3 to s_5, we re-execute the integration algorithm as for s_2. After s_5, each site has executed an sequence of operation equivalent to:

```
mf(1,0,a,{a}),
ab(1,0,0,{"gaspard","melchior","balthazar"}),                    2
op1=mv(0,1,a,0,b,{b}),
op2=db(1,2,{"melchior","balthazar"}),                            4
op3^2=mv(0,1,b,0,b1,{b1}) ⊞ mf(2,0,b,{b,b1}),
op4^2=ab(2,0,0,{"zidane"}),                                      6
op5^4=ab(1,2,2,{">>","melchior",
                "balthazar","=","abdou","<<"});                  8
```



8 Implementation

*S*5 is a web service of synchronization [1]. Users can register and create channels for synchronizing data. A channel is queue of timestamped operations. Once a channel is created, channel registered users can create replicates on their local disks and start synchronizing. Figure 12 represents one channel with 3 replicates. This channel contains 262 operations. All the replicates are up-to-date.

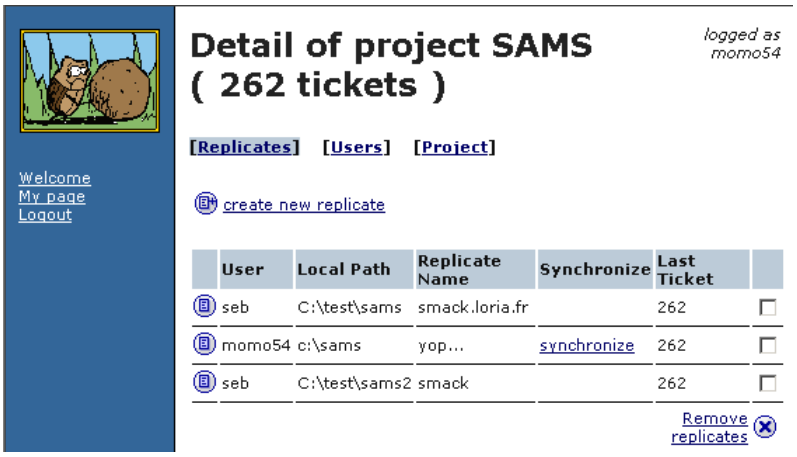


Figure 12: S5 web client

We use diff algorithms [3, 12] to detect changes since last synchronization. Diff algorithm generates the local logs required by the integration algorithm.

We use *S*5 for several month now, and we observed that the number of operations is growing fast. On some channels we have more than 4000 operations. An algorithm for compressing log of operations using the transformational approach has been developed in [17]. We plan to implement it in order to compress channels.

[1] You can try the S5 prototype online at http://woinville.loria.fr:8080/S5. It requires to have the jdk1.4.+ installed on your computer.

9 Related Works

Many tools exist in different research areas dealing with synchronizations. We compare our work with file synchronizers, PDAs synchronizers, configuration management tools, synchronization issues in distributed systems and replication in database systems.

File Synchronizer The overall goal of a file synchronizer is to detect conflicting updates and propagate non conflicting update. To achieve this goal, the semantic of the file system primitives must be well defined as in Unison [1]. However, this approach presents several drawbacks: (a) the approach is restricted to a file system. (b) Synchronization is often limited to two replicates. (c) Reconciliation is coarse grained. It does not attempt to synchronize files contents. (d) A general correctness criterion is not defined. (e) The system interacts with user each time a conflict is detected. If there are 100 conflicts, the system will interacts 100 times with the user. If we just make the comparison between S_5 and this kind of synchronizers, S_5 handles *n* replicates, ensures convergence, causality and intention preservation, synchronizes files contents, resolves automatically conflicts in all cases.

PDA synchronizer ActiveSync, HotSync, I-Sync are now largely used to synchronize data between a desktop computer and PDAs. These synchronizers allow to synchronize several kind of data like an address book, a calendar, tasks, notes , bookmarks, files ...
However, this approach is an extension of the file synchronizer approach: it detects conflicting updates and propagates non conflicting updates. So we have exactly the same problems: no correctness criteria, problems with conflict resolution ...
The genericity of transformational approach makes it easy to write such synchronizers. We can define a type calendar with three operations: AddRendezVous, RemoveRendezVous and UpdateRendezVous. Then we define all transformation functions and make the proof of the condition C_1. The result is a safe synchronizer, ensuring convergence, causality and intention preservation.

CM and Merge Tools In Configuration Management Environments [2, 25, 4, 7] users can work in parallel, produce data divergence and reconciliate later using the copy-modify-merge paradigm. If we look closer on how things are done, we observe that reconciliation is done by tight cooperation between version manager and merge tools. (a) When a reconciliation is required (i.e. often when a user updates his workspace), version managers provides required version to merge tools [12]. Merge is done locally, in the workspace of the user. (b) Merge tools extracts from different versions, concurrent logs of operations using Diff algorithms [3]. Of course, diff algorithms are specific to data types. (c) Finally, concurrent operations are merged using ad-hoc algorithm specific to data types.
The transformational model is more general, more uniform, safer than this model. In this approach, each merge tool has its own merge algorithm. The software that merge two divergent file system trees is not the same as the software that merge two divergent text files. Maybe, they are not consistent together, they do not apply the same strategy.
In the transformational approach, the merge algorithm is shared by all transformation functions. It preserves Convergence, Causality and Intentions (CCI) if underlying transformation functions ensure condition C_1. By this way, we can extend the synchronizer by adding new transformation functions without violating CCI properties.

Distributed systems Maintaining consistency of shared data is a big issue in distributed systems. Coda[11], Bayou[13], Ficus[15] allow users to work disconnected and use reconciliation procedures when people reconnect.
Bayou[13] first used an epidemic algorithm to propagate changes between weakly consistent replicates. When a conflict is detected, merge procedures associated with operations are executed. If the merge procedure cannot find a solution, conflict resolution is delegated to users. Bayou use a total update ordering. Other systems [16] use a partial update ordering and then take advantages of update commutativity. Causality is used to determine the partial ordering.
Distributed systems and transformational approach are similar in many points: both approaches detect conflicts, merge procedures and transformation functions looks identical, commutativity and condition C_1 are quite similar and causality are used in both approaches. However, the transformational approach allows to *transform* operations. C_1 is some sort of "transformational commutativity". It allows to compute more complex state of convergence. Unlike merge procedures, transformation functions ensure convergence in all cases.

The IceCube [10] is a generic approach for reconciliating divergent data. IceCube does not define a general correctness criterion for synchronization but uses semantic constraints that the reconciliation algorithm has to preserve. IceCube considers two kind of constraints: (a) Static constraints can be evaluated without using the state of replicate. Commutativity of operations can be expressed has a static constraint. (b) Dynamic constraints can refer a state of replicates.
Basically, IceCube explores all possible combinations of concurrent actions. First, IceCube rejects all combinations violating static constraints. For the others, IceCube simulates integrations on replicates and reject combinations violating dynamic constraints. Resulting combinations are ranked and proposed to user.
This approach is interesting because, IceCube is looking for the combinations of concurrent operations that minimize conflicts of reconciliation. Maybe, on this point, transformational approach will not find the optimal reconciliation. On the other hand, IceCube has intrinsics drawbacks: (a) Combinatorial explosion can occur during the first stage of reconciliation, even if static constraints restrict the number of possible schedules. (b) Constraints are specific to applications and have to be defined. (c) IceCube is interactive, (d) IceCube does not transform operations. What happens if there is just two concurrent operations $mkfile(\text{"}/a\text{"})$ and $mkdir(\text{"}/a\text{"})$. All possible schedules are bad. In this situation, IceCube will just ask users what it has to do as classical file synchronizer.

Database Systems Replication and database consistency has been investigated extensively [8, 14]. Replication conflicts can occur in a replication environment that permits concurrent updates to the same data at multiple sites. If two transactions working on two different replicates, update the same row at the same time, a conflict can occur.
Oracle[5] provides built-in resolution methods for resolving update conflicts. The "latest timestamp" value resolves a conflict based most recent update. the Additive method adds the difference of two conflicting "update value" operations to the current value. The "overwrite" method replaces the current value with the new value. Users can define their own conflict resolution methods. If convergence cannot be achieved then a notification is sent to the administrator. Some built-in resolution methods seem to preserve convergence but not for any kinds of conflicts (uniqueness and delete/update) and not for any configuration of replicates. Transformational approach is more general than replicates management in database systems. We can implement built-in or user defined resolution methods of Oracle as transformation functions and prove formally the convergence.

10 Conclusion and perspectives

Transformational Approach can be considered as a theoretical foundation for synchronizing data. We proposed a generic synchronizer ensuring convergence, causality and intention preservation. It relies on underlying specific transformation functions verifying condition C_1. We wrote *correct* transformation functions for a file system, text files, XML files [9], String.... We validated our approach with the S_5 prototype.

We have several research directions:

1. We want to develop transformation functions for handling more shared data types like database primitives, DTDs in XML...

2. We are currently building network of synchronizations. It implies that a single replicate can be synchronized with several timestampers. By this way, we can develop the dataflow part of a software process.

3. A lot of work has been done for undoing operations in real-time groupware[21]. It requires that at least transformation functions verifies condition C_2. We have started to improve our transformation functions to handle the undo operation. This approach can be used as an alternative to compensation.

4. We are currently modifying the SPIKE theorem prover in order to build an integrated development environment for transformation functions. Within this environment a user enters functions like in this paper and calls the theorem prover like a compiler. If there are errors, the environment gives counter-examples immediately. We believe that this kind of environment can greatly improve the process of production of transformation functions.

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