Exploiting Schemas in Data Synchronization

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HARMONY

Optimistic Replication

- Many copies of distributed data stored on often disconnected hosts
- Any copy may be updated at any time
- Hosts occasionally ***synchronize***
  - Merging updates that they agree on
  - Resolving conflicting updates

Optimistic Replication

- Many copies of distributed data stored on often disconnected hosts
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- Hosts occasionally ***synchronize***
  - Merging updates that they agree on
  - Resolving conflicting updates
- Many advantages: availability, scalability, quality control
- Main challenge: synchronization

> "...based on the ***optimistic presumption*** that ***conflicting updates are rare***, and that the ***contents are consistent enough*** with those on other replicas." —Saito & Shapiro (2002)

HARMONY Project

Research goal: Facilitate optimistic replication by building a generic synchronization framework for heterogeneous, tree-structured data.

This talk: Focus on Harmony's synchronization algorithm.

- ***Local:*** intuitive, easy to predict behavior
- ***Schema-aware***: preserves structural invariants

Running Example

XML Address Book

```xml
<xcard>
  <vcard>
    <n>Steve</n>
    <org>Stanford</org>
    <email>freunds@cs.stanford.edu</email>
  </vcard>
  <vcard>
    <n>Kim</n>
    <org>Williams</org>
    <email>kim@cs.williams.edu</email>
  </vcard>
</xcard>
```

Updated Address Book

```
<xcard>
  <vcard>
    <n>Steve</n>
    <org>Williams</org>
    <email>freund@cs.williams.edu</email>
  </vcard>
  <vcard>
    <n>Kim</n>
    <org>Williams</org>
    <email>kim@cs.williams.edu</email>
  </vcard>
</xcard>
```

Another Update

```
<xcard>
  <vcard>
    <n>Kim</n>
    <org>Pomona</org>
    <email>kim@cs.pomona.edu</email>
  </vcard>
  <vcard>
    <n>Steve</n>
    <org>Stanford</org>
    <email>freunds@cs.stanford.edu</email>
  </vcard>
</xcard>
```

Goal: Synchronized Address Book

```
<xcard>
  <vcard>
    <n>Steve</n>
    <org>Williams</org>
    <email>freund@cs.williams.edu</email>
  </vcard>
  <vcard>
    <n>Kim</n>
    <org>Pomona</org>
    <email>kim@cs.pomona.edu</email>
  </vcard>
</xcard>
```

Data Model

Trees

Harmony's data model is unordered, edge-labeled trees where every child of a node has a distinct name.

Equivalently, a tree is a partial function from names to trees.

$$\left\{ \begin{array}{r} \texttt{email} \mapsto \left\{ \texttt{kim@cs.williams.edu} \mapsto \{\} \right\} \\ \texttt{n} \mapsto \left\{ \texttt{Kim} \mapsto \{\} \right\} \\ \texttt{org} \mapsto \left\{ \texttt{Williams} \mapsto \{\} \right\} \end{array} \right\}$$

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$$\left\{ \begin{array}{r} \texttt{email} \mapsto \left\{ \texttt{kim@cs.williams.edu} \mapsto \{\} \right\} \\ \texttt{n} \mapsto \left\{ \texttt{Kim} \mapsto \{\} \right\} \\ \texttt{org} \mapsto \left\{ \texttt{Williams} \mapsto \{\} \right\} \end{array} \right\}$$

Within a tree, we'll abbreviate $\texttt{k} \mapsto \{\}$ as $\texttt{k}$.

Lists

Lists are encoded as "cons cells"; the list

$$\left[t_1, t_2, \ldots, t_n\right]$$

is represented by

$$\left\{\begin{array}{l} \texttt{hd} \mapsto t_1 \\ \texttt{tl} \mapsto \left\{\begin{array}{l} \texttt{hd} \mapsto t_2 \\ \texttt{tl} \mapsto \left\{ \ldots \mapsto \left\{\begin{array}{l} \texttt{hd} \mapsto t_n \\ \texttt{tl} \mapsto \left\{\texttt{nil}\right\} \end{array}\right\}\right\} \end{array}\right\} \end{array}\right\}$$

XML

The XML element

```
<tag>
   subelt_1 ... subelt_n
</tag>
```

is represented by the tree

$$\left\{ \texttt{tag} \mapsto \begin{bmatrix} \langle \texttt{subelt}_1 \rangle \\ \vdots \\ \langle \texttt{subelt}_n \rangle \end{bmatrix} \right\}$$

Encoded Address Book

The original XML address book, encoded as a tree:

$$\left\{ \texttt{xcard} \mapsto \left[\begin{array}{l} \texttt{vcard} \mapsto \left[\begin{array}{r} \texttt{n} \mapsto \left[\texttt{Steve} \mapsto [] \right] \\ \texttt{org} \mapsto \left[\texttt{Stanford} \mapsto [] \right] \\ \texttt{email} \mapsto \left[\texttt{freunds@cs.stanford.edu} \mapsto [] \right] \end{array} \right] \\ \texttt{vcard} \mapsto \left[\begin{array}{r} \texttt{n} \mapsto \left[\texttt{Kim} \mapsto [] \right] \\ \texttt{org} \mapsto \left[\texttt{Williams} \mapsto [] \right] \\ \texttt{email} \mapsto \left[\texttt{kim@cs.williams.edu} \mapsto [] \right] \end{array} \right] \end{array} \right] \right\}$$

Synchronization: Simple Algorithm

Notation

- ***names***, ranged over by $\mathtt{k}$
- a ***path*** p is a sequence of names
- a ***tree*** is a finite map from names to trees
- the ***contents*** of a tree t at some name k, written $t(k)$, is either a tree or $\bot$
- write $\mathcal{T}$ for the set of all trees
- write $\mathcal{T}_\bot = \mathcal{T} \cup \{\bot\}$
- $\mathcal{X}$ is a special tree that marks conflicts in the archive

Simple Algorithm

$$sync \quad \in \quad (\mathcal{T}_{\mathcal{X}\perp} \times \mathcal{T}_{\perp} \times \mathcal{T}_{\perp}) \longrightarrow (\mathcal{T}_{\mathcal{X}\perp} \times \mathcal{T}_{\perp} \times \mathcal{T}_{\perp})$$

$sync(o, a, b) =$

if $a = b$ then (a, a, b) – *equal replicas: done*

else if $a = o$ then (b, b, b) – *no change to* a

else if $b = o$ then (a, a, a) – *no change to* b

else if $o = \mathcal{X}$ then (o, a, b) – *unresolved conflict*

else if $a = \perp$ then $(\mathcal{X}, a, b)$ – *delete/modify conflict*

else if $b = \perp$ then $(\mathcal{X}, a, b)$ – *delete/modify conflict*

else – *proceed recursively...*

let $(o'(k), a'(k), b'(k)) = sync(o(k), a(k), b(k))$

$\forall k \in dom(a) \cup dom(b)$ in

(o', a', b')

Uh oh...

Two problems: (1) entries are not aligned correctly; (2) synchronizer doesn't preserve schemas!

$$\left\{ \texttt{xcard} \mapsto \begin{bmatrix} \texttt{vcard} \mapsto \begin{bmatrix} \texttt{n} \mapsto \left[\texttt{Kim} \mapsto [] \right] \\ \texttt{org} \mapsto \begin{bmatrix} \texttt{Pomona} \mapsto [] \\ \texttt{Williams} \mapsto [] \end{bmatrix} \\ \texttt{email} \mapsto \begin{bmatrix} \texttt{freunds@cs.williams.edu} \mapsto [] \\ \texttt{kim@cs.pomona.edu} \mapsto [] \end{bmatrix} \end{bmatrix} \\ \texttt{vcard} \mapsto \begin{bmatrix} \texttt{n} \mapsto \left[\texttt{steve} \mapsto [] \right] \\ \texttt{org} \mapsto \left[\texttt{Stanford} \mapsto [] \right] \\ \texttt{email} \mapsto \left[\texttt{freunds@cs.stanford.edu} \mapsto [] \right] \end{bmatrix} \end{bmatrix} \right\}$$

Alignment and Lenses

Alignment

Alignment consists of identifying the parts of each replica that represent the "same data".

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Alignment consists of identifying the parts of each replica that represent the "same data". Two approaches:

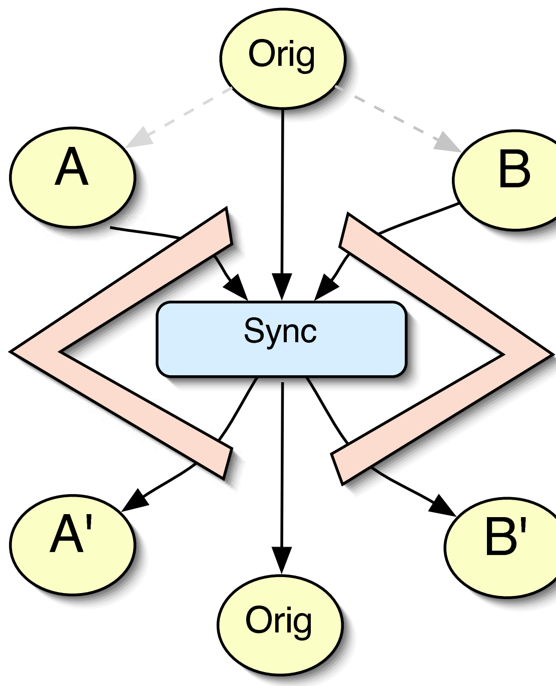
- ***Global*** alignment strategies analyze the entire replica to come up with a "best alignment". Usually heuristic (e.g., minimizing "edit distance").
  Examples: Diff-based tools.
- ***Local*** alignment strategies are simpler; e.g., align the the children with the same name.
  - To be effective, we must pre-align the replicas so that the common structure is exposed.

Lenses

- Can pre-align replicas by transforming them ***before*** synchronization.
  - E.g., for XML address books encoded as trees, can discard order and lift up a key from each entry.
- After synchronization, we must “undo” the transform to recover the original format.
- Harmony includes a domain-specific language for writing bi-directional transformations on trees, called ***lenses***.
  - Every well-typed program is “well-behaved”.
- (Also facilitates ***heterogeneous*** data synchronization.)

Synchronization Architecture

Each replica is passed through a lens before and after synchronization.



Pre-aligning with lenses

$$\left\{ \texttt{xcard} \mapsto \left[\begin{array}{l} \texttt{vcard} \mapsto \left[\begin{array}{rl} \texttt{n} \mapsto & \left[\texttt{Steve} \mapsto [\,] \right] \\ \texttt{org} \mapsto & \left[\texttt{Stanford} \mapsto [\,] \right] \\ \texttt{email} \mapsto & \left[\texttt{freunds@cs.stanford.edu} \mapsto [\,] \right] \end{array} \right] \\ \texttt{vcard} \mapsto \left[\begin{array}{rl} \texttt{n} \mapsto & \left[\texttt{Kim} \mapsto [\,] \right] \\ \texttt{org} \mapsto & \left[\texttt{Williams} \mapsto [\,] \right] \\ \texttt{email} \mapsto & \left[\texttt{kim@cs.williams.edu} \mapsto [\,] \right] \end{array} \right] \end{array} \right] \right\}$$

`hoist "xcard"`

Pre-aligning with lenses

```
[ vcard ↦ [ n ↦ [ Steve ↦ [] ]
            org ↦ [ Stanford ↦ [] ]
            email ↦ [ freunds@cs.stanford.edu ↦ [] ] ]
  vcard ↦ [ n ↦ [ Kim ↦ [] ]
            org ↦ [ Williams ↦ [] ]
            email ↦ [ kim@cs.williams.edu ↦ [] ] ] ]
```

```
hoist "xcard";
List.map (hoist "vcard")
```

Pre-aligning with lenses

$$\left[\begin{array}{l}\left[\begin{array}{rl}\texttt{n} \mapsto & [\texttt{Steve} \mapsto []] \\ \texttt{org} \mapsto & [\texttt{Stanford} \mapsto []] \\ \texttt{email} \mapsto & [\texttt{freunds@cs.stanford.edu} \mapsto []]\end{array}\right] \\ \left[\begin{array}{rl}\texttt{n} \mapsto & [\texttt{Kim} \mapsto []] \\ \texttt{org} \mapsto & [\texttt{Williams} \mapsto []] \\ \texttt{email} \mapsto & [\texttt{kim@cs.williams.edu} \mapsto []]\end{array}\right]\end{array}\right]$$

```
hoist "xcard";
List.map (hoist "vcard";
          List.flatten; map(List.hd []; List.hd []))
```

Pre-aligning with lenses

$$\left[\begin{array}{l}\left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{freunds@cs.stanford.edu}\mapsto[]\}\\ \texttt{n}\mapsto\{\texttt{Steve}\mapsto[]\}\\ \texttt{org}\mapsto\{\texttt{Stanford}\mapsto[]\}\end{array}\right\}\\ \left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{kim@cs.williams.edu}\mapsto[]\}\\ \texttt{n}\mapsto\{\texttt{Kim}\mapsto[]\}\\ \texttt{org}\mapsto\{\texttt{Williams}\mapsto[]\}\end{array}\right\}\end{array}\right]$$

```
hoist "xcard";
List.map (hoist "vcard";
          List.flatten; map(List.hd []; List.hd [];
                            map (const {} [])))
```

Pre-aligning with lenses

$$\left[\begin{array}{l}\left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{freunds@cs.stanford.edu}\}\\ \texttt{n}\mapsto\{\texttt{Steve}\}\\ \texttt{org}\mapsto\{\texttt{Stanford}\}\end{array}\right\}\\ \left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{kim@cs.williams.edu}\}\\ \texttt{n}\mapsto\{\texttt{Kim}\}\\ \texttt{org}\mapsto\{\texttt{Williams}\}\end{array}\right\}\end{array}\right]$$

```
hoist "xcard";
List.map (hoist "vcard";
          List.flatten; map(List.hd []; List.hd [];
                            map (const {} []));
          pivot "n")
```

Pre-aligning with lenses

$$\left[\begin{array}{r} \texttt{Steve} \mapsto \left\{\begin{array}{r} \texttt{email} \mapsto \{\texttt{freunds@cs.stanford.edu}\} \\ \texttt{org} \mapsto \{\texttt{Stanford}\} \end{array}\right\} \\ \texttt{Kim} \mapsto \left\{\begin{array}{r} \texttt{email} \mapsto \{\texttt{kim@cs.williams.edu}\} \\ \texttt{org} \mapsto \{\texttt{Williams}\} \end{array}\right\} \end{array}\right]$$

```
hoist "xcard";
List.map (hoist "vcard";
          List.flatten; map(List.hd []; List.hd [];
                                  map (const {} []));
          pivot "n");
List.flatten; map(List.hd [])
```

Pre-aligning with lenses

$$\left\{\begin{array}{r}\texttt{Kim}\mapsto\left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{kim@cs.williams.edu}\}\\ \texttt{org}\mapsto\{\texttt{Williams}\}\end{array}\right\}\\ \texttt{Steve}\mapsto\left\{\begin{array}{r}\texttt{email}\mapsto\{\texttt{freunds@cs.stanford.edu}\}\\ \texttt{org}\mapsto\{\texttt{Stanford}\}\end{array}\right\}\end{array}\right\}$$

```
hoist "xcard";
List.map (hoist "vcard";
          List.flatten; map(List.hd []; List.hd [];
                                map (const {} []));
          pivot "n");
List.flatten; map(List.hd [])
```

Schema-Aware Synchronization

Mangled Results

The synchronization algorithm is still a bit too eager: it will often merge changes in ways that yield mangled results.

$$o = \left\{ \texttt{org} \mapsto \left\{ \texttt{Williams} \right\} \right\}$$

$$a = \left\{ \texttt{org} \mapsto \left\{ \texttt{UC Santa Cruz} \right\} \right\}$$

$$b = \left\{ \texttt{org} \mapsto \left\{ \texttt{Pomona} \right\} \right\}$$

$$a' = b' = \left\{ \texttt{org} \mapsto \left\{ \begin{array}{l} \texttt{Pomona} \\ \texttt{UC Santa Cruz} \end{array} \right\} \right\}$$

More Difficulties

Similarly, suppose we want every address book entry to contain either an email address or an organization.

- start with a record containing both `email` and `org`
- delete `email` in one replica
- delete `org` in the other replica
- note that all three variants satisfy
- now synchronize...
- both deletions get propagated, yielding an ill-formed result.

A Simple Schema-Aware Synchronizer

$bettersync(S, o, a, b) =$

let $(o', a', b') = sync(o, a, b)$ in

if $(a' \notin S)$ or $(b' \notin S)$

then $(\mathcal{X}, a, b)$ – *schema conflict*

else (o', a', b')

A step too far...

This algorithm is too coarse-grained: A schema conflict ***anywhere*** results in a synchronization failure ***everywhere***!

We need to detect schema violations locally...

Final Algorithm

$sync(S, o, a, b) =$

if $a = b$ then (a, a, b) – *equal replicas: done*

else if $a = o$ then (b, b, b) – *no change to a*

else if $b = o$ then (a, a, a) – *no change to b*

else if $o = \mathcal{X}$ then (o, a, b) – *unresolved conflict*

else if $a = \perp$ then $(\mathcal{X}, a, b)$ – *delete/modify conflict*

else if $b = \perp$ then $(\mathcal{X}, a, b)$ – *delete/modify conflict*

else – *proceed recursively...*

let $(o'(k), a'(k), b'(k)) = sync(S(k), o(k), a(k), b(k))$

$\forall k \in dom(a) \cup dom(b)$ in

if $(dom(a') \notin doms(S))$ or $(dom(b') \notin doms(S))$

then $(\mathcal{X}, a, b)$ – *schema conflict*

else (o', a', b')

Path Consistency

To ensure that we can "project" a schema one a given name, we need to consider only schemas of a restricted form.

Definition: A schema S is ***path consistent*** iff, for all trees $t, t' \in S$ and paths p, we have

$$t(p) \neq \bot \ \wedge \ t'(p) \neq \bot \implies t[p \mapsto t'(p)] \in S,$$

where $t[p \mapsto t'(p)]$ is the tree obtained by replacing the subtree of t at p by the corresponding subtree of t'.

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where $t[p \mapsto t'(p)]$ is the tree obtained by replacing the subtree of t at p by the corresponding subtree of t'.

Path-consistent schemas are a "semantic analog" of ***single-type tree grammars*** used in W3C Schema. They are expressive enough to describe a wide range of examples.

Specification

A good synchronizer should...

1. Never "back out" changes
2. Never "make up" contents
3. Stop at conflicting paths (leaving replicas in their current states)
4. Always leave the replicas in a well-typed form

safety conditions

5. Propagate as many changes as possible without violating above rules

maximality condition

The (Theoretical) Punchline

Theorem: The final (schema-aware) synchronization algorithm is safe and maximal.

Proof: See paper.

The (Practical) Punchline

Bookmark Synchronizer Demo

Implementation Status

- Core implementation and several demos running:
  - bookmarks (Mozilla, Safari, Internet Explorer)
  - XML address books
  - structured text
- Unison integration coming soon.
- Public release this summer!

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http://www.cis.upenn.edu/∼bcpierce/harmony