

# DENICEK: Computational Substrate for Concrete, Collaborative, Interactive Programming

Tomas Petricek

tomas@tomasp.net

Faculty of Mathematics and Physics, Charles University  
Prague, Czech Republic

## Abstract

Research on interactive programming systems gave rise to a range of programming experiences, including programming by demonstration, local-first collaborative editing, schema and code co-evolution, provenance tracking and incremental recomputation. Those experiences are compelling, but they are hard to implement on the basis of existing programming languages and systems.

We contribute the Denicek computational substrate. Denicek represents a program as a series of edits that construct or transform a document consisting of data and formulas. Denicek provides two primitive operations on series of edits, merging and conflict checking, that form the backbone of the implementation of the aforementioned programming experiences.

We discuss the architecture of Denicek, document key design considerations and elaborate the implementation of the programming experiences listed above. To evaluate the proposed architecture, we use Denicek as the basis of a simple innovative data exploration environment. The case study shows that the Denicek computational substrate provides a pathway to the design of richer and more accessible interactive programming systems.

## Keywords

Do, Not, Us, This, Code, Put, the, Correct, Terms, for, Your, Paper

### ACM Reference Format:

Tomas Petricek. 2018. DENICEK: Computational Substrate for Concrete, Collaborative, Interactive Programming. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation email (Conference acronym 'XX)*. ACM, New York, NY, USA, 8 pages. <https://doi.org/XXXXXXX.XXXXXXX>

## 1 Introduction

Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

TODO: Maybe do not talk about “programs” because this is more documents with formulas - not that fancy programs. Computational documents?

explain computational substrate

JUSTIFICATION - this is a technical paper but belongs here!

### 1.1 Programming Experiences

list

### 1.2 Substrate

how it works very roughly

The coolest trick - almost everything (PBD, collaboration, evaluation) is done through merge!

### 1.3 Contributions

one main thing - substrate - with other things

## 2 Background

all the references

---

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from [permissions@acm.org](mailto:permissions@acm.org).  
*Conference acronym 'XX, June 03–05, 2018, Woodstock, NY*

© 2018 Copyright held by the owner/author(s). Publication rights licensed to ACM.  
ACM ISBN 978-1-4503-XXXX-X/18/06  
<https://doi.org/XXXXXXX.XXXXXXX>

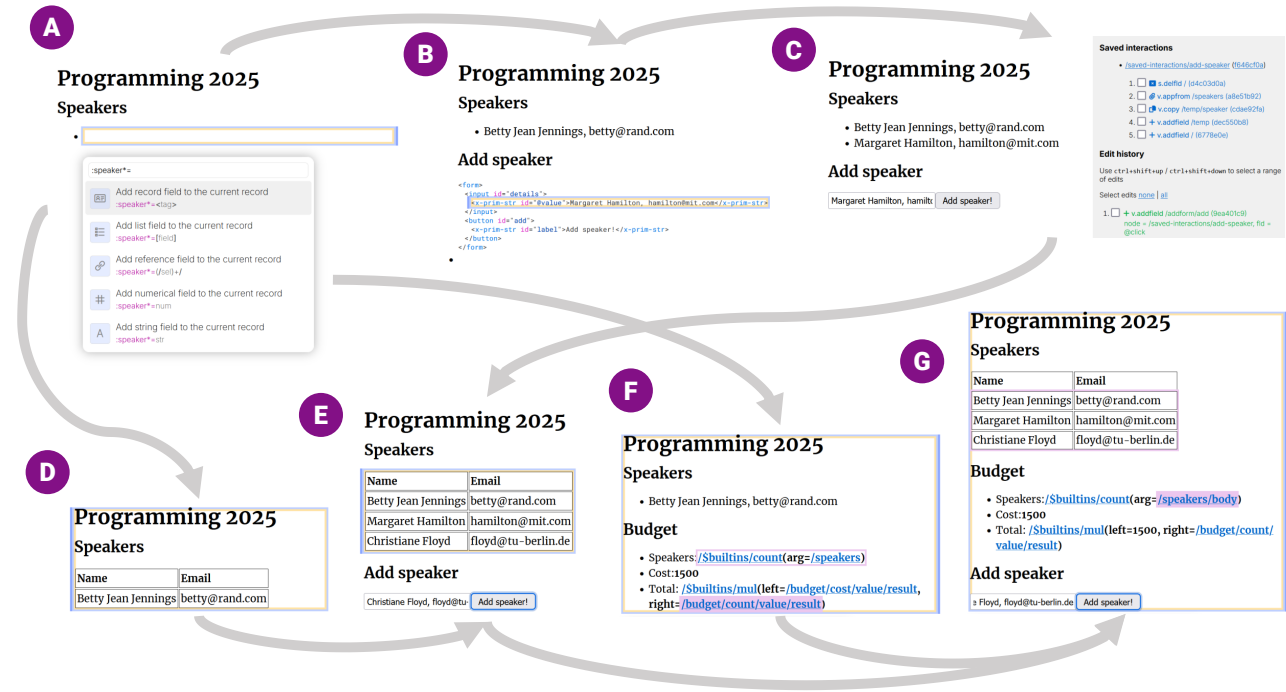


Figure 1: Organizing a conference using Denicek. The Walkthrough shows construction of a user interface for adding speakers (A, B, C); refactoring of the list and merging edits (D, E); and formulas with schema and code co-evolution (F, G).

### 3 Walkthrough

To provide an overview of the programming experiences supported by the Denicek substrate, we use a web-based implementation of Denicek with a structure editor that supports navigation in document and issuing of edit commands. The editor implements support for a range of programming experiences, discussed in §5.

**A Adding a Speaker.** The user starts with an empty document, which is represented as a record. They add a field for each heading and a list `<ul>` as a field named `speakers`. They use the command toolbox to add the first speaker.

**B Creating a User Interface.** To simplify adding of further speakers, the user creates a textbox and a button. They enter new speaker details, construct a temporary `<li>` element outside of the main list, copy the value from the textbox into the new element using source view, and then copy the new element into the speakers list.

**C Saving the Interaction.** After adding the speaker from the textbox, the user opens history view, selects edits that added the speaker and saves those as the `add-speaker` interaction. They attach this as a handler for the `click` event of the button.

**Programming by Demonstration.** Denicek implements programming by demonstration (§5.2) by letting the user to save and replay past interactions, either directly or by attaching them to a UI event.

**D Refactoring Document Structure.** Another user starts with the initial version of the document and turns the list into a table. This is done by invoking a series of commands that change tags, wrap elements, copy and transform values.

**E Merging Edits.** The two document versions can be automatically merged. The refactoring is applied to all existing speakers. New speakers added using the “Add speaker!” button are also automatically turned into the new format.

**Collaborative Editing and Interactivity.** Denicek’s merging reapplies edits from another branch on top of the current history (§5.1). Merging is asymmetric, but the order does not matter here. The same merging operation is used when handling user interaction (§5.3).

**F Adding Budget Calculation.** A third user adds budget calculation to the initial document. Formulas are represented as special `x-formula` nodes whose arguments are other nodes or references to other nodes or formulas (highlighted on mouse hover).

**Incremental Recomputation.** Evaluating a formula yields additional edits that augment the document with the result. Those edits are kept at the top of the document history and are removed in case of a conflict (§5.4), providing incremental recomputation.

**G Merging Formulas.** When the budget calculation is merged with the other edits, references in formulas are automatically updated to point to the new list. Adding new speaker via the “Add speaker!” button invalidates the evaluated result.

**Schema Code Co-Evolution.** References are understood by the substrate and so they are updated by structural edits (§5.5). The evaluation mechanism can replace formulas with values, but also augment them to keep an evaluation trace for provenance analysis (§5.7).

Selector	Notation	
<b>Field</b>	field	Refers to record field of a given name
<b>Index</b>	number	Refers to list element at a given index
<b>Any</b>	*	Refers to all children of a list node





Kind	arguments	
	<b>List</b> <i>tag, child<sub>1</sub>, ..., child<sub>n</sub></i>	Ordered list of nodes, addressable by index. Renders as <tag> with children
	<b>Record</b> <i>tag, field<sub>1</sub>, child<sub>1</sub>, ..., field<sub>n</sub>, child<sub>n</sub></i>	Record with children addressable by <i>field</i> name. Renders as <tag>.
	<b>Reference</b> <i>selectors</i>	Reference to another document location. Displays the /selectors as a link.
	<b>Primitive</b> <i>string</i> or <i>number</i>	Numerical or textual primitive value. Renders as an HTML text node.

Figure 2: Structure of selectors and document nodes

## 4 The Denicek Substrate

Denicek represents programs as sequences of edits that construct and transform a computational document. In this section, we describe the structure of documents and edits, as well as the operations that form the backbone of the system and are used to implement a wide range of programming experiences, discussed in §5.

### 4.1 Selectors, Documents and Edits

A computational document is a tree, consisting of four kinds of nodes (Fig. 2). Denicek follows the *naive realism* [3] principle and makes the entire document visible to the user, although parts can be collapsible or hidden using CSS. Records and lists are rendered as HTML elements of a specified tag with children becoming child elements. Field names are hidden in the rendered document.

References to document location are used in both document itself (reference nodes) and in edits (target of the edit). They are represented as a sequence of selectors (Fig. 2). The document model assumes that lists are homogeneous and records heterogeneous, and so the *Any* selector makes it possible to refer to all children of a list, but there is no way to refer to all children of a record.

**Document Edits.** The supported document edits and their behavior are listed in Fig. 3. All edits require *target* to which they are applied. Target is a reference and can contain the *Any* selector, in which case the edit is applied to multiple nodes simultaneously. Most edits can only be applied to target node(s) of a particular kind.

The edits are designed to allow any transformation of a document through a series of steps whose effect can be tracked by the substrate. As illustrated earlier, Denicek updates references when document structure changes. Fig. 3 distinguishes between edits that keep existing references in a document unchanged (above) and edits that affect references (below). When a selector is *invalidated*, e.g., when deleting a field or a list item to which there is a reference, Denicek rejects the edit. Copying also invalidates selectors because it is ambiguous whether selectors referring to the original location should refer to the source or the target of the copying after the edit (and references cannot refer to multiple structurally incompatible locations). Updating a field, wrapping, reordering or deleting a list item requires updating references in the document correspondingly.













	Edit arguments	Target	Selectors
	<b>Add</b> <i>target, field, node</i> Add <i>node</i> as a <i>field</i> to the specified record.	Record	Unchanged
	<b>Append</b> <i>target, node</i> Append <i>node</i> to the end of the specified list.	List	Unchanged
	<b>AppendFrom</b> <i>target, selectors</i> Append node from <i>selectors</i> to the end of the specified list.	List	Unchanged
	<b>PrimitiveEdit</b> <i>target, transform</i> Apply primitive <i>transform</i> to the specified primitive.	Primitive	Unchanged
	<b>UpdateTag</b> <i>target, old tag, new tag</i> Change the tag of a specified list or record from <i>old</i> to <i>new</i> .	Tagged	Unchanged
	<b>UpdateField</b> <i>target, old field, new field</i> Rename the field of a specified record from <i>old</i> to <i>new</i> .	Record	Update
	<b>DeleteField</b> <i>target, field</i> Delete the field <i>field</i> of a specified record.	Record	Invalidate
	<b>DeleteItem</b> <i>target, index</i> Delete the item at a given <i>index</i> of a specified list.	List	Update
	<b>Reorder</b> <i>target, permutation</i> Reorder items of a specified list according to a <i>permutation</i> .	List	Update
	<b>WrapRecord</b> <i>target, tag, field</i> Wrap the specified node as a <i>field</i> of a new record with <i>tag</i> .	Any	Update
	<b>WrapList</b> <i>target, tag</i> Wrap the specified node as a sole element of a new list with <i>tag</i> .	Any	Update
	<b>Copy</b> <i>target, selectors</i> Copy node(s) from <i>selectors</i> , replacing the specified target(s).	Any	Invalidate

Figure 3: Summary of document edit types in Denicek

**Automatic Reference Update.** There are two situations in which automatic update of references is undesirable. If an edit is applied to a singular element of a list (reference contains the *Index* selector), references that refer into any element of the list should be unchanged. Such edits may turn document into an inconsistent state, but they typically do so temporarily during document construction (checking such edits is discussed in §8.3).

Documents can also contain values that can be of multiple different kinds (i.e., a union type). In such case, references should not be updated when the kind of the value changes. For example, a formula may be either unevaluated or evaluated. As discussed in §5.4, evaluation involves wrapping, but this should not affect references to the formula. To support those cases, it is possible to annotate edits that normally affect selectors (Fig. 3, below) as non-structural. This annotation is required when the target reference contains the *Index* selector.

**No Conditional Edits.** An important aspect of the design is that the effect an edit has on references inside the document does not depend on the current value of the document. This makes it possible to define merging solely in terms of edits, without reference to current document state. (The effect of *Copy* depends only on the existing document structure, but not on its value; while *AppendFrom* affects only single list element and is thus labelled as a non-structural edit.)

This design choice makes it impossible to encode computational logic directly in the edits (e.g., through conditional edits). As we will see in §5.3, such logic has to be provided as an additional mechanism on top of the underlying Denicek substrate.

## 4.2 Primitive Operations

Denicek provides three primitive operations. A sequence of edits can be applied to a document, two sequences of edits can be checked for conflicts or merged. Denicek identifies edit histories by a (git-like) hash, computed from the hash of the parent and the current edit, which is used to identify common shared part of the history during conflict checking and merging.

*Applying Edits.* When applying an edit, Denicek locates the target node and transform it according to the edit. If the edit may affect references in the document (Fig 3, below), Denicek updates matching references in the document according to the rules shown in Fig. 4 provided that (i) the edit is not explicitly marked as non-structural, and (ii) the target reference does not contain *Index* selector, i.e., it targets all elements of any involved lists. Also note that matching references in the document may be more specific than the edit target. For example, if we rename old to new at `/foo/*`, a reference `/foo/3/old` will become `/foo/3/new`. If the document contains a reference that would be invalidated by an edit, the edit is rejected.

*Conflict Detection.* Two edits are conflicting if the order in which they are applied matters. This is the case if they target the same node, or if one targets a node that is nested inside the node targetted by the other. For edits with dependencies (*AppendFrom* and *Copy*), a conflict also occurs if the other edit modifies the dependency.

Given two edit histories, one way to resolve conflicts is by removing (or marking as disabled) all edits from one of the histories that conflict with edits done by the other history. To do this, we first collect all targets of edits in the other history. We then iterate over edits from the first history to see if they depend on or target any of the affected targets. If an edit is removed, its target reference is added to the set of affected targets, so that other subsequent edits that depend on its original result are also removed.

*Merging Edit Histories.* Removing all conflicting edits is sometimes useful, but there are many cases where conflicting edits, in the above sense, can be reconciliated. Say we have edit histories with the same common shared part  $E$ ,  $E_1$  and  $E_2$ . If the edits in  $E_1$  and  $E_2$  conflict, the results of applying  $E, E_1, E_2$  and  $E, E_2, E_1$  would be different. We can, however, construct edit histories  $E'_1$  and  $E'_2$  such that the results of applying  $E, E_1, E'_2$  and  $E, E_2, E'_1$  are the same.

The key operation that enables such reconciliation takes two individual edits that occurred indpendently,  $e_1$  and  $e_2$ , and produces  $e'_1$  that has the same logical effect as  $e_1$ , but can be applied after  $e_2$ . There are two aspects of such reconciliation:

- (1) *Apply Edit to Newly Added.* If  $e_1$  is adding a new list item, but  $e_2$  is changing elements of the target list, we apply the edit  $e_2$  to the node added by  $e_1$  so that, when it is added after the transformation, the added node has the new structure.
- (2) *Transform Matching References.* If  $e_1$  targets a node that is inside a node whose structure is changed by  $e_2$ , the target reference in  $e_1$  is updated in a way that corresponds to the new structure. That is, using the same rules, shown in Fig. 4, that apply when transforming references inside a document.

Applying an edit to a newly added node involves a number of cases. When the new node is added using *Add* or *Copy*, but the target location is modified, this is an unresolvable conflict (because those

<b>UpdateField</b>	<i>target, old field, new field</i>	– Replace Field for matching references. <code>/target/old_field/nested</code> $\Rightarrow$ <code>/target/new_field/nested</code>
<b>DeleteItem</b>	<i>target, index</i>	– Decrement Index greater than $n$ in matching refs. <code>/target/n/nested</code> $\Rightarrow$ <code>/target/(n-1)/nested</code>
<b>Reorder</b>	<i>target, permutation</i>	– Update Index using permutation in matching refs. <code>/target/n/nested</code> $\Rightarrow$ <code>/target/permutation(n)/nested</code>
<b>WrapRecord</b>	<i>target, tag, field</i>	– Insert extra Field selector after matching prefix. <code>/target/nested</code> $\Rightarrow$ <code>/target/field/nested</code>
<b>WrapList</b>	<i>target, tag</i>	– Insert extra All selector after matching prefix. <code>/target/nested</code> $\Rightarrow$ <code>/target/*/nested</code>

Figure 4: How document edits transform references

two operations would overwrite existing nodes). When the new node is added as a new list item using *Append*, it can be transformed (by applying the other edit directly to the new node).

Finally, when the new node is added using *AppendFrom*, it is copied from another document location. We cannot transform the node in the soource location (this would have unintended effects) or after adding it (we do not know its new index because of aforementioned *non-conditionality* of edits). Denicek reconciliates such edits by first copying the source node to a new temporary location, transforming it there and then using *AppendFrom* from the temporary location.

## 5 Implementation

The key claim of this paper is that the computational substrate described in the previous section makes it easy to support a range of experiences that make programming more concrete, collaborative and interactive. In this section, we describe how to use the substrate to support local-first collaborative editing (§5.1), programming by demonstration (§5.2 and §5.3), schema and code co-evolution (§5.5), incremental recomputation (§5.4), provenance tracking (§5.7) and concrete programming via managed copy & paste (§5.8). We describe the programming experience in isolation in this section. Next section provides a more comprehensive evaluation through a case study that combines multiple of them together.

### 5.1 Local-First Collaborative Editing

like git rebase

### 5.2 PBD (create textbox but not button)

### 5.3 Interaction (add button + remove done)

### 5.4 Incremental recomputation

### 5.5 Schema code co-evolution

### 5.6 Provenance tracking

### 5.7 Managed copy & paste

## 6 Design Discussion

Although Denicek does not explicitly track document structure (or schema, or type), all documents have an implicit structure.

- c.f. notes
- memory mapped graphics etc.
- unifying lists and records?

AppendFrom - hard to avoid! because recorded edits cannot know length (but having -1 in index would break too)

## 7 Case study

(data science environment)

## 8 Discussion

### 8.1 Heuristic evaluation

### 8.2 Limitations

### 8.3 Future work

use type system to check temporarily invalid state

other formal things \* non-conditionality of edits \* show that they can transform document from any to any without removing/reading values

PROPERTIES - can change any document to any other - sure, via remove add - but also more semantically (if it contained all values, can we do it without removing and adding them?)

maybe

DESIGN PROCESS = formative examples + evaluation case study

xx

xx

introduction

background

related work

design process / goals

case study

formative research

formative study

analysis

system

implementation

evaluation / heuristic evaluation

discussion and limitations

## 9 Introduction

The computational substrate using which software is built determines the capabilities that the software can provide. An imperative substrate that views programs as instructions modifying bytes in memory makes it almost impossible to allow end-user inspection or reprogramming of running software.

A computational substrate defines what software is built from. This may be objects as in Smalltalk, lists as in Lisp, or memory with data and code as in UNIX/C. The different substrates enable different kinds of programming experiences. For example, object-oriented programming has historically been linked to the development of graphical user interfaces (where objects can correspond to elements on the screen). It has also enabled the development of visual programming environments such as the Alternate Reality Kit, based on message sending between objects.

In principle, any computational substrate can be used to develop any programming experience, but the greater the impedance mismatch between the substrate and the desired experience, the more difficult it will be to provide the experience and combine it with the rest of the system and other programming experiences developed for the system. (One can implement support for programming-by-demonstration using C/C++, for example as part of a game scripting engine, but it will not work with the rest of the ordinary C/C++ ecosystem.)

### 9.1 Substrate

The question asked in this paper is, what would be the ideal programming substrate for supporting a range of programming experiences that make programs more collaborative, transparent and allows for a gradual transition from non-programmer to a programmer. We want a programming substrate that makes it easy to develop programming experiences such as:

- *Programming by demonstration* – Allow non-programmers to construct simple programs by performing examples of the expected behaviour. [12].
- *Local-first collaboration* – Multiple users should be able to use and modify a single program, preferably without requiring a central server. [7]
- *Provenance tracking* – The execution of the program should leave an understandable trace that lets the user understand why program resulted in a particular result.
- *Schema evolution [extra-ish]* – When the user evolves the structure of the program, data and code should co-evolve automatically to match the new structure.
- *Notational freedom [extra-ish?]* – Allow users to adapt the program using a notation that suits them and is appropriate for the programming task at hand. [Joel]
- *Concrete programming [extra?]* – It should be possible to reuse parts of program or program logic without constructing abstractions, for example by managed copy & paste. [4, 5]

substrate as defined by [6]

[2, 12] [1]

[7, 8] [9–11] [13, 15] [14]

Joel's definition of substrate in Onward! Bret Victor talk <https://www.youtube.com/watch?v=ef2jpiTEB5U>

In what ways is a substrate "natural"?

thinglab - create line by cloning, it sticks to mouse pointer, clicking sticks it to something else squeak - has all the browsers (method search...)

computational substrate how it differs from computational media? more low-level - media suggests that there it comes

## 10 The whatever system

### 10.1 Document + Edits

defines

- selectors
- nodes
- edits

### 10.2 Walkthrough

\* todo list? (or counter, but that is a bit boring)

## 11 Themes

\* programming by demonstration - binding interactions to gui elements (event handlers) \* provenance tracking - Amy Ko's whyline, Probe Log by HPI, enables linked visualizations \* merging of edit histories / collaborative editing - bonus - can share restricted link to allow users fill out forms (allow partial edits only / def by selector?) \* schema change - change data & code accordingly \* everything is an edit - interaction with the GUI - evaluation? tbd \* copy & paste abstraction (requires finishing new approach to formulas!) - edit before copy to propagate edit to other places (or edit after copy to make it specific to a case) - higher order copying from <https://tomasp.net/academic/papers/copy-paste/paint22.pdf> \* augmenters - cf. bonnie nardi (calls them something else - Jonathan says) - add programming by demonstration data wrangling gui to table (trigger interactions) cf. lorgnette

## 12 Applications

\* todo list / counter / maybe too simple \* (if used in the walkthrough, maybe something else? board game as in varv - tic tac toe? or 7guis?) \* conference organizer \* data exploration (ala histogram) \* linked charts

## 13 Extras

\* metablocks? \* self-sustainability \* some non-browser implementation of this (as in Varv?)

explicit structure self-sustainability notational freedom

Maybe have 'enabled' for edits afterall? (we can merge with conflicts and disable some edits, but keep them in history for info)

NOTES type Edit = Kind : EditKind Dependencies : Selectors list – only needed for evaluated edits

VALUE vs STRUCTURE distinction \* good in theory, nice for implementation \* tricky to use! needs some assistance tools

TODO - things to work on \* "represent" edits somewhere in document as "library of functions" and then call those from buttons (rather than embedding them directly) allow some kind of abstraction (as in Histogram) to make them reusable \* figure out how to do evaluation better (based on the stored abstractions? but need to store provenance...)

SEMANTIC CONDITIONS [https://www.youtube.com/watch?v=nBnc2ToS\\_j0](https://www.youtube.com/watch?v=nBnc2ToS_j0) (has a section on this in background)

SUBSTRATE DESIGN PROBLEMS \* selectors - all for structure / index for data (but it is useful to allow others...) (multiselect also bad for checks!) \* groups/conditions/preconditions (c.f. email to jonathan) tried conditions on edits; trying groups with check edits \* what to do with "disabled edits"? for example when we remove all checked (before, this created edit groups with "check" but if the check was false, the group was ignored and this messed up merging - because we wouldn't know if the edit had any effect or not)

Evaluation \* evaluated edits have to be migrated to the end (if there are conflicts, they are dropped) Think of this as maintaining a tree:

e3 | e2 evaluated | / e1 | e0

this has to be serialized as e0 -> e1 -> e2 -> e3 -> evaluated

evaluated edits do not become part of the main history but hang on the side

ISSUES \* if we merge a thing with saved-interactions with something, hashes will change!

NOTES \* ListAppendFrom - we need this, because we cannot encode this. \* for records, we can RecordAdd(sel, fld, ..) @ Copy(sel @ [Field fld], src) but this does not work for lists - because we do not know the index! (and we cannot look into current document, because it will differ for saved-interactions)

TODO \* many things with <tag> selectors currently do not work (e.g. 'matches' for highlighting) because if we collect path of a current node, we collect indices and get /some/2/another - and cannot tell if this matches /some/<li>/another - we'd have to collect more detailed path info!

INTERACTION \* replay stored event handlers against the old version? (this way, adding an item to a speakers list gets migrated & adds a new table row!) \* similarly!! we need merge in order to apply edits to multiple targets (when you remove all items in a list, the indices change) (but I guess we should do this against version at the time of saving too....)

[this & evaluation = the unreasonable effectiveness of merging]

Notes on storing and reusing edits \* references need to be represented as references so that they get updated (NO! not if we reply them against old version, which seems better - but there are 2 design choices) \* how to apply them to multiple targets? use Move to update the selectors instead of replacing the prefix manually

IDEA: Type check edit groups to ensure they preserve structure but not individual edits eg when adding list item

CONDITIONALS <https://toby.li/files/p311-radensky.pdf>

#### REMAINING IMPLEMENTATION TODOs:

\* Some kind of provenance visualization \* Some kind of matchers/transformers mechanism (ideally to add interactive buttons to tables) \* Apply to all (remove completed in TODO)

## References

- [1] Weihao Chen, Xiaoyu Liu, Jiacheng Zhang, Ian Iong Lam, Zhicheng Huang, Rui Dong, Xinyu Wang, and Tianyi Zhang. MIWA: mixed-initiative web automation for better user control and confidence. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software Technology, UIST 2023, San Francisco, CA, USA*, pages 75:1–75:15. ACM, 2023.
- [2] Allen Cypher and Daniel Conrad Halbert. *Watch what I do: programming by demonstration*. MIT press, 1993.
- [3] Andrea A. diSessa and Harold Abelson. Boxer: A reconstructible computational medium. *Commun. ACM*, 29(9):859–868, 1986.
- [4] Jonathan Edwards. First class copy & paste. Technical Report MIT-CSAIL-TR-2006-037, Massachusetts Institute of Technology, 2006.
- [5] Jonathan Edwards and Tomas Petricek. Interaction vs. abstraction: Managed copy and paste. In *Proceedings of the 1st ACM SIGPLAN International Workshop on Programming Abstractions and Interactive Notations, Tools, and Environments*, pages 11–19, 2022.
- [6] Joel Jakubovic and Tomas Petricek. Ascending the ladder to self-sustainability: Achieving open evolution in an interactive graphical system. In *Proceedings of the 2022 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software*, pages 240–258, 2022.
- [7] Martin Kleppmann, Adam Wiggins, Peter Van Hardenberg, and Mark McGranaghan. Local-first software: you own your data, in spite of the cloud. In *Proceedings of the 2019 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software*, pages 154–178, 2019.
- [8] Clemens Nylandsted Klokmose, James R Eagan, and Peter van Hardenberg. Mywebstrates: Webstrates as local-first software. In *UIST'24: Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. ACM, 2024.
- [9] Amy J Ko and Brad A Myers. Designing the whyline: a debugging interface for asking questions about program behavior. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 151–158, 2004.
- [10] Amy J Ko and Brad A Myers. Finding causes of program output with the java whyline. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1569–1578, 2009.
- [11] Eva Krebs, Patrick Rein, Joana Bergsiek, Lina Urban, and Robert Hirschfeld. Probe log: Visualizing the control flow of babylonian programming. In *Companion Proceedings of the 7th International Conference on the Art, Science, and Engineering of Programming*, pages 61–67, 2023.
- [12] Germán Leiva, Jens Emil Grønbaek, Clemens Nylandsted Klokmose, Cuong Nguyen, Rubaiat Habib Kazi, and Paul Asente. Rapido: Prototyping interactive ar experiences through programming by demonstration. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, pages 626–637, 2021.
- [13] Roly Perera, Umut A Acar, James Cheney, and Paul Blain Levy. Functional programs that explain their work. In *Proceedings of the 17th ACM SIGPLAN international conference on Functional programming*, pages 365–376, 2012.
- [14] Roly Perera, Minh Nguyen, Tomas Petricek, and Meng Wang. Linked visualisations via galois dependencies. *Proceedings of the ACM on Programming Languages*, 6(POPL):1–29, 2022.
- [15] Wilmer Ricciotti, Jan Stolarek, Roly Perera, and James Cheney. Imperative functional programs that explain their work. *Proceedings of the ACM on Programming Languages*, 1(ICFP):1–28, 2017.