

Design Choices of Document-Oriented Programming Systems

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Abstract Many interesting programming systems treat programming as document manipulation. Examples include spreadsheets, data science notebooks, educational environments like Boxer and multiple recent research programming systems. In such systems, the programmer interacts with a document containing a structured representation of both code and data. They modify the code and data, trigger computations and view the results from the unified document interface. Those *document-oriented programming systems* have a specific set of design choices. The concepts that we need to understand them and design them differ from the well-understood design choices known from programming languages and other programming systems.

The aim of this paper is to identify the key design choices that characterise different document-oriented programming systems. We review both historical and recent examples of such systems and identify twelve design choices that cover four aspects of the system design: (i) what structure and representation of document they use, (ii) how is programming embedded within the systems, (iii) how the user interface displays documents and allows for their editing, and (iv) how are computations within the system evaluated.

The catalogue refines our earlier work on technical dimensions of programming systems. It is rooted in our need to understand the design choices and their consequences when designing multiple different document-oriented programming systems over the last multiple years. The catalogue provides a high-level map of the design space of document-oriented programming systems, makes it possible to identify differences and similarities across different systems and also suggests under-explored design choices and combinations of choices as areas for future research.

The key contribution of this work is perhaps not the catalogue of design choices itself, but the fact that we identify a new programming paradigm. Document-oriented programming systems have rich historical roots, widely-adopted contemporary examples, but they are also an active research area. We hope the review presented in this paper will aid future development of this new paradigm.

The Art, Science, and Engineering of Programming

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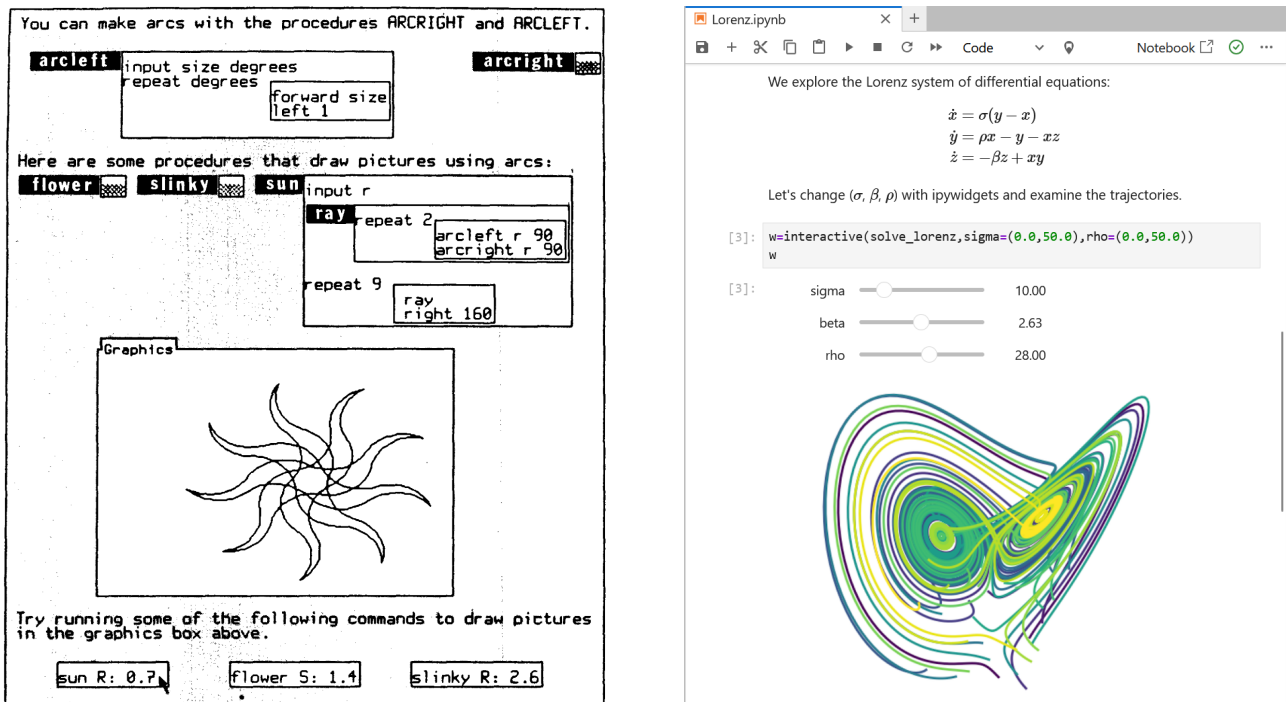


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■ **Figure 1** In Boxer [23] (left), code and data are represented as nested boxes. All code and state exists in the document. Executing a box runs the code, which can make changes to the document. In Jupyter [45] (right), documents consist of sequence of cells. The results of evaluating a code cell are displayed in the document, but the full state is managed by the underlying hidden kernel.

1 Introduction

Document-oriented programming systems are programming environments that are built around a user interface modelled after a document editor. The document interface is typically used for editing the underlying program, for executing the program or its fragments, as well as for using interactive elements embedded in the document. The origins of the paradigm can be traced to the 1980s [23]. The paradigm has a rich history, but there has also been a renewed interest in the design of document-oriented programming systems in recent years, both in practice and in research (Figure 1).

As the examples of document-oriented programming systems illustrate, there are many ways in which the document metaphor can be used as the basis for a programming system. In particular, there is a great variety in the kind of document structure used, how rich user interfaces are embedded within the document, how programming is integrated with the document and also how computations are executed.

We argue that to advance research on document-oriented programming systems, we need to precisely characterise what a document-oriented programming system is, understand the design choices available to the designers of document-oriented programming systems, and document the design choices made in existing document-oriented programming systems.

1.1 Definition

The term *programming system* has been used to talk about “an integrated and complete set of tools sufficient for creating, modifying, and executing programs” [41]. The term shifts the focus from programming languages to a more general notion that also encompasses the interactive graphical environments in which programming is done.

Document-oriented programming systems are a particular kind of programming systems, built around the central metaphor of a document. Such systems represent programs as documents that include data, code, documentation, but sometimes also evaluation state and other artefacts. The programming and using of programs in a document-oriented programming system is also done through the document interface.

To make the category of document-oriented programming systems more precise, we use Technical Dimensions of Programming Systems [41]. The framework identifies a number of axes along which programming systems can be placed and contrasted. Document-oriented programming systems occupy a particular sub-space of the entire design space mapped by the technical dimensions framework. The sub-space can be delineated in terms of three main categories of technical dimensions.

- **Notation.** The *primary notation* in a document-oriented programming system is a document. Many systems are based on structured text documents, but some include other media such as images or video. Other document structures include spreadsheets, stacks of cards or text-based Markdown documents. The document often includes *secondary notations* representing formulas or code, possibly in multiple different programming languages. The *notational structure* is thus built around multiple complementing notations.
- **Interaction.** In the main *mode of interaction* in document-oriented programming systems, the user can modify the document, edit and execute code embedded in the document and also interact with any interactive elements in the document. The effects of interacting with the document are mostly immediate, although only a few systems are live. The *feedback loops* in document-oriented programming systems thus typically aim to minimize the gulf of evaluation. Within the main mode of interaction, there may be multiple more specific sub-modes, for example when editing code in a code editor embedded within the document.
- **Customization.** In document-oriented programming systems, it is typically possible to modify the document at any point during the use of the system. In terms of technical dimensions, the *staging of customization* is such that the modification of the document or code embedded in it does not require a special *mode of interaction*. The customization is also done using the original notations of the system. However, it is rarely possible to modify the system itself from within the document and this typically requires a different mode of interaction (such as editing system source code outside of the document and restarting the system).

The aforementioned aspects define *document-oriented programming systems*. While the design space can be further mapped using existing technical dimensions, many design choices that are specific to document-oriented programming systems, are not included in the framework and deserve further examination.

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1.2 Contributions

Technical dimensions of programming systems [41] map the broad design space of programming systems. As the authors pointed out, programming systems built around text-based programming languages form one well-understood cluster in the space.

In this paper, we identify and zoom in on another interesting cluster of programming systems. Document-oriented programming systems deserve a close examination. The systems in this cluster share multiple technical characteristics and often aim to make programming more accessible. They have a rich history, include some of the most widely used programming systems (spreadsheets) and form an active research area.

- We characterize the notion of a document-oriented programming system in terms of the technical dimensions framework (Section 1.1).
- We review a number of document-oriented programming systems to provide reference points for discussion about system design (Section 2).
- We present a catalogue of twelve central design choices that designers of document-oriented programming systems face (Sections 3, 4, 5, 6), alongside with interesting examples illustrating the different choices.
- We illustrate one of the uses of our catalogue (Section 1.3) by identifying four interesting under-explored combinations of design choices (Section 7).

To develop the catalogue, we draw from our own experience developing multiple document-oriented programming systems [42, 59, 27, 34, 29], extensive literature review and also discussions at multiple workshops dedicated to past and future programming systems (Boxer Salon 2022, Substrates 2025).

1.3 Using this Paper

The aims of this paper are to highlight an interesting programming systems paradigm, develop a better understanding of the design choices within the paradigm and facilitate further research on document-oriented programming systems. The different aims are best served by different ways of using the paper.

- Readers who want to get an overview of document-oriented programming systems can focus on the introduction (§1) and examples (§2). They can then read the summary paragraphs for each of the design choices and learn about interesting designs by examining the examples (“Example” sections) throughout the paper.
- Researchers who are interested in comparing document-oriented programming systems can read the summary paragraphs for each of the design choices and then proceed to the details of the design choices that are relevant for their systems.
- Designers of novel document-oriented programming systems may find it useful to skim through the entire catalogue to explore interesting, but under-researched alternatives to some of the widely used and established design choices.

Although the paper can be read cover to cover, it is better approached with a specific document-oriented programming system or a design question in mind.

2 Examples

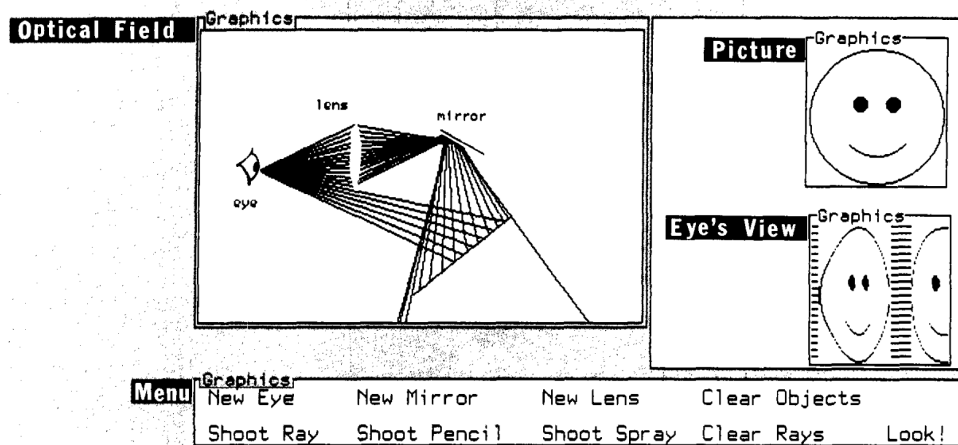
There are many programming systems that match our definition of a *document-oriented programming system*. In this section, we provide a brief overview of some of them, focusing on systems that appear frequently as examples in our catalogue.

2.1 Historical Origins: Boxer

The Boxer system [23, 24] was developed in the early 1980s as an educational interactive computational environment. One of the envisioned use cases of the system was the writing of interactive textbooks. The readers of such textbook would be able to explore interactive explanations in the textbook, modify parameters, but also see the logic implementing the explanations and potentially customize it (Figure 2).

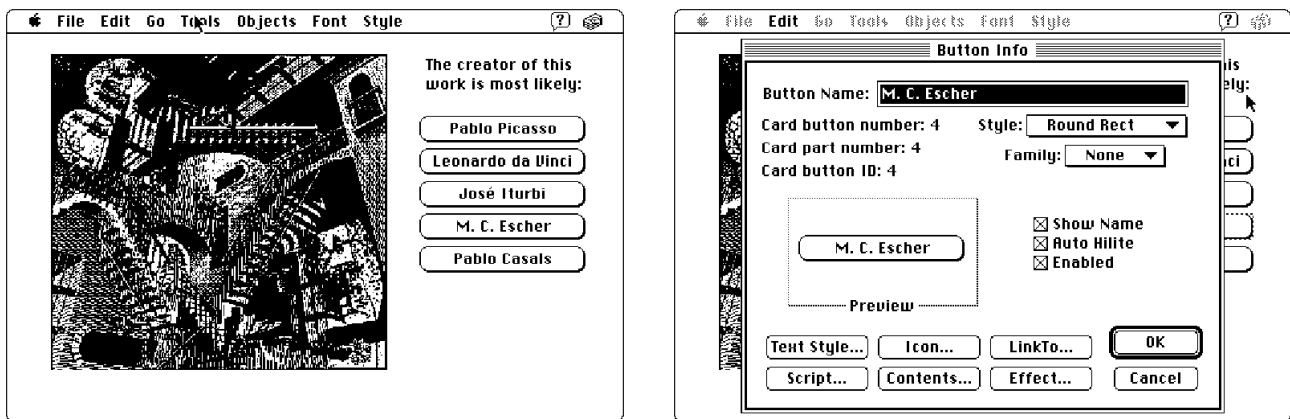
In Boxer, the document consists of nested boxes. There are two main kinds of boxes. DATA boxes contain text, graphics and other boxes. DOIT boxes contain program text, other DOIT and DATA boxes [47, p.2]. Boxes are used to represent structured data (such as a collection of records) as well as nesting structure in code (body of a loop). The system also includes GRAPHICS boxes that can display visual output and respond to user interactions.

The Boxer environment lets the user manipulate the document. They can create new boxes, modify text and code in existing boxes and delete boxes. Boxer uses *spatial metaphor*, leveraging the commonsense knowledge of space to make computing more comprehensible [23, p.2]. Another important principle of Boxer is *naive realism*, which means that what the users see on their screen is “their computational world in its entirety” [23, p.3]. Boxes can be shrunk to hide their contents and even put in closets to hide them [25], but they are always present in the document and can always be located and accessed.



■ **Figure 2** A page from a Boxer textbook on optics. Readers can construct new experiments, but also explore the implementation. (Image source [23])

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■ **Figure 3** HyperCard. (Screenshot from Archive.org [20])

Computation in Boxer is represented as code in DOIT boxes. The code can be executed by clicking on the box. Conceptually, evaluation of code is based on *copying semantics*. When the running code references another box, the evaluation behaves as if the referenced box was copied in the place where it is referenced from. (The consequence of this model is that the system uses dynamic variable scoping.) Computation can modify state of the document. If it also produces a result, the result is placed in a new DATA box in the document.

Boxer also provides a range of functions for manipulating boxes in the document. For example, the BUILD command can be used to construct a new box from a box that serves as a template with placeholders, in a manner similar to meta-programming in Lisp. However, the underlying Boxer runtime that provides the basic user interface and evaluation logic remains hidden from the user and cannot be modified directly from within Boxer.

2.2 Commercial Success: HyperCard, Spreadsheets and Jupyter

Boxer illustrates many of the key aspects of document-oriented programming systems, but it is not widely known. However, there has also been a number of systems that are based on a less interesting combination of design choices, but were widely used.

HyperCard. In HyperCard (Figure 3), the document is a stack of cards that contain graphics, text and interactive elements. As usual for document-oriented programming systems, both the editing and using of programs is done through the same document interface. What the user can do with a document is determined by the current user level, ranging from Browsing (just viewing) to Painting (change text and graphics) and Scripting (specify actions, write code).

Simple interactivity can be implemented by linking buttons to cards (when a button is clicked, the specified card is displayed). Further logic can be implemented by writing scripts in the HyperTalk programming language. Scripts can be attached to document elements, they are imperative and can modify the document. In particular, they can create and delete objects and change their properties. Unlike in Boxer, HyperTalk

scripts are represented as textual properties of elements. They are not normally displayed as part of a card and are edited through a text editor in a separate window.

HyperCard exhibits the key characteristics of a document-oriented programming system. The user works with it through a document structure (stack of cards) and they can modify program while using it. HyperTalk is a text-based scripting language, but scripts can access and modify the document.

Spreadsheets. Spreadsheets are a prime example of a successful end-user programming system [51]. Like HyperCard, they satisfy the criteria for a document-oriented programming system. The document structure is a grid of cells and the user edits and runs the programs they create through the document interface.

Unlike in HyperCard or Boxer, evaluation in spreadsheets is immediate and the computation results update as soon as data or a formula is modified. The basic programming model is based on a formula language. Formulas can refer to other cells (using a relative or an absolute location reference) and produce results that are displayed in the spreadsheet. Formula evaluation does not modify the document. The system displays the results in the cells, but the underlying document remains unchanged (i.e., a formula in a cell is not *replaced* with the result). A range of different variations on spreadsheets has been explored [8], including spreadsheets with a more expressive formula language, user-defined functions and static type checking.

As document-oriented programming system, spreadsheets have a very regular and limited document structure, but it serves as a primary notation and an interface for both using and programming. They are also interesting for their reactive evaluation.

Jupyter. Notebook systems for data science such as Jupyter [45] (Figure 1, right) are also document-oriented programming systems. The document structure is a notebook, consisting of a sequence of rich text blocks, code cells and program outputs. The notebook interface lets the user edit the notebook, run computations, review the results and possibly also change computation parameters interactively [61].

The document structure in notebook systems is a simple list of cells. Code included in the notebook typically does not manipulate the document directly. It performs some computation and the result of the computation is visualized by the notebook system using a table, chart or another kind of custom visualization. In Jupyter, the runtime state is maintained by a background kernel process and executed code snippets from the notebook modify the state. (An out-of-order execution of cells can result in an inconsistent state, an issue that some systems aim to address by automatic invalidation based on a dependency graph [60].)

In notebook systems, the user again works with a document, although they mostly edit code in an embedded text-based code editor. The document state exists in a background process, which sets Jupyter apart from other document-oriented programming systems discussed in this section.

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2.3 Current Research: Subtext and BootstrapLab

The systems discussed in the previous section structure programs as documents and use the document interface for their editing, but they do not use the document itself for structuring code and for evaluation, an approach suggested by Boxer. A number of research projects aim to explore this direction [27, 59, 42].

Subtext. Subtext is a series of research document-oriented programming systems [31]. Most systems of the Subtext family use a document structured as a tree. Data and code are also represented using a tree structure. For example, a conditional expression is a tree node with two sub-trees for the two cases, similarly to how Boxer used nested boxes. Manipulating the document is also the mechanism for using programs created using Subtext. A computation can be triggered by updating an input value or through the graphical user interface and the result will appear in the document.

Subtext experimented with a number of interesting aspects of the programming model and program evaluation. In Subtext 1 [27], the programming model is based on concrete examples and copying. Programs are constructed by creating examples, constructing computations with concrete values (as in spreadsheets). Code reuse is achieved by copying and modifying examples. In terms of technical dimensions [41], Subtext's *Abstraction Construction* proceeds from concrete cases.

Another central theme in Subtext is the use of *materialized execution*. Rather than reducing a function call with a parameter to the result of the call, Subtext lets the user explore the individual steps of the execution. The call node can be expanded to see a sub-tree containing a copy of the function called, with the function parameter replaced with the actual argument. Inspired by an earlier implementation of the mechanism [26], Subtext 7 [28] also allowed users to modify the execution traces. This makes it possible, for example, to debug test failures and see what alternative executions would lead to the correct result.

Subtext 8 [29] introduced a different underlying representation of the document. Rather than storing the document itself, the primary representation of the document becomes a history of edit actions through which the document is performed. The representation erases the distinction between program execution and user interaction. Whatever can be done by running a program can also be done by the user through direct manipulation. A sequence of past actions can also be lifted into a reusable entity, providing a mechanism for programming by demonstration.

Successors to Subtext including Baseline [34] and Denicek [59] further refine the model based on edit history to support collaborative development, schema change management and other user experiences.

BootstrapLab. BootstrapLab [42] is a prototype document-oriented programming system that explores how the structured document representation can be combined with self-sustainability. This property, known from systems such as Smalltalk, refers to the ability to construct most of the programming system using itself. This focus results in a number of interesting design choices regarding the system's programming model and an approach to constructing the graphical user interface.

BootstrapLab is based on a mutable document. The basic built-in programming mechanism is a low-level assembly-like language that can be used to create programs that modify the document tree structure. (Instructions in the language are ordered sub-nodes in the tree that are executed one by one.) However, BootstrapLab then imagines using this low-level language to create a high-level functional language with an interpreter that would work similarly to the evaluation model of Subtext, i.e., by attaching the steps of the evaluation process, as well as the final result, to the document tree. Unlike in Subtext, this functionality would not be built-in feature of the system, but something built within the system, using its low-level capabilities.

BootstrapLab also shows that the user interface for editing documents does not have to be built-in as in most other document-oriented programming systems. To achieve this, BootstrapLab treats a particular sub-tree of the document as a memory-mapped display containing a tree structure that defines what the user sees as a tree-structured vector graphics akin to SVG. BootstrapLab programs can modify the memory-mapped display to, for example, visually render a part of the document tree and allow its editing through a tree view, reconstructing the graphical interface known from Subtext.

3 Design Choices: Structure

The first set of design choices relates to the structure of the document. They determine what kind of document the user sees and works with, as well as how the document is represented internally by the system.

3.1 Document Shape

The document shape is the visible structure that the user manipulates and interacts with. This is the primary visible notation of the system. In many document-oriented programming systems, the shape is a tree consisting of different kinds of nodes.

- *Tree-Shaped Documents.* The tree can be displayed directly to user using some form of tree view widget that lets users directly manipulate the tree (Subtext [27], BootstrapLab [42]). The tree can be modelled after forms (Forms/3 [15]) or structured mixed-media documents such as HTML (Webstrates [43], Webnicek [59]), in which case the user can often view and edit the document directly (WYSIWYG) or through a source view (tree view widget).
- *Sequence of Cells.* Computational notebooks for data science (Jupyter [45], Wrattler [60], Datnicek [59]) and programming systems built for journalist (Idyll [19], Planet Hazel [2], The Gamma [58]) use a flat structure where the document is a sequence of cells of different kinds, including textual cells, code cells, interactive cells or outputs of a computation.
- *Two-Dimensional Grid.* In spreadsheet systems [1], the document shape is a regular two-dimensional grid. Cells in the grid can contain data and formulas. In some systems, other structures are overlaid over the grid (such as named ranges) and there may be a secondary notation (macro language).

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- *Other Choices.* Other choices are less common. HyperCard [3] documents are stacks of cards, which can contain freely positioned graphical, textual and interactive elements. An unstructured representation is used in Potluck [48], where the document is a plain-text Markdown document (although rendered as rich text).

Example: Ampleforth. In Ampleforth [11], the document shape is not fixed beforehand. The Ampleforth system is embedded in the live programming environment of the object-oriented programming language Newspeak [14], which runs in the web browser.

Internally, Ampleforth documents are Newspeak objects, but they are displayed as rich text documents containing media (using standard capabilities of the web browser) and also interactive Ampleforth elements (which send messages to the underlying Newspeak objects). An Ampleforth document can thus have many different specific shapes. As illustrated by the DocuApps project [12], this includes structured documents, presentation slides and spreadsheets.

The BootstrapLab [42] system has a similar capability. Its underlying representation is a graph (primarily a tree, but with arbitrary links), but what is displayed to the user can be reprogrammed within the system itself. The example implemented in the prototype is a tree view, but other renderings are possible.

3.2 Document Representation

Whereas *Document Shape* is concerned with the user-facing side of a document-oriented programming system, *Document Representation* focuses on the internal data structures that the system maintains. In the technical dimensions framework [41], the two aspects are referred to as *surface notation* and *internal notation*.

- *Document Itself.* In many systems, their internal notation closely resembles to the surface notation and what they display to the user is a direct rendering of their document representation (Boxer [23], HyperCard [3], Jupyter [45], Forms/3 [15]).
- *Underlying Model.* Document-oriented programming systems can be embedded in another programming system with a more basic underlying representation. This can be a soup of objects (Ampleforth [11]) or a graph structure (BootstrapLab [42]).
- *Edit History.* In a number of systems, the ground truth is not the document itself, but a sequence of edit operations through which the document has been created (Subtext 8 [29], Denicek [59], Baseline [34, 32]). The document is computed by reapplying the operations, but the history can be used to implement programming by demonstration.

Example: Webstrates. In Webstrates [43], there is no gap between the *internal notation* and the *surface notation*. The Webstrates system is built on top of the web platform and it uses the web browser's Document Object Model (DOM) as the canonical document representation. Webstrates make the document collaboratively editable by synchronizing it between devices. However, editing is done directly to the document through the browser developer tools or through Codestrates [63], which is a development platform built on top of Webstrates.

3.3 Modularity

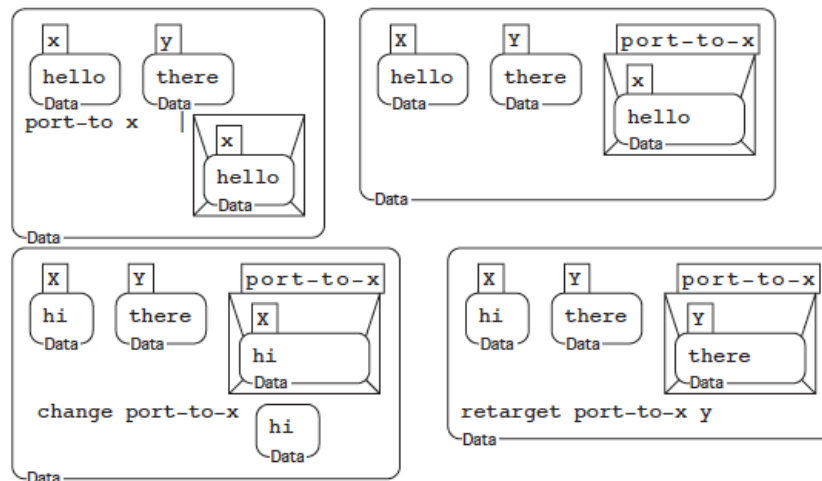
The choice of modularity mechanism determines how can aspects of programs be reused. The design choice corresponds directly to the technical dimension *factoring of complexitiy*. In programming languages, this is often the key concern and possible solutions range from classes and inheritance to domain-specific languages and type classes. In document-oriented programming systems, most programs are more direct and only implement more basic modularity mechanisms (possibly posing an interesting open question for the future of the paradigm).

- *Transclusions*. Transclusions [52] is a hypertext concept, where a resource, or a part of a document, is included in multiple different places at once. In document-oriented programming systems, they allow modularity without introducing additional concepts (such as a function call) to the end-users. They can be used to reuse a component existing inside the document (Boxer [23]), as well as content that may exist elsewhere in the underlying model (Ampleforth [11]).
- *Internal References*. A simpler mechanism for code reuse is a reference to an entity defined elsewhere in the document. (See §6.3 for different referencing mechanisms.) Unlike with transclusions, the entity is not displayed in the document location where it is referenced (the user typically sees the entity name). References can refer to functions (BootstrapLab [42]) or interactive components (Livelits [55]).
- *Managed Copy and Paste*. Several systems encourage users to reuse code using copy & paste, but keep track of the copies (Subtext [27], Baseline [33], Forms/3 [15], Denicek formulas [59]). A change made to a copy can be local (change of input), or propagate back to the source (fixing a bug).
- *External References*. In many document-oriented programming systems, the ability to define new abstractions within the document is limited and so modular components or code are defined outside of the document. Those can be external libraries (Jupyter [45]) or interactive components ([19]).
- *Edit History Reference*. In systems where the underlying representation of a document is a history of edits (see §3.2), it is also possible to spcify behavior by referring to a part of the history (replaying the edits then performs the behavior again). The mechanism can be used to implement programming by demonstration [22] (Subtext 8 [27], Denicek [59]).

Example: Boxer. In Boxer, parts of a document can be reused through ports (Figure 4). They are views of another box and, despite looking differently, behave identically to their target. The Boxer Structures report [25] lists a number of typical uses of ports.

Ports can be used as a user interface mechanism to provide easy access to another box hidden somewhere in the document, or to create an easy to follow hyperlink. They can be used to share data between parts of a document. Ports are also useful as object references, for example to create a list of objects (existing elsewhere in a document) to be processed. Although Boxer supports named references to variables and procedures, ports can also be used for this purpose to avoid name mix-ups.

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■ **Figure 4** Portals (a transclusion mechanism) in Boxer. A port is created using the `port-to` command (left top) and is itself a box that can be named (left right). Changing the value of the portal box changes the original source (bottom left) and portals can be redirected (bottom right). Image source [25].

4 Design Choices: Programming

An essential characteristic of document-oriented programming systems is that they allow some kind of programming. However, our definition admits both end-user document systems with limited programming capabilities and systems that can be fully reprogrammed from within themselves. Systems also differ in their programming model, as well as where and how they store program code.

4.1 Programming Model

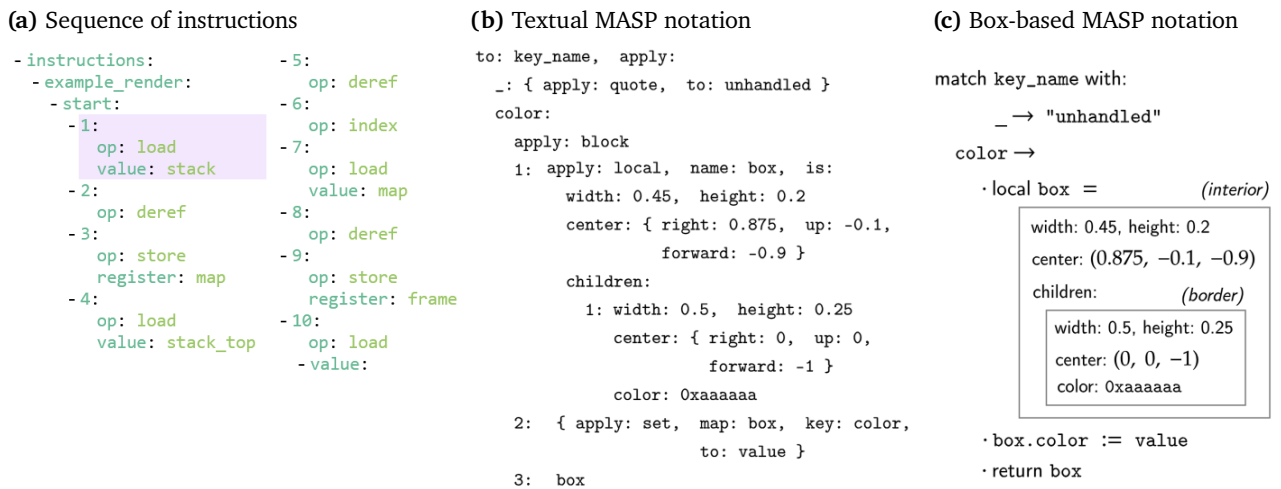
The basic programming model of a document-oriented programming system can be built around the standard programming language paradigms.

- *Imperative*. In the imperative programming model, code embedded in the document consists of operations that mutate some state (see §6.2). In some systems, commands can modify the document itself (HyperCard [3], Ampleforth [11], Boxer [25], Webstrates [43], Subtext 8 [29]), while in others, commands can only modify state that exists behind the scene but not the document structure (Jupyter [45]).
- *Declarative*. In the declarative model, code in the document describes a computation that should be performed in order to obtain some result (Subtext 7 [28], Forms/3 [15]). The result may be displayed alongside the document, or placed in the document (see §6.2), but the code does not explicitly modify the document.
- *Reactive*. When the declarative programming model makes it possible to write code that explicitly responds to user interactions with the system, it can be referred to as reactive (Renkon-pad [54], Lopecode [46]). Note that spreadsheets support live updates, but only in response to change of the source (data).

- *Transformation.* Another variation on the declarative programming model exists in systems where computations operate on document fragments and their result is also a document fragment. The evaluation may transform the document (Web-nicek [59]), but the model has origins in systems that generate new documents as the result (XSLT [18], Document calculus [21])

Example: BootstrapLab. BootstrapLab [42] shows that a document-oriented programming system may support multiple different programming models. The primitive programming model in BootstrapLab is imperative. Code is represented as a sequence of low-level instructions that modify a set of registers, stored in a known location in the document tree (Figure 5 (a)). The special instruction pointer register is a reference to the next instruction to be executed. The low-level programming model includes operations such as key lookup, copying, and conditional jump.

A high-level programming model envisioned in BootstrapLab is the MASP language, modelled after LISP (Figure 5 (b)), but using maps instead of lists. The document structure (nested maps) represents the abstract syntax tree of functional-first programs. The code can be rendered as a textual tree, but also visually (Figure 5 (c)). The MASP interpreter stores all immediate information, as well as the final result, directly in the document (see §6.2). Although this was not fully implemented in the BootstrapLab prototype, a MASP interpreter or compiler could be built using the low-level programming model.



■ **Figure 5** Two different programming models in BootstrapLab [42]. **(a)** Imperative instructions to mutate document that read the top of a stack and store the result in a register (a special document node). **(b)** A functional document transformation that replaces color field with a filled rectangle that has the given color. **(c)** Visual rendering of the same MASP code. (Image source [40])

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4.2 Metaprogramming Capabilities

Document-oriented programming systems differ by the degree to which they can be modified from within themselves. This is known as *self-sustainability* in the technical dimensions framework [41]. As most document-oriented programming systems are not self-sustainable (i.e., not implemented and modifiable from within themselves), we refer to the design choice as *Metaprogramming Capabilities*.

- *No Metaprogramming*. In many document-oriented programming systems, computation can only produce results that are displayed in the document (Spreadsheets [1], Idyll [19], Potluck [48], Forms/3 [15]).
- *Limited Metaprogramming*. In most notebook systems, code written by the user cannot arbitrarily modify the structure of the notebook, but there may be a special operation for, for example, adding a new cell (Jupyter [45], Observable [53]).
- *Document Metaprogramming*. In a number of document-oriented programming systems, code running in the system has the capabilities to freely modify the structure of the document, but it cannot modify the system itself (HyperCard [3], Webstrates [60], Wrattler [60], Boxer [23]).
- *Full Metaprogramming*. Only document-oriented programming systems where much of the system itself is implemented within itself can be modified from within code in the document. (Ampleforth [11], BootstrapLab [42], Lopecode [46]). The degree depends on what the minimal unmodifiable runtime of the system is.

Example: Lopecode. Metaprogramming capabilities of most notebook systems are very limited, but Lopecode [46] shows that this is not inevitable. The system is built on top of the reactive kernel from Observable [53], which maintains a dataflow graph of the computation. Everything else, including the document model based on cells and the editor is implemented (and can be modified from) Lopecode notebooks.

4.3 Code Representation

How is code represented in a document-oriented programming system and where can it be found? We consider these two aspects together as a single design choice.

- *Naive Realism vs. Hidden Representation*. In the naive realism model, everything that exists in the system is available in the document (Boxer [23], Jupyter [45], Subtext [27], Forms/3 [15]). In contrast, systems where code exists outside of the document use the hidden representation model (HyperCard [3], Ampleforth [11]).
- *Structured Representation vs. Textual Representation*. Most document-oriented programming systems use a structured representation of a document, such as a tree (see §3.1). In such systems, code can be represented as an AST using the same structure and edited using a strucute editor (Boxer [23], Subtext [27], Denicek [59], Hazel [55]). The alternative is to use a textual representation of code alongside with an (embedded) text editor (Jupyter [45], Potluck [48], Ampleforth [11]).

4.4 Document Structure Checking

In programming languages, static typing is the most common mechanism for early *error detection* (see technical dimensions [41]). In document-oriented programming systems with *Document* or *Full Metaprogramming* (see §4.2), it is possible to use a mechanism akin to type checking to ensure that operations transforming the document result in a well-formed document structure.

Documents manipulated by systems that use the *Tree-Shaped Document* model (see §3.1) may be irregular containing, for example, different structure of data in different document sections. As such, it is also an interesting problem to define what is considered a well-formed document structure.

- *Minimal Structure.* Systems where document structure is very regular (Spreadsheets [1]) do not typically need sophisticated structure checking to ensure the document is well-formed (but even they have possible constraints, such as cycles). In computational notebooks (Jupyter [45]), checking may be useful for the embedded code, but not to ensure the well-formedness of the notebook structure.
- *Implicit Structure.* Document systems that let users programmatically manipulate documents with more complex shapes may allow arbitrary modifications of the structure (Webnicek [59], BootstrapLab [42]). Changing the structure in a way that is incompatible with other code in the document then results in a runtime error, reported when the other code is executed.
- *Explicit Structure.* In some systems, the document structure can be explicit using a mechanism such as a type system or using prototypes. This is an under-explored area of research in programming systems (Subtext 10 [30], Baseline [32]), but examples exist in document manipulation (XDuce [39], Ur/Web [17]).

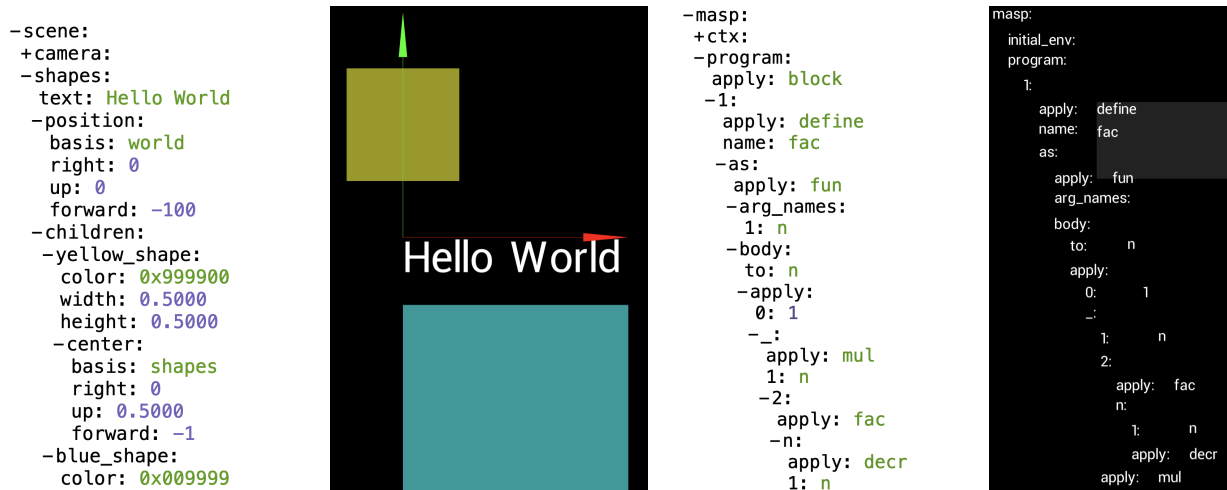
Example: Subtext 10 and Baseline. An example of a system with explicitly checked document structure is Subtext 10 [30], which served as the basis for a more recent prototype implementation Baseline [34]. Subtext 10 uses a form of static type checking that is based on concrete values. The type of a collection is determined by a special element (with index ***) that serves as a default value (or a prototype [9]).

The default value is used when adding a new item to the collection to ensure that all items have the same structure. Similarly, a structural document edit (e.g., adding, renaming or removing a record field) can only be applied to the default value and results in the change being applied to all items of the collection. In Subtext 10, default values were also proposed for function arguments.

5 Design Choices: Graphical Interface

Whereas some of the design choices related to structure (§3) and programming (§4) coincided with the more general technical dimensions [41], the design choices concerning user interface are new in this paper. We consider two complementary mechanisms, for display and for editing.

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■ **Figure 6** Memory-mapped display mechanism in BootstrapLab. A sample scene consisting of text, rectangles and arrows (a) with rendering (b). A tree representing a MASP function, rendered outside of BootstrapLab (c) and using the memory-mapped display mechanism (d). Image source [40].

5.1 Display Mechanism

A defining characteristic of document-oriented programming systems (§1.1) is that the user sees and interacts with a document. There are multiple display mechanisms through which the document can appear on screen.

- *Naive Realism.* Systems where the document representation is the document itself, or edit history from which the document is obtained (see §3.2), the system may have a standard mechanism for displaying the document (Boxer [23], Webstrates [43], Webnicek [59]). Custom graphical elements can be constructed using components of the standard mechanism such as graphics boxes [25] or HTML.
- *Renderer with Widgets.* In systems where the document representation is less expressive, custom graphical elements can be implemented as widgets that are defined outside of the document itself. They can then be created programatically from within the document or used automatically to display (end edit) specific types of values. (Livelits [55], Jupyter Widgets [61], Forms/3 [15]).
- *API Calls.* Document-oriented programming systems where code exists outside of the document can modify the displayed document through some API provided by the system, for example to construct document elements and draw (HyperCard [3]) or generate document fragments (Ampleforth [11]).

Example: BootstrapLab. An under-explored approach for document rendering has been used in BootstrapLab [42]. The document in the system is a tree structure consisting of nodes that map keys to other nodes or primitive values. The document is not displayed directly to the user. Instead, it contains a special sub-tree (scene) that defines a visual structure to display (as a scene consisting of vector shapes).

The system can display arbitrary part of the document by filling the scene sub-tree with shapes rendering the specified sub-tree (Figure 6). The mechanism, inspired by memory-mapped screen on microcomputers, makes it possible to keep all code and data in a tree-shaped document, but fully control what is displayed on the screen.

5.2 Editing Mechanism

The editing mechanism used in a document-oriented programming system is usually tightly linked with the display mechanism. However, it is worth separating the two design aspects as a system can, for example, display a document visually, but use a plain text editor.

- *Structure Editing.* Common approach is to let the user directly edit the structure of the document through a structure editor that works directly with the underlying structure such as tree nodes (Denicek [59], Webstrates [43], Boxer [23]).
- *Projectional Editing.* If the display mechanism lets users construct widgets for some parts of the document, the widgets may behave as projectional editors [70] and propagate interactively made edits back to the document (Livelits [55]). Some widgets are display-only and do not modify the document (Jupyter Widgets [61]).
- *Plain Text.* In some systems, the primary means of editing is text-based. Text editing may be used only for code and markup (Spreadsheets [1], Jupyter [45]), but there are also systems where the whole document is edited as plain text (Potluck [48]).
- *In-System Editor.* Systems that provide sufficient expressive power and rendering capabilities to fully control the display and handling of user events can, in principle, support any kind of editing interface, even if they typically use one of the above design choices (Ampleforth [11], BootstrapLab [42], Lopecode [46]).

6 Design Choices: Evaluation

The fourth and last category of design choices discussed in this paper relate to how are computations in a document-oriented programming system evaluated. The design aspect is related to the choice of a *Programming Model* (§4.1), but here we focus more specifically on how the evaluation of code happens.

6.1 Evaluation Mode

The first choice is concerned with what triggers evaluation. The different choices have been discussed extensively in the context of live programming and our list below partly follows the established levels of liveness [66, 67]. In technical dimensions [41], the evaluation mode is determined by the structure of *feedback loops*.

- *Explicit Trigger.* In this mode, computation is triggered explicitly by a user action. The choice is common in systems where computation modifies state (imperative *Programming Model*, see §4.1) or where computations are long-running (Jupyter [45]).

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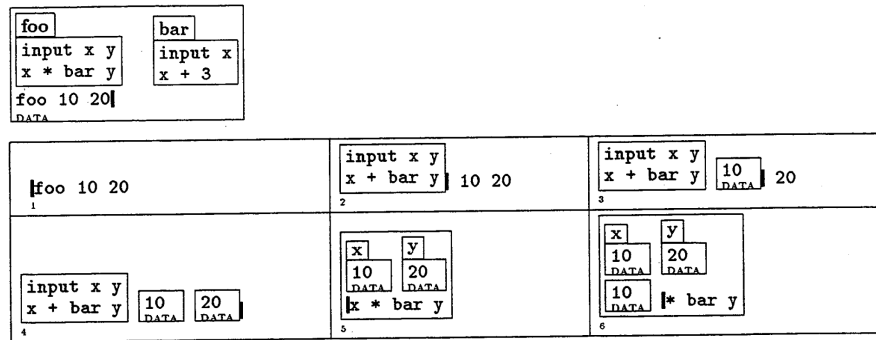
- *Implicit Trigger.* More immediate feedback may be provided by automatically recomputing the affected parts of the document when code or data change. This is a widely used approach for declarative systems and systems focusing on small code snippets (Spreadsheets [1], Potluck [48], Ampleforth [13], Forms/3 [15]).
- *Live Update.* The last mode refers to systems where ongoing evaluation reflects changes to data and code made during evaluation (liveness level 4 [66]). This mode is under-explored, but can likely be supported by reactive document-based programming systems (Lopecode [46], RenkonPad [54]).

6.2 Evaluation State

A design concern specific to document-oriented programming systems is the interaction between the evaluation mechanism and the document representation. A number of interesting design options arises when the evaluation mechanism stores information directly in the underlying document during (or at the end of) the evaluation.

- *Ephemeral Results.* Many systems do not modify the document in any way when evaluating computations (Spreadsheets [1], Jupyter [45]). The results are stored in some representation that exists outside of the document and are displayed to the user, but cannot be directly programmatically manipulated by other computations (besides from constructing other computations that refer to them).
- *Materialized Results.* In systems based on the imperative programming model (see §4.1), the computation directly modifies the document and result of a computation is also stored in the document (HyperCard [3], Webstrates [43]). This could be the case in declarative systems too, although such systems typically use one of the subsequent two choices.
- *Internalized Execution.* A document-oriented programming system can choose to use no other memory or information storage aside from the document that it is working with. In this case, the individual steps of the execution repeatedly modify the state of the document until the computation terminates (BootstrapLab [42], Boxer [23], see the example below).
- *Materialized Execution.* Finally, a system can record every single step of the execution of a computation in the document. This way, the full execution trace is materialized in the document and can be accessed from other code inside the document, for example in order to analyse provenance or execution of tests. The approach has only been implemented experimentally and would require optimization to work well in practice (Denicek [59], Subtext 7 [28], BootstrapLab/MASP [42]).

Example: Boxer. The evaluation model of Boxer [23] is based on the idea of *copying semantics*. In this model, the evaluation of a reference to another box proceeds by replacing the reference with the box itself. The user does not see this during normal use of the system, but the Boxer movie stepper [47] makes it possible to see how the execution proceeds step-by-step. As illustrated in Figure 7, the execution can be seen as a sequence of (mutable) transformations of the document.



■ **Figure 7** First six step of the execution of `foo 10 20` in the Boxer movie stepper. The box above shows the original source code. The box below shows the successive steps. (1) The evaluation starts, (2) function definition replaces the reference, (3, 4) arguments are wrapped in data boxes, (5) input is replaced with boxes passed as arguments and (6) `x` is replaced with the variable value. (Image source [47])

6.3 Identification of Nodes

When manipulating documents, the document-oriented programming system (and code that it runs) needs some mechanism for referring to other elements in the document. There are multiple approaches and a programming system may support a combination of these.

- *Human-Readable Identifiers.* The most common approach is to let users name elements they want to refer to using a variable name or human-readable identifier for a document element (Jupyter [45], HyperCard [3], Boxer [23], Webstrates [43]). Names are typically global, although a system could also support namespaces.
- *Absolute Paths.* In systems with a richer document structure, elements can be referred to by a pre-defined addressing scheme (Spreadsheets [1]) or by using a path (a sequence of node names) from the root (Denicek [59], HyperCard [3]). In HyperCard, elements on different cards can have the same name and one refers to them using a path consisting of the stack name, card name and an element name.
- *Internal Unique Identifiers.* To sidestep fragile named references, some programming systems use internal unique identifiers, not visible to the user. The user may see a name, a visual representation of the reference or the referenced value, directly in place of the reference (Subtext [27]). Note that maintaining internal unique identifiers typically requires using a structure editor.
- *Relative References.* In addition to other mechanisms, document nodes can refer to document other nodes through paths that are relative to their location in the document (Spreadsheets [1], Denicek [59]). In trees, this typically requires the ability to refer to a parent element. In spreadsheets dollar references (e.g., `B10`) are absolute and ordinary references (e.g., `B10`) are relative.
- *Selectors.* A richer referencing mechanism allows the user to specify nodes using a combination of paths and selectors, for example to refer to all children of a node, children of a specific tag or class (as in CSS selectors), or an element of a given shape anywhere in the document (Webstrates [43], Denicek [59]).

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Example: Denicek and Subtext. Identification of nodes poses an interesting problem in systems where document nodes can be moved and renamed, or in systems based on edit histories (see §3.2) where edits need to be merged or reconciled. Two systems that tackle this problem are Baseline [34] and Denicek [59].

Consider a document with a root node *pioneers* containing two children named *lovelace* and *hamilton*. In Denicek, one can refer to a specific node using an *Absolute Path* such as */pioneers/lovelace* or to multiple nodes using a *Selector* */pioneers/**. Subtext, by contrast, uses *Internal Unique Identifiers* and the selection made by the user results in a collection of IDs, referring to the selected nodes. The design choice affects how the systems handle renaming. In Subtext, renaming *pioneers* to *compsci* has no effect on the unique identifiers. In Denicek, the operation requires updating all references, for example, from */pioneers/** to */compsci/**.

The design choice has interesting consequences when merging edits. If a user makes edit using a selector (such as */pioneers/**) in a system identifies nodes through *Selectors*, the edit affects all nodes including those that may have been created independently and have been merged with the current document (a scenario illustrated in [35]). When the system identifies nodes through *Internal Unique Identifiers*, only nodes known when the edit was done will be affected. On the other hand, merging of edits is challenging when the system uses expressive language of selectors (and Denicek restricts the expressivity of selectors to make merging tractable [59]).

7 Research Directions

One of the uses of the catalogue of design choices presented in this paper (see §1) is to identify interesting under-explored designs for document-oriented programming systems. We discuss four research directions that illustrate such use of the catalogue.

Metaprogramming over Execution Traces. One of the choices for managing evaluation state (see §6.2) is to use *Materialized Execution* where individual steps of the execution are recorded as nodes in the document. This is only implemented in a few experimental systems and an efficient implementation requires further research. However, the model enables interesting capabilities, especially when combined with metaprogramming capabilities (see §4.2) that make it possible for computations inside the document to manipulate the document, i.e., the *Document* or *Full Metaprogramming*.

A system with the two features would make it possible to create programs that analyze the execution of other programs embedded within the same document. This may be used for analysing unit test failures (using a diff of the failing execution and the last successful execution), to implement language-integrated provenance [37] or to collect information for automatically generating linked data visualizations [57].

Memory-Mapped Display. A design choice that has been explored briefly in BootstrapLab [42] is the use of *Memory-Mapped Display* as the display mechanism (see §5.1). The choice requires programming systems where computations can modify the document, i.e., support *Document* or *Full Metaprogramming* capabilities (see §4.2).

The choice makes it possible to build document-oriented programming systems where individual programs have full control of what the user sees. The design choice is akin to the design of the Smalltalk programming environment, which is itself implemented in Smalltalk and uses the primitive graphics API of the runtime with reflection in order to build tools such as the class browser [38]. The combination would make it possible to build a document-based equivalent of the Smalltalk design.

Unifying Execution and Interaction. A theme that has been suggested by Subtext 8 [29] is unifying program execution with user interaction. The combination of design choices that enables this is the use of *Edit History* as the document representation (see §3.2) together with *Internalized* or *Materialized Execution* evaluation state (see §6.2). The combination means that evaluating code in a document generates edits that modify the document that are indistinguishable from edits that could be performed by the user through a graphical interface. The combination could enable a range of programming by demonstration user experiences where reusable programs are constructed by enacting the computation using sample concrete values as in Pygmalion [65].

Variations on Spreadsheets. Spreadsheet systems such as Excel can be characterized by using the *Two-Dimensional Grid* as the document shape (see §3.1), *Declarative* programming model (see §4.1) with *Implicitly Triggered* evaluation (§6.1) and the support for *Absolute* and *Relative References* as the node identification mechanism (§6.3).

Interesting programming systems can be imagined by varying one of the design choices. One variation is to generalize the document shape from a regular two-dimensional grid to other structures. This combination has been partly explored by Forms/3 [15] and recently Nezt [5], but there are likely multiple other variations. It may also be interesting to generalize the node identification mechanism to arbitrary *Selectors*, allowing the users to construct formulas that use more general queries to collect data from the spreadsheet.

Another variation on spreadsheets would be to use the *Edit History* choice of document representation (see §3.2). The combination would enable some of the affordances of Subtext and Baseline [34, 29]. It could be possible to construct computations by interactively manipulating concrete values and capturing the edit history as a formula. It could also be possible to define merging of edit histories and address schema change challenges arising from diverging versions of spreadsheets [36, 16].

8 Related work

The history of document-oriented programming systems discussed in this paper has inevitably been selective. The papers referenced as examples are generally pioneering historical systems, widely-used systems, or current research projects.

The idea of *documents as user interfaces* [7] focused on user interaction rather than programming, but is closely related to document-oriented programming systems. It inspired research on active documents [62] where document editor can include logic for collaborative editing, annotating documents or managing files on disk. The logic in

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those systems, however, is not a part of the document. `EmbeddedButtons` [6] attaches the logic to buttons that can be included in documents, copied and shared.

Despite our definition (see §1.1), the boundary of what qualifies as a document-oriented programming system remains fuzzy. There are several related systems and formal models that we choose not to include as examples. The document calculus [21] captures systems for generating (static) documents, but it does not model interactive documents. We included the Hazel structure editor [56] as an example of a system with widgets (livelits) [55] and also because of the notebook vision presented as Planet Hazel [2], but excluded structure editors [68] and projectional editors [71], even if they can be used for editing programs with projection widgets akin to livelits [50].

There are also multiple programming systems that have some of the characteristics of document-oriented programming systems, but not all. `RekonPad` [54] is based on the DOM programming model, but uses it to build a window-based interface. Systems built on top of `Webstrates` [63, 44] are also relevant, but do not fundamentally change the underlying model. `Varv` [10] and `Infusion` [4] are closely related, but do not view program as a document. More historically, the `UI2` or `Morphic` [69, 49] user interface in `Self` has the directness and liveness of many document-oriented programming systems, but does not directly use the document metaphor.

Methodologically, our work builds on *Technical Dimensions of Programming Systems* [41]. We “zoom in” to examine a more narrow space and uncover domain-specific design choices. The potential uses of our paper are also similar and include comparison of existing systems and exploration of a design space. Our aim is to map design space, rather than provide a comprehensive literature review and so our choice of example systems is selective. Using a rigorous literature review methodology, as for example in the review of exploratory and live programming and coding [64] would be interesting, but possibly more difficult due to the lack of established terminology.

9 Conclusion

Document-oriented programming systems have been around in various forms and constitute an interesting research field, but systems in this area often exist in isolation. By defining the notion of a *document-oriented programming system*, we aim to highlight an appealing programming paradigm that has been around for a long time, but remained somewhat out of sight. Programming systems in this category share a number of characteristics, but also differ in important ways. Our catalogue of design choices maps the design space of document-oriented programming systems. It provides a basis for comparing existing systems and envisioning new research directions to explore previously under-explored combinations of design choices.

Many of the document-oriented programming systems discussed in this paper pursue ambitious goals, such as making programming more transparent, more accessible to non-experts, and supporting gradual progression from an end-user to a developer. In fact, systems such as `HyperCard` achieved those goals in a specific context! We hope that our work contributes to better understanding and supports research on programming systems that share these aspirations.

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