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Programming for humans: a new paradigm for domain-specific languages

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Summary

Programming is a difficult, specialist skill. Despite much research in software engineering, programmers still work like craftsmen or artists, not engineers. As a result, programs cannot easily be modified, joined together or customised. However, unlike a craft product, once a programmer has created their program, it can replicated infinitely and perfectly. This means that programs are often not a good fit for their end-users because this infinite duplication gives their creators an incentive to create very general programs.

My thesis is that we can create better paradigms, languages and data structuring techniques to enable end-users to create their own programs.

The first contribution is a new paradigm for programming languages which explicitly separates control and data flow. For example, in a web application, the control level would handle user clicks and database writes, while the data level would handle form inputs and database reads. The language is strongly typed, with type reconstruction. We believe this paradigm is particularly suited to end-user programming of interactive applications.

The second contribution is an implementation of this paradigm in a specialised visual programming language for novice programmers to develop web applications. We describe our programming environment, which has a novel layout algorithm that maps control and data flow onto separate dimensions. We show that experienced programmers are more productive in this system than the alternatives.

The third contribution is a novel data structuring technique which infers fuzzy types from example data. This inference is theoretically founded on Bayesian statistics. Our inference aids programmers in moving from semi-structured data to typed programs. We discuss how this data structuring technique could be visualised and integrated with our visual programming environment.

Acknowledgments

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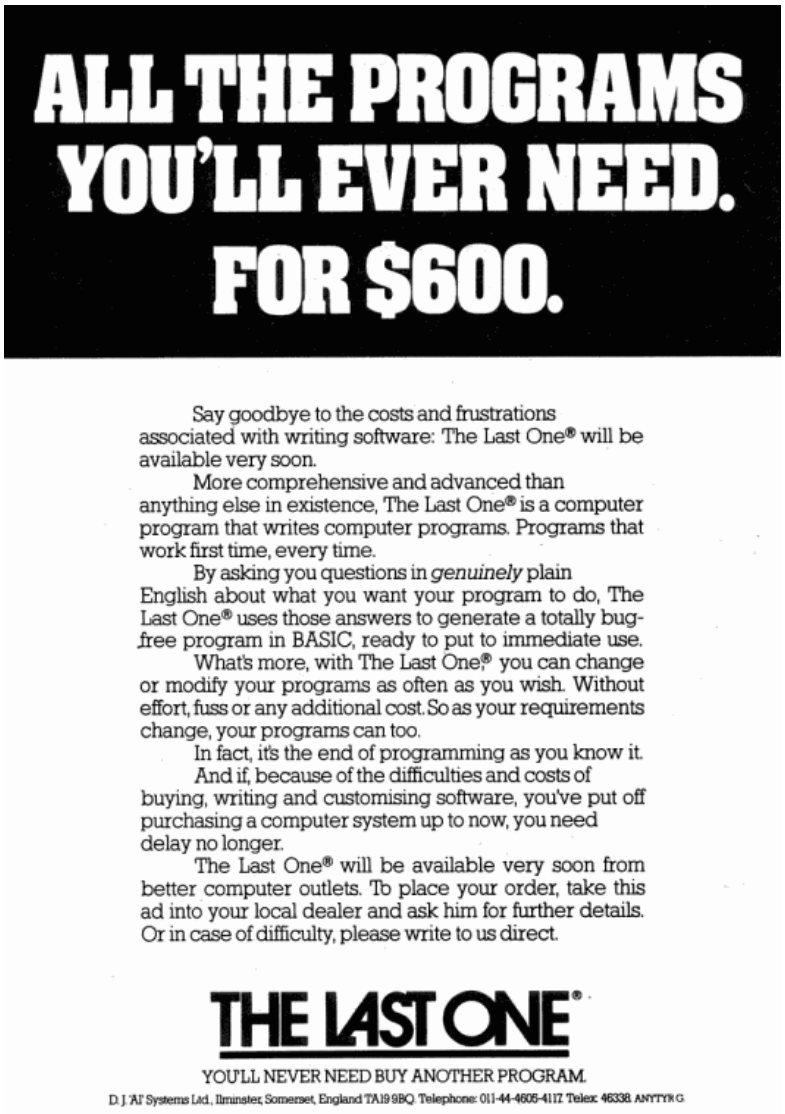
Chapter 1

Introduction



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Seeing this old advert for "The Last One" several years into my PhD inspired both fear and relief. Fear, because the idea of end-user programming has had a long pedigree but few results. But relief, because the problems that led to the creation of "The Last One" still exist and a solution would be even more valuable now than it was in 1983. The problem is this: allowing end-users rather than programmers to develop their own

applications, based on their data and their processes. End-users have varied and exacting needs for an enormous variety of small-scale automation and data processing tasks. For example, users might want to track inventory in a small company, keep a personal gift registry, or create an online tournament scoreboard. These kinds of problems can be solved with a small database and some simple forms, reports, calculations and processes, but are too small-scale to warrant getting a professional programmer to build them. Thus, there should be a way for end users to create such programs themselves.

Many different systems have attempted this, from COBOL's use of psuedo-natural language in order to make it usable by non-programmers to the somewhat empty promises of fourth generation languages. No general system for end-user programming has yet succeeded, and it seems unlikely one ever will.

Having said that, many end-user data systems have been extremely successful in particular niches. Hypercard was a genuinely innovative system and widely used for the creation of databases and simple end-user programs (Apple, 1998). Visicalc and its main descendant Excel continue to be used for financial and other mathematical record-keeping and modelling (Bricklin and Frankston, 1979; Microsoft, 2010b). Wikipedia demonstrates how many collaborators can work together to create a linked semi-structured database. Each of these systems has been successful in a limited domain. However, there are no general end-user programming tools for the kind of processes we described above.

The thrust of this thesis is therefore to investigate failures in creating end-user programming tools and find new ways to overcome the problems identified by these failures. Attempts to create end-user programming environments have fallen into three different sorts of failure: excessive power, excessive specialisation, and excessive weakness.

Power It is very straightforward for computer scientists and commercial programmers to add to end-user programming languages until they reach what we might call "computational takeoff" – generally in the form of Turing-completeness. Whilst Turing-completeness is a useful metric for general purpose programming languages, as a proxy for "being able to write the sort of programs the user wants" it is overkill by several orders of magnitude.

Specialisation Where languages are entirely specialised within specific domains, they tend not to be useful for end-user programming. End-user programs may not fit inside a pre-defined domain, and where they do they will often cross into others. A useful end-user programming language must be able to work with a variety of domains simultaneously and must have ways to allow the user to express their own data and algorithms.

Weakness Environments like Excel, whilst offering a variety of abilities in visual formatting, structuring data and deriving facts from data, do not have the ability to build user interfaces or interact with external data sources or sinks. The user is locked into the interactive data system, which while useful, is not a programming environment. A useful

language must be expressive enough to automate the repetitive tasks a user has to do in this kind of system.

All of these problems coalesce into one: an end-user programming language (EUPL) must have capabilties that accurately match the needs and abilities of its users. Finding a solution to the problem of matching EUPLs to users depends on understanding the requirements and skills of users. In general, naïve users do not understand recursion, abstraction, particularly in the form of user-defined functions, locking, or the relational model. That is not to say that recursion is not an elegant mathematical construct for certain types of expert program; only that it is unsuitable for end users. Abstraction is not a problem per se, but the *cognitive dimensions of notations* and attention investment models show that the costs usually outweigh the benefits for end-users (Green, 1989; Blackwell, 2002). Even professionals disagree about how much abstraction is necessary – for example, Pierce argues for no duplication whatsoever (Pierce, 2002, p. 339), while Fowler suggests that the third copy should be the sign abstraction is needed (Fowler et al., 1999, p. 58). One particular area of abstraction – user-defined functions – has been extensively studied, for example in adding functions to Excel (Peyton Jones et al., 2003). By and large these studies have shown the perceived costs outweigh the benefits for most users. Even in professional programs, some level of code cloning has been considered beneficial to maintainability (Kapser and Godfrey, 2006). Novice programmers have been shown to make far fewer errors using transactions rather than explicit locking in concurrent programs, despite a slightly harder-looking learning curve (Rossbach et al., 2010). Excel shows that users are capable of using understandable references and mathematics. They also understand multi-parameter functions, although less readily than single-parameter mathematical ones. Users understand operations on collections more readily than manual iteration, and they understand and explain the operation of systems in terms of responding to events.

In order to be successful, programming languages for end-users need to take this understanding of users' capabilities into account. In particular, they should have tools and structures for data modelling that end-users can understand, semantics for side effects that prevent common errors but are still easy to comprehend, and integrate these features within a useful domain.

The ultimate goal of this thesis is to suggest better ways to create end-user programming environments. It does this by suggesting better paradigms and interfaces for end-user programming, and new techniques for type inference that are useful for end-user programming.

The rest of this dissertation proceeds as follows. Chapter 2 reviews the relevant literature on end-user programming. We discuss state of the art techniques for end-user programming, both in terms of techniques for end-users and evaluation techniques for researchers. We explain how the web acts as an unusual platform, but a potentially useful one for end-user programming. We classify the execution models of a variety of programming languages and identify an area of interest where there are currently few

good languages. We describe how data structuring and modelling has been done by end-users, and review techniques for aiding users in this. Finally we investigate the current state of the art in end-user web-based database programming.

Chapter 3 describes a new programming paradigm and compares it extensively to existing ones. The execution model that it provides is particularly suited to end-user programming and fits within the niche identified in Section 2.8. The types and semantics of our paradigm are explained in detail and we provide proof sketches of important properties. We show how concurrency can also be naturally supported by this paradigm and how it compares with other language paradigms.

Chapter 4 details and evaluates our web-based end-user programming environment. We evaluate it using example applications, a small-scale user study, and a comparison to existing tools within the cognitive dimensions of notations framework.

Chapter 5 discusses a novel algorithm for type and model inference for end-user data. We explain the algorithm in terms of the principles it uses before describing optimisations needed to acheive reasonable performance. We use a Bayesian technique to evaluate models which we show is both more principled and more configurable than existing approaches. Generated data is used to show the effectiveness of the algorithm. We conclude by describing how this algorithm could be integrated with our programming environment to give users a more natural view of their data.

Chapter 6 concludes this dissertation, and describes some avenues of further work.

The key contributions of this thesis are as follows:

- A new programming paradigm that is particularly suited to end-user programming. This paradigm is rooted in research into end-user and novice programmers. It also provides a straightforward approach to concurrency, particularly in web-based systems.

- A programming environment designed for end-user web database programming. Whilst the environment is not complete, early indications suggest it is a good basis for end-user programming and improves on the state of the art.

- A new algorithm for inferring types in semi-structured data. This algorithm is particularly suited to the kinds of data produced by end-users. We also discuss how this algorithm could be integrated with an end-user programming environment to make the learning curve significantly more shallow.

Chapter 2

Technical Background and Literature Review

> "Those who cannot remember the past are condemned to repeat it."
>
> *The Life of Reason, Volume I*
> George Santayana (1905)

End-user programming allows non-specialist users to create programs that can automatically process and act on their data. A system for end-user programmers must be useful, so it can be used to solve problems the user has, and usable, so it can be used by the user to solve those problems. Arguably the most successful end-user programming system has been Excel, which has demonstrated that non-specialists can do complex data processing.

In order to evaluate end-user programming tools, we need to consider more than just the programming language syntax and semantics. Research has shown that the environment in which programs are read, written, tested and debugged is just as important (Green and Petre, 1996). Many alternatives to the pure text of standard programming languages and environments have been evaluated for use by end-user programmers. One important area of success has been in reducing the burden of syntax on end users through visual environments, and in helping them create programs they and others can comprehend more easily. We discuss some of the key features of useful end-user programming environments and look at the cognitive dimensions of notations framework which gives a basis for comparing notations within these environments. Overall, useful and usable end-user programming languages are rare, but possible. Successful ones have typically been focused around environments with live data and a strong, concrete explanatory metaphor. As we identify in Section 2.3, users think in terms of events (if this happens then this should follow) and collections (the total is the sum of product prices times order quantities), and this is reflected in these successful languages.

The web provides a powerful platform for end-user programmers to share their programs with others. As a platform for client-server applications, it has a number of unusual properties: heterogeneous client capabilities, a continuation-based evaluation strategy, distributed concurrency and the need to scale to millions of clients. Libraries and programming languages have been developed to handle the complexities of the web execution model and have co-evolved with the web. In particular, there have been repeating phases of simple scripting-based approaches and more complex, statically-typed systems. Research and practice has often focused on integrating or eliminating databases and hiding the complexity of the web platform in order to reduce the problem of impedance mismatch. Several attempts have been made at creating an end-user language for the web, but none of these have proven to be sufficiently useful and usable. These have fallen into four main categories: customisable tools for data collection and processing, which are generally useful but can never scale down to a particular user's precise needs; mashup and automation tools, which can improve other programs but do not allow users to store or process their own data; web databases, which provide useful ways to store and report on data, but are not programmable enough to flexibly automate users' processes; and finally end-user programming tools that combine data storage and reporting with processing, which are useful. However, many of these end-user tools fall down by making their processing functionality too complex and their data structuring too weak. We address these problems in this dissertation.

Excel has proven to be the most popular end-user programming language, but its paradigm is too weak for general programming. Paradigms for programming languages can be categorised according to the three dimensions of concurrency, interactivity and Turing-completeness. Few languages have focused on the area of concurrent interactivity. This work suggests a paradigm for languages in this area which is better for end-user web programming.

End-user programming environments have also often overlooked the area of data storage and persistence. End users need guiding in creating suitable data abstractions but few programming environments aid this. Relational and other approaches are too complex and counter-intuitive for end users. Users often generate data that is called semi-structured since it has some structure, but is not necessarily uniformly or well typed. A system that could adapt to such data would be more suitable for end users. However, it is difficult to design languages to handle this data because there are no general and well-founded techniques for data type inference on semi-structured data. We discuss various approaches that have been taken to this area in Section 2.10, and show how a combination of statistical techniques for automated schema matching and ad-hoc methods for type inference could be combined in Chapter 5.

2.1 What is end-user programming?

End-user programming allows non-specialist computer users to create automatic processes for their data without necessarily using or understanding general purpose programming languages. They may write computer programs occasionally or often, but are not primarily engaged in programming. End-user programmers are typically solving complex problems in a domain where they have specialised knowledge. Some examples of end-user programmers are financial analysts using Excel, administrators creating databases to manage organisation information, and graphic designers using macro tools for repetitive image processing and effects. Many other examples of end-user programmers are given by Ko et al. (Ko et al., 2011).

End-user programming also includes cases where a user has less specialised domain knowledge. For example, consider the owner of a restaurant who wants to create an online booking system for their regular customers. They have no particular domain knowledge about booking systems, only the requirements of their restaurant and some ideas about the requirements of their customers. As in this case, often end-user programmers will have other users utilise their software, so they will need to use software engineering techniques for ensuring accuracy and reliability. We discuss some of these techniques further below.

End-user programming is an important area of computer science since there are many more end-user programmers than professional programmers (Myers et al., 2006). End-user programming is necessary where experts have domain knowledge but need to do more computation or organisation of data than can be done manually. Thus, end-user programmers need to use computers to achieve their main goals. However, current tools for end-user programming are lacking. For example, about 95% of real-world Excel spreadsheets have been found to contain errors (Powell et al., 2009). This clearly highlights the need for better tools for creating end-user programs.

In addition to areas where computers are necessary, there are also many data collection and processing tasks that are done manually because they are too small to merit a programmer and the end user does not have suitable tools to automate them. Excel is very good for off-line financial calculations; however, there is a need for more end-user programming tools that suit other problem domains. This dissertation aims to explore ways of filling part of that gap.

2.2 Programming languages and environments

When considering how software is written, it is important to give as much consideration to the environment the user works within as the language in which their programs are written. This distinction between notation (the language) and environment (the tools used to manipulate the language) was first made by Green (Green, 1989). As a well-known example, the experience of writing Java in a modern IDE with auto-completion

and refactoring tools is quite different to writing Java on a line-editor. An environment gives the user additional powers to discover information. For example, an environment can aid navigation by showing a list of subclasses. An environment can also allow the user to make conceptual changes that cannot be done in a single step at the source-code level, such as automatically updating all the callers of a function after the user reorders the definition of its arguments.

In order to consider environments and their properties, it is necessary to make a distinction between what is part of the language and what belongs to the environment. Obviously the syntax of the language is part of the language, although environments may also provide views of programs in other languages, e.g. an automatically-generated UML class diagram. The syntax can be further divided into the *primary notation*, which affects the semantics of the program; and the *secondary notation*, which does not affect the semantics. Secondary notation encompasses things like whitespace, comments, and the exact choice of variable and function names (since anything beyond enumeration conveys information to the programmer but does not change the semantics).

The semantics are generally part of the language, although the environment may have an effect on them. For example, setting a breakpoint in a debugger can affect the semantics of the program if execution is then terminated or values in the running program are changed.

The libraries of a language can be considered as part of the notation where they are built-in or where the programmer is expected to be familiar with them, otherwise they fall outside this classification and become part of the program itself. Similarly, features external to the notation, for example, data storage, I/O or GUI toolkits, can be considered as libraries. Accessing these features may also require the programmer to understand an additional notation and environment accessed through an interface or via a library. This is most clearly illustrated by the use of SQL to communicate with a database within a program – a separate notation and environment with a simple library in-between.

The environment is what the programmer uses to interact with the notation. Statically, this includes any editing and browsing functionality. When a program is run, this can also occur in the environment, for example using a debugger. Additionally, some programming languages do not distinguish edit-time and run-time, meaning the program is always *live* inside the environment, for example in Excel. Tanimoto describes four levels of liveness in an environment (Tanimoto, 1990): 1. informative, 2. runnable, 3. edit-triggered updating and 4. stream-driven updating. In Tanimoto's classification, only level 4 environments, which respond to external changes, are considered live. In our example, Excel does not generally allow access to external changes, so it is a level 3 language by Tanimoto's classification. However, since Tanimoto made his classification, environments at level 3 have also begun to be considered as live, especially compared to the level 2 code/execute cycle of standard programming languages.

Programming environments vary widely in their complexity and abilities. A programming environment may vary from a command-editor coupled with a compiler to an

advanced IDE with many refactoring and navigation tools like Eclipse (Eclipse, 2004). We also consider tools like read-eval-print-loops (*REPL*s) and Excel to be programming environments. Finally, the user interface of many advanced programs may be an environment for the configuration or use of that program, e.g. Wordpress or Photoshop.

2.3 Designing environments for end-user programmers

End-user programming environments often use notation that is very dissimilar to the standard textual notations used in professional programming languages. Many of these notations are visual in nature, typically consisting of diagrams and often using shape, colour, position and style to represent meaning. These notations also often support more intricate secondary notation. One of the problems with this more varied notation is that, while diagrams drawn by experts may appear more understandable, novices' diagrams are often confusing and lack consistency (Petre, 1995). This consistency can also be a problem in textual programming languages: correctly formatting programs is frustrating for novice programmers. However, good formatting, particularly correct indentation, increases the comprehension of novices and experts alike (Pane and Myers, 1996, Section 6-3). This justifies Python's use of significant whitespace, since it forces novices to indent code correctly by giving semantic meaning to the layout (Python, 2012, Section 2.1.8).

These alternative notations and environments are popular for end-user programming for several reasons. Firstly, they help avoid the problem of syntax. A visit to an introductory programming class will demonstrate that writing even syntactically correct programs in a professional programming language is difficult and frustrating for novices who wish to become computer scientists. Various environments have been proposed that make textual syntax less challenging, for example, structured editors (Ko and Myers, 2006). Diagrams are inherently structured, and so gain some of the advantages of structured editors in bypassing syntax. Additionally, because diagrams are designed to be edited visually, some of the problems of structured text editing (e.g. inability to perform large-scale edits or to represent partial changes) are avoided.

A larger problem solved by visual environments is helping users to understand their code better. Ko et al. identify six barriers to end-user programming, including problems with choosing and using primitives and with understanding the operation of their program (Ko et al., 2004). Visual environments present possibilities for suggesting and demonstrating primitives to users, which helps with several of the barriers mentioned. Additionally, as debuggers help professional programmers to understand bugs in their programs, environments where a user can observe and understand the operation of their program are also useful for end-user programmers.

Finally, recognising that programs do not need to be written in code opens the door to possibilities such as programming-by-demonstration (Cypher, 1993) and programming-

by-example (Halbert, 1984). Edwards suggests a technique for professional programmers to convert examples into permanent unit tests (Edwards, 2004) – there is no reason similar techniques could not be used to aid end-user programmers in testing their programs.

For these reasons, visual languages and environments are still the primary technique for end-user programming: they balance the ability to express complexity with concreteness and direct manipulation. However, there are several problems with visual environments.

The most obvious problem with visual languages is *scaling*, that is, representing and editing large programs. Burnett et al. identify several problems in scaling visual languages (Burnett et al., 1995): 1. using screen real estate efficiently; 2. navigating within programs; 3. providing a static representation of programs; 4. inserting documentation; 5. making procedural abstraction comprehensible; 6. event handling; 7. type checking; 8. persistence; and 9. efficiency. Good solutions have been found to some of these problems. In particular, efficient screen updating and execution are no longer a problem; type checking using unification and inference with symbolic representations of different types is well understood and accepted; cognitive dimensions of notations and the attention investment model have provided tools for designing and evaluating abstractions; inline documentation is now simple and common; and visual languages using flow-chart-like syntaxes to represent programs have solved the problem of static representation since pure programming-by-demonstration systems have largely been abandoned.

The problems of making effective use of screen real estate and allowing the user to navigate effectively cannot be solved generally, but a variety of techniques have been developed to mitigate them. Visual languages targeted at end-users tend to suffer less from real estate problems since the programs written in them tend to be simple and therefore short. Visual languages also tend to group parts of programs together, for example, showing all of the events associated with a particular entity, providing a mechanism for showing related parts of the program at the same time without having to show the entirety.

We discuss the remaining issues of event handling and persistence below and further in Chapters 3 and 5 respectively.

Pane makes several suggestions for better programming languages for children (Myers et al., 2004). These suggestions are based on studies of children and adults and therefore apply generally to end-user programming. The studies asked participants to carefully describe the solution to programming tasks on paper in whatever way they wanted. These tasks were focused around the game of PacMan. The following observations seem especially relevant to end-user programming languages: operations were often described as happening in response to events (as in, "When PacMan loses all his lives, it's game over"); and operations were aggregated over sets of items without explicitly describing iterating over the items (for example, "Move everyone below the 5th place down by one.")

Petre et al. identify a small but significant problem: it can be impossible to take a version to bed, both figuratively and literally. Often programmers prefer to move away from the computer and into an environment where more ponderous, abstract thought is encouraged (Petre et al., 1996). This links to the need for a static representation of

programs that could, for example, be printed out for this purpose.

Green and Petre use analysis based on the cognitive dimensions of notations to evaluate the usability of visual programming environments (Green and Petre, 1996). Cognitive dimensions of notations (CDNs) are a set of somewhat orthogonal measures of properties of programming languages, for example, the *abstraction gradient* (ability and extent to which program can be encapsulated) or the *viscosity* (amount of effort needed to make a change to a program). Because the dimensions are not fully orthogonal, a change to improve an environment in one dimension may impair usability in other dimensions. For example, adding the ability to make functional abstractions might lead to an improvement in usability from the point of view of the abstraction gradient, but increases the number of *hidden dependencies*. It is obvious that every notation inevitably has trade-offs. CDNs can be used to map the design of a programming language or to evaluate an existing design in order to understand these trade-offs.

McIver and Conway identify several problems in the design of introductory programming languages (McIver and Conway, 1996). Since end-user programmers are often using languages designed for introductory programmers, and have a similar novice skill level, much of the same analysis applies. In particular, the principles of differentiating semantics with syntax; providing a small set of orthogonal features; meeting the expectations of the user; and providing good error diagnosis also apply to end-user programming languages.

2.4 Prior end-user programming languages

Few end-user programming languages have been successful, either by being widely-used, sold commercially, or found to be effective in extensive user testing. Languages that have been successful have had several features in common. All successful languages have combined some symbolic code with a visual or graphical interface. Most of them have had a live environment where changes take immediate effect. Each of the languages is specialised to a concrete domain with a strong metaphorical or actual link to the real world, or an application the user is already familiar with.

Basic was for a while perhaps the mostly widely known programming language. However, as an end-user programming language it was weakened by a lack of libraries and interfaces that would provide the user with an framework for creating useful applications.

Logo was widely used to teach programming in the '90s. It had a strong metaphor and a simple progression of abilities, but lacked the ability to do useful tasks. This lack of useful abilities meant it did not drive users towards learning more about how to use it.

Excel is the most popular end-user programming language (Scaffidi et al., 2005). Excel provides a concrete view of tabular data and makes it easy to incrementally improve and augment a program in a live environment. Excel has a variety of built-in types and functions that are particularly focused on financial modelling, and so it is not surprising that this is the primary use of Excel. However, Excel is general enough to be used as a

database for a wide variety of problem domains.

Hypercard, whilst now defunct, was extremely popular during the early '90s (Apple, 1998). Its card metaphor for record keeping was instantly understandable and it allowed the user to progressively learn the associated HyperTalk programming language.

Microsoft's integration of Basic with its office productivity applications to create Visual Basic for Applications (VBA) was quite successful and as well as enabling professional programmers to integrate with Office, it also enabled end-user programmers to create programs that worked with their data. VBA also had a programming-by-demonstration facility which enabled programmers to record actions carried out in the normal way and then repeat them. This was very powerful because recorded macros were converted into VBA code which could then be further viewed and edited by the programmer. This teaching tool narrowed the gap between demonstrating actions and writing code, and made VBA's programming-by-demonstration facility more interesting and useful than many others.

There are several languages for scientists and engineers who are not primarily programmers. Prograph and Labview use a circuit diagram metaphor which is familiar to electrical engineers and they are primarily aimed at building simulations of physical circuits and hardware (Matwin and Pietrzykowski, 1985; National Instruments, 2012). Labview can also integrate with physical hardware interfaces, further cementing the metaphor.

In contrast, Matlab is more like a traditional programming language, but is specialised towards mathematicians and scientists with features like matrices, advanced mathematical functions and graphing libraries built-in (MathWorks, 2012). Matlab is typically used in a REPL, and used in this fashion it is familiar to mathematicians, who are used to writing out sequences of equations and then solving them and potentially plotting the results.

Programming environments for novice programmers are extensively surveyed by Kelleher and Pausch (Kelleher and Pausch, 2005). Given the cross-over between end-user and novice programming, we review the most relevant environments here.

The Fabrik environment (Ingalls et al., 1988) allowed end users to create user interfaces and wire up components of those interfaces with dataflow connections. Primitives were provided for ordinary graphical user interfaces such as buttons and text boxes as well as for drawing graphics. No symbolic code was used; instead users join together blocks that produce and consume data.

Forms/3 (Burnett et al., 2001a) is a spreadsheet-based system that adds functional abstraction and concept of time to create a full programming language. Functional abstraction allows regions of spreadsheets to share a single formula which can include terms dependent on the location of each cell. This is equivalent to structured-grid computation. Forms/3 uses a discrete global time to turn each value in the program into a stream of values, as is done in Lucid (Wadge and Ashcroft, 1985). This use of time makes Forms/3 Turing-complete.

Scratch (Maloney et al., 2010) is an end-user programming environment designed for children to create animated stories and interactive games. Scratch uses a visual program-

ming environment made up of different types of jigsaw-like blocks which fit together in specific ways which correspond to correctly-typed programs. Execution is event-driven, enabling complex behaviours to be sequenced.

We discuss end-user programming environments for web applications later in Section 2.7 after we have described the web platform and the challenges it presents.

2.5 Web execution model

The web was originally conceived by Berners-Lee as a platform for scientists to share and discuss data and results (Berners-Lee, 1989). From this simple beginning the web has become the dominant platform for distributed programs. The web is made up of two components: the hypertext transfer protocol (HTTP) and the hypertext markup language (HTML). We describe the current usage and extensions to these technologies, before discussing some of the challenges and benefits of using the web as a platform for distributed programs.

The web is built on a fairly simple, stateless client-server protocol, HTTP (Berners-Lee et al., 1996; Fielding et al., 1999). Servers respond to requests made up of four parts: a *method*, a *URL*, zero or more *headers* and an optional *payload*. The method is the type of request being made of the server. Typical methods are `GET`, which retrieves data from the server, and `POST`, which sends data to the server. Various other methods exist, such as `PUT`, `DELETE` and `HEAD`, but these are rarely used and are unnecessary for web applications, although the REpresentational State Transfer (REST) technique of Fielding makes use of them (Fielding, 2000). The URL (Uniform Resource Locator) names the particular document or piece of information to be retrieved or sent to the server (Berners-Lee et al., 1994). The headers may be used for things like negotiating the form of response, informing the server about the client's capabilities and to affect caching behaviours. The payload may be used to send data from the client to the server in conjunction with the `POST` method.

The server responds with a *status*, similar optional headers and a payload. The status indicates the result of the client operation on the server. Various status codes are defined by the HTTP standard, for example, `200` for success, `404` for "resource not found" and `500` for internal error. HTTP also defines a range of status codes (such as `303` for "See other") which can direct the client to make another request suggested by the server. This process is called redirection. The payload from the server is typically an HTML document or a resource such as an image that was included in such a document.

Originally, HTML was a simple document formatting language, with the added ability to create hyperlinks – pieces of text that, when selected by the user, caused the client to request and display a new document from a server. A *browser* is an HTTP client that can render HTML for the user.

In practice, and as a standard, HTML has evolved extensively over time. For our

purposes, the most significant addition to HTML was the ability to create forms, which allowed users of a web site to submit information to the server using the `POST` method described above. Web application user interfaces are built from these form controls. Two other additions to HTTP and HTML make it more amenable to creating fully-featured applications: cookies and AJAX.

Since HTTP is stateless, headers are used to communicate client identity and state between the client and server in the `Cookie` and `Set-Cookie` headers (Kristol and Montulli, 1997). *Cookies* are short pieces of data and are typically used as a nonce to identify the client to the server. The server is responsible for storing any state information about the client between requests if that information needs to be kept secret or not editable by the client. For example, rather than storing the currently logged-in user's credentials in a cookie, which could be subverted by the client, credentials are stored on the server, and the cookie merely stores a handle to them. On the other hand, preference information, for example user interface settings, need not be secured and can be kept in a cookie and stored directly on the client. Cookies can be temporary or have a lifespan, allowing credentials and preferences to be preserved on the user's machine.

For some time, HTML has embedded the programming language Javascript, which could initially be used for simple tasks such as form validation. More recently, scripts can be embedded into HTML which can manipulate what is displayed to the user (dynamic HTML) and scripts have been given the ability to communicate with servers through asynchronous XML messages (asynchronous Javascript and XML (AJAX)). These techniques make much more dynamic web applications possible, e.g. updating a report based on data entered by the users without a round-trip to the server or adding rows to a table dynamically using new data received from the server.

HTML5 is a new version of HTML which incorporates many new powerful features such as client-to-client communication, client databases and location-awareness. However, no browsers yet support all of these. Browser vendors have continually competed over features and frequently introduced new ones without standardisation. This, coupled with the fact that users may be running any version of any browser, means that web applications need to be written to support heterogeneous clients with potentially wildly varying capabilities.

The combination of URLs and stateless clients, combined with client features such as bookmarking (storing a URL for future retrieval), has created an overall system where the server does not and cannot know the exact state of the client. This situation was first described by Queinnec, who identified browsers as consumers of continuations (Queinnec, 2000) and characterised by Graunke and Krishnamurthi, who identified three properties of the web that differed from traditional user interfaces: back and forward buttons, cloning windows, and bookmarking (Graunke and Krishnamurthi, 2002). Both of these papers suggest continuation-based solutions, but they do not address the problem of actually implementing a continuation-based approach in a programming language without native continuations, and they do not handle global session state effectively. For example, if

a user opens multiple windows on a shopping site, these windows should share a single shopping basket.

With my supervisor, I showed how HTTP and HTML could be improved to support web applications with these properties more naturally, and how these properties could be handled at the server level without needing continuations, in an earlier paper (Message and Mycroft, 2008). Overall, whatever technique is used, any language or environment for creating web applications needs to provide support for handling the unusual UI capabilities of browsers, in particular unexpected navigation and window duplication.

Because of the possibility of window duplication, coupled with the multi-user nature of the web, and the possibility of a session being abandoned without the user logging out, concurrency is also a tricky problem for web applications. In order to support concurrency, it should be safe for multiple users to use the same part of an application at the same time. However, actions taken by the users may conflict, and the users cannot be aware of the conflict. For example, suppose two users, Alice and Bob, load the editing screen of the same Wikipedia article. What should be done if Alice adds a sentence at the beginning of the article and clicks save, but before her save is processed Bob has also edited the article? We could have locked the article when Bob first requested it for editing. This would have prevented Alice attempting to make a concurrent modification. However, this is not practical on the web since Bob may abandon a web application at any point, without the server being notified. One solution is to add a time-limit to Bob's lock on the document. This style is used in web applications with hard reservation requirements, for example, a flight reservation which is held until Bob has paid, or a time limit expires.

This reservation mechanism is too heavy-handed for typical web application, especially if edits often do not overlap, or if it is difficult or impossible to measure the scope of an edit before it has been made. In most cases, an optimistic form of concurrency control (OCC), as suggested by Kung and Robinson, is preferable (Kung and Robinson, 1981). In OCC, instead of holding locks on data items that have been viewed in a transaction, a transaction instead simply records when the transaction began and which data items are retrieved. Writes to the database are stored in a per-transaction shadow copy so that they do not interfere with other transactions until they are committed. When a transaction comes to commit, it is checked against all the transactions that committed after it began. If a committed transaction has interfered with state that the current transaction depends upon, or their writes overlap, the current transaction is aborted and retried. In this way, long-running transactions can be supported with low overheads by deferring checking isolation until commit time. This is also useful if many transactions are abandoned, since the overhead of checking isolation is completely avoided in that case. In any case, whatever concurrency technique is used, it is necessary for web applications to support concurrent, long-running transactions.

Web applications also need to scale to a large number of clients. In general, it is impossible to guarantee being able to handle all clients on one machine, and the demands of high uptime and low latency generally require that multiple, distributed servers are

available. This makes handling state shared between processes difficult. In general, web applications are split into three tiers to help mitigate this: a fast, stateless front-end which handles requests for static resources and load-balances other requests; a layer of stateless application servers that do the processing required by the application; and a distributed database where all state is stored. This strategy and variations of it are used for most web applications. Because of this, any web programming language needs to support a distributed database and generally stateless operation in order to be scalable.

Overall, the web is a useful platform for client-server applications, but has some awkward properties which web programming must address: heterogeneous clients, a continuation-based evaluation, distributed concurrency and high scalability.

2.6 Web programming languages

Programming languages and libraries have evolved over time to handle the complexities of the web execution model. Early web applications were written in general purpose languages, such as C, and used the simple CGI protocol to accept HTTP requests and return HTTP responses (Robinson and Coar, 2004).

Since C and other systems languages are not ideal for the kind of string handling needed for web applications, scripting languages such as Perl quickly became popular for creating web applications. Most famously, the PHP and Coldfusion languages were created specifically for web applications and had syntaxes that combined HTML and code. The overheads of the CGI protocol (particularly for interpreted languages with a large startup time) meant that various other methods to connect programs to HTTP were devised, primarily integrating scripting language run-times with web servers.

The Java Enterprise Edition (JEE) was released at this point in history in 1999 and integrated a Java run-time with a web server, as well as a variety of mechanisms for state management. JEE was one of the first realistic attempts at creating a system that would make it possible to write web applications that were inherently scalable. However, this meant that JEE was excessively complex for small and medium sized applications, and this led to a commercial backlash against it, although it is still used by some large systems.

None of these systems attacked the problem of unexpected navigation in browsers, and this is where some early research already mentioned on web applications as continuation-based systems took place (Queinnec, 2000; Graunke and Krishnamurthi, 2002). However, these new continuation-based systems were unsuitable for use with existing programming languages.

At this point, powerful and flexible frameworks for web applications began appearing. Frameworks are libraries that also control how the program interacts with external systems. Most web frameworks were based on the Model-View-Controller design (Reenskaug, 1979). These frameworks mostly addressed the problems of handling heterogeneous clients

and allowed programs to be written with more structure than previously. Perhaps the most famous of these are Struts (Apache, 2007) and Ruby on Rails (Hansson et al., 2004), both of which focused on convenience and convention over the perceived complexity of solutions like JEE.

Academic research then focused on producing languages which combined web programming into one consistent language. The Links (Cooper et al., 2006) system integrated client-side code running in the browser, server-side HTTP handling code and code that compiled into SQL for communicating with databases into one language. Links also supported concurrent message passing and stored state on the client, which helps with both the problem of unusual browser navigation as well as handling concurrent clients.

JWIG (Christensen et al., 2003) and its predecessor `<bigwig>` (Møller, 2001) focused on ensuring the HTML output was free of errors and that form elements in HTML matched up with data reads in the server on the data POSTed back to it.

The Hop (Serrano et al., 2006) system provided a dialect of Lisp that separates the user interface and the application logic of the program so that each can be run on the client and server respectively.

These special languages provided a variety of interesting analyses, static checks and features for custom web programming. However, they were often tied to relatively weak research run-times or clunky source translation systems. Further research into programming languages for web applications has tended to focus on doing similar things to these special languages but using the type systems of advanced research programming languages, such as Haskell (Thiemann, 2005), Curry (Hanus, 2006) and Ur (Chlipala, 2010). These systems have focused on using advanced type system features to ensure the safe construction of HTML and to checking the connection between forms and programs. None of these efforts have been helpful for improving end-user programming.

2.7 End-user web programming languages

Several attempts have been made at creating an end-user language for the web. These fall into various categories which we enumerate below. We only consider languages in the final category as useful end-user programming languages for web applications. Systems in the other categories lack the ability either to create customised user interfaces, to store data, or to carry out side effects in response to input.

Customisable applications Programs like Automattic's WordPress and Microsoft's Frontpage enable end-users to create static sites or sites with predefined functionality. Although these systems provide a great number and variety of features, as well as allowing users to connect together various plug-in modules offering a variety of functionality, ultimately they do not enable users to structure data or do customised processing, i.e.

programming. We also include form creation tools such as Google Docs and formsite (a web app for creating surveys and reporting on the results) in this category.

Mash-ups and automation tools Other research and commercial tools have been developed to allow end-users to create so called "mash-ups", combinations of the data or functionality of existing web applications.

Mash-up creation tools include Yahoo Pipes, Intel Mash Maker, JDA, WIPER, Needlebase and Marmite (Yahoo!, 2007; Ennals et al., 2007; Lim and Lucas, 2006; Lim et al., 2007; Wong and Hong, 2007).

Yahoo Pipes provides a data flow programming language for combining web data sources, but has no functionality to allow the end-user to receive and store input (Yahoo!, 2007). There is also no way to build a user interface.

Intel Mash Maker provides a toolbar for automatically integrating data sources, for example allowing leg room information to be displayed on a flight booking web site (Ennals et al., 2007). It has no way of storing or processing data that belongs to the user.

The JDA system allows end-users to reuse parts of Javascript from around the web to build applications (Lim and Lucas, 2006). However, large questions of usability remain and it is not clear how much users will actually be able to build mash-ups using JDA.

WIPER allows users to combine existing data sources and Javascript components within a visual programming environment (Lim et al., 2007). As with other mash-up tools, the inability to store data or co-ordinate side effects makes it unsuitable for creating web applications.

Needlebase is similar to Intel Mash Maker in that it can be used to scrape and extract data from web sites (ITA, 2010). It can also merge data from multiple sources and enables users to create customised reports.

Marmite is an end-user programming environment that enables users to combine existing web applications using a simple data flow language (Wong and Hong, 2007). It does not store data but enables the combination of data sources and the display of information in different formats.

Various tools exist for allowing end users to automate web applications and services. The Koala/coScripter and Chickenfoot systems allow users to script interactions within web applications. IfThisThenThat and TarPipe allow users to script interactions between web applications, generally through services those applications provide.

Koala (later coScripter) uses pseudo-natural-language programming to allow the user to specify actions to occur within applications (Little et al., 2007; Leshed et al., 2008). The Chickenfoot environment contains a simple programming language with heuristics for extracting the names of form fields and other elements of web applications in order to aid the user in scripting them (Bolin et al., 2005).

A system called, aptly enough, IfThisThenThat allows end-users to trigger side effects on web applications based on actions from other applications (Tibbets and Tane,

2011). IfThisThenThat is not a full programming language, but suggestive of the sort of combination of triggers and actions this thesis discusses later.

TarPipe is a system that functions similarly to IfThisThenThat but casts actions as data flow between components rather than control flow (Pedro and Rodrigues, 2008). It is primarily aimed at publishing workflows, for example so that a twitter feed announces new blog entries.

We do not consider these mash-up and automation tools further as they either do not provide mechanisms for creating data or do not allow the user to specify actions to carry out in response to data being entered, and thus do not fit our definition of a web programming language.

Web databases Various research and commercial projects have put database systems similar to Microsoft Access onto the web. These tools are characterised by their ability to capture, store and report on data, but they lack the ability to do complex processing or carry out side effects based on the data.

The FAR project by Burnett et al. was a WYSIWYG database reporting tool designed for creating e-commerce websites (Burnett et al., 2001b). FAR made advanced reporting possible, but did not have a way to capture input or process it.

iFreeTools and appnowgo allow users to create database tables, forms and reports (Sahasvat, 2009; appnowgo, 2010).

Ragic builder is a tool for building database applications (Ragic, 2008). The user interface of reports and forms can be customised extensively, although the actual behaviour of the application is limited to standard create, update and delete actions (CRUD). Ragic allows editing of data through a spreadsheet-like interface, including drill-down into linked data.

AppRabbit has similar abilities to these tools. Additionally, it can automatically turn spreadsheets into databases with relationships (AppRabbit, 2010).

DabbleDB provided a powerful interface for managing the relationships between tables within a database and enabled the user to semi-automatically normalise their data (Smallthought Systems, 2007). Since its development was discontinued, it is difficult to say whether useful applications could be developed with it, but the data management tools alone were powerful. We discuss automatic structuring of data further in Section 2.10 and Chapter 5.

End-user programming environments Having discussed these other types of tool, we now consider the main existing tools for end-user programming in detail. The tools we discuss below, and the system we describe in Chapter 4, combine aspects of the categories above: allowing both data storage and customisable manipulation. There are two academic research projects that have produced usable web application environments, app2you and WebRB. We will consider these before reviewing the commercial systems in this area.

app2you Provides a very straightforward interface for creating certain types of applications (Kowalczykowski et al., 2009). In particular, app2you provides constructs for simple form creation and storing the corresponding forms in tables. It also provides very strong constructs for workflow management, but no general ability to run arbitrary processing on data or to affect multiple tables with a single operation. Additionally, app2you does not provide fully-featured data processing tools like sorting and filtering. Because of these limitations, although app2you is very slick for certain applications, it is not applicable to a wide variety of programs. For example, it would not be possible to build something like an invoicing system with calculated discounts.

WebRB Leff and Rayfield describe a system which enables users to create web applications based on a relational database (Leff and Rayfield, 2007). Their visual programming system overlays programs on top of a WYSIWYG interface builder. This does not help the user to lay code out well and causes figurative spaghetti code. The relational model is not generally a good fit for end-users' mental models. The language supports side effects based on user actions, but there is no strong type system to ensure side effects occur safely. WebRB uses run-time restrictions on redirections and only permits a form to edit one table, which seems unnecessarily restrictive but stems from the weak computational model. The system lacks features for formatting or layout, which is important to users in creating useful applications, e.g. creating attractive reports.

Commercial tools Agility is a relational-database-based programming tool with support for customising workflows and a visual programming language for more complex applications (outsystems, 2008).

Longjump is an online relational database with support for workflows and actions (Relational Networks, 2007). More advanced applications require programming in Java to be supported.

openjacob is a database application builder with a dataflow slant, some visual programming tools for creating custom workflows and a relational database model (FreeGroup, 2006).

Tersus is a commercial visual environment for creating database-driven web applications (Brandes et al., 2007). It uses the visual paradigm for editing code and also uses representative UI components for layout. The environment requires installation which would discourage usage by the ordinary end-user and may not be possible in commercial contexts. The programming language, while graphical, is not designed for non-specialist programmers. For example, there are no restrictions on programs to ensure termination.

Zoho Creator is a full-featured web database application builder including supporting business processes, reporting and email (Zoho, 2006)

Each of these tools has a variety of similar features and some unique ones. They all have in common a relational database model and relatively complex visual programming languages. We discuss these areas further below and suggest new approaches to struc-

turing user data in Chapter 5 and to designing programming languages for end-users in Chapter 3. This thesis also contributes a new web programming language for end users that improves in these areas, which we detail in Chapter 4.

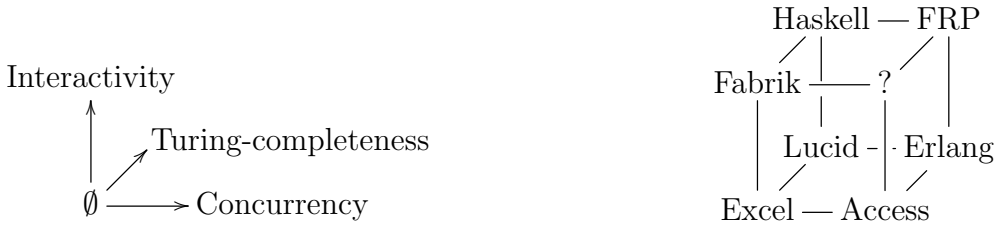
2.8 Programming language execution models

Excel is the most successful programming language for end-user programmers. According to Myers et al. (2006) there are many times as many end-user programmers as professionals, and according to Abraham and Erwig (2006) Excel is the most popular tool for end-user programming. The popularity of Excel can also be seen in its long pedigree, reaching back to VisiCalc in the '80s; the number of derivative tools, for example Open Office Calc, Gnumeric and Google Docs; and the lack of successful alternatives with different semantics or data models, despite over twenty years of investment and innovation in products like Access, Hypercard and DabbleDB. A conservative estimate would be that there are ten times as many end-user programmers using Excel on a day-to-day basis as there are professional programmers in all languages combined.

Computation in Excel is equivalent to computation in a pure data flow graph with no cycles. As such, Excel is quite limited in the programming tasks it can complete. Because of Excel's success with end users, and the wide variety of problems that can be modelled in Excel, visual data flow languages are the right starting point for any paradigm aimed at end-user programming.

There are three main areas where the semantics of the Excel programming paradigm can be extended: (1) the ability to handle control flow as well as data flow, in particular in creating a user interface to a program; (2) concurrent access to programs by more than one user; and (3) the language could be expanded to be Turing-complete. We refer to these directions as *interactivity*, *concurrency* and *Turing-completeness* respectively. These are not the only plausible set of dimensions but they are useful because they classify the majority of current programming paradigms and suggest an under-explored area for programming paradigms. We should note that since we started from a data flow language, not all programming languages fit well into this classification. In particular, most mainstream imperative languages contain mutable state which is not well-modelled by data flow.

These directions are orthogonal in that they can each be added separately or together to an Excel-like programming language. These dimensions are shown in Figure 2.1a. Using these dimensions, we can construct the diagram shown in Figure 2.1b which gives a representative language for each of the eight possible vertices. This diagram is similar to Barendregt's *lambda cube* (Barendregt, 1991). We believe that the interactivity and concurrency vertex would be the current sweet spot for an end-user programming language but there are no representative languages in this area, which we have therefore marked with '?'. We have already discussed Excel, so we will now look at the three primary



(a) Dimensions

(b) Representative languages

Figure 2.1: Cube of extensions to the data flow paradigm

vertices (with one dimension added), two of the secondaries (with two dimensions) and the single tertiary vertex (with all three extra dimensions.)

Lucid: Turing-completeness There are several approaches for making a data flow language Turing-complete. The most popular is to add history to each variable so data flow can depend on the current or past values of variables. Languages that implement this paradigm include Lucid and Forms/3 (Wadge and Ashcroft, 1985; Burnett et al., 2001a).

Access: Concurrency Adding concurrency to Excel leads to a system like Access, which also structures the data somewhat differently but is still essentially a data flow language (Microsoft, 2010a). With the same data model as Excel, Google Docs is also within the Excel+concurrency vertex. The other web-based database systems described in Section 2.7 also fit into this category.

Fabrik: Interactivity We give a firmer definition of interactivity, especially with respect to the distinction between data and control flow in Chapter 3. For now, interactivity refers to the ability to create a user interface that is separate from the program itself. A few projects have added just interactivity to a simple data flow language but Fabrik is representative of this category of languages[1] (Ingalls et al., 1988). The Scratch programming system also provides an interactive data flow-based programming language, although again full Scratch is Turing-complete (Maloney et al., 2010).

Haskell: Turing-completeness + Interactivity Adding programmable interactivity to a Turing-complete data flow language like Lucid gives us a language like Haskell, where pure functions are equivalent to Lucid-like data flow, and computation with the IO monad enables interactivity (Peyton Jones and Wadler, 1993). Most other programming languages are in this area, although, as already mentioned, the data flow element is not really present in imperative languages that are mutable-by-default, so they do not exactly fit into the categorisation anywhere.

[1]Fabrik provides interactivity based on a bidirectional data flow model that cannot do arbitrary computation. However, Fabrik provides constructs like looping that can be used to do arbitrary computation; we are ignoring those constructs here, since Fabrik is still interesting without them.

Erlang: Concurrency + Turing-completeness Moving a concurrent system to be Turing-complete without explicitly addressing interactivity gives us a system like Erlang (Armstrong, 2003). In Erlang, each process can be seen as a Turing-complete data flow program, and additionally the processes can communicate. Allowing Erlang processes to communicate with non-Erlang processes or networks or peripherals moves Erlang into the tertiary vertex which we address next.

FRP: Concurrency + Interactivity + Turing-completeness The tertiary vertex in the cube adds concurrency, interactivity and Turing-completeness to a data flow language. We believe the best characterisation of this vertex is functional reactive programming (FRP), first introduced by Elliott and Hudak (Elliott and Hudak, 1997). Cooper and Krishnamurthi give an account of how FRP can be seen as an extension of data flow (Cooper and Krishnamurthi, 2006). Functional reactive programming is based on data flow, but with the addition of time, which easily models interactivity and concurrency, and adds Turing-completeness through feedback and recursion[2].

?: Concurrency + Interactivity There are a few languages that could fit into the Excel+interactivity+concurrency vertex such as WebRB and app2you, as well as some of the commercial systems discussed at the end of Section 2.7. However, we do not believe any of these languages represents a general paradigm in the same way the other languages already discussed do. As there are no established paradigms in the interactive, concurrent, but not Turing-complete space, one of the contributions of this thesis is to create one. This new paradigm could describe these languages better. We could characterise this paradigm three different ways: FRP without completeness, Access with interactivity, or Fabrik with concurrency.

To expand on each of these, firstly we consider FRP. FRP is too powerful and complex for end-user programming. Turing-completeness is not necessary for the vast majority of programs. A useful paradigm for end-user programming should retain the power of FRP in the cases where it is needed to support concurrency and interactivity without the overall complexity.

Access lacks the ability to build interactive user interfaces because it is impossible to initiate or coordinate side effects since it is not a programming language on its own. Typically Visual Basic for Applications (VBA) is added to Access, but this suffers from an impedance mismatch between the imperative, single-threaded VBA program and the concurrent database. VBA is not a clean or sensible solution to making Access more powerful and is not suitable for non-technical end users. Instead, interactivity should be integrated within the environment of a system like Access and the notation for controlling interactivity should be part of the overall notation rather than a bolted-on extra.

[2]It is interesting to note how merely adding time and all that entails moves us to the opposite vertex of our cube.

Fabrik achieves the aims of simplicity and interactivity, but is unsuitable for end-user developers in the current era since it is not web-based and it is not clear how it could be expanded to support multiple simultaneous users. Fabrik is also incompatible with current desktop systems and tied to primitives which, while powerful, now appear far too simplistic and require excessive work in combining them. With a suitable concurrency model, a Fabrik-like language could easily be connected to a modern web interface.

We take up this thread again in Chapter 3 where we detail such a paradigm and show how it relates to those already discussed and how it is superior for end-user programming. We now move to the area of improving tools for structuring user data.

2.9 Data structures and storage

An end-user programming environment for managing and processing data must make persistent data part of the notation and the environment, and must help the user to structure their data. Persistent data must be part of the notation in order to avoid the impedance mismatch of having a separate notation for the persistent parts of the system from the non-persistent parts. The well-understood impedance-mismatch between SQL and ordinary programming languages is a typical manifestation of this (Ireland et al., 2009). Attempts to automatically map between programming languages and databases (Object-Relational Mapping) have been considered so incorrect as to be called "The Vietnam of Computer Science" (Neward, 2007) – a quagmire from which none can escape. A language designed for processing persistent data must contain that data within the notation. A good example of this is the Links project for web application development which includes data persistence within the language (Cooper et al., 2006).

As well as being part of the notation, persistent data also needs to be integrated into the programming environment. By putting persistent data in environments, users avoid the problem of versioning and maintaining separate data repositories from program repositories. If some of the data in a program is persisted automatically, it becomes necessary for the environment to manage that persistence. However, this automatic persistence also creates some problems, particularly in managing side effects. Environments that mix persistent data with purely declarative programs like Excel cannot represent programs with side effects. Adding history like Lucid makes modelling side effects possible but not convenient. The most natural approach to handling side effects with persistent data is probably the one taken by Scratch, where persistent data objects can be modified by operations with side effects. This then means we need to account for sequencing and serialisation of side effects, which we discuss further in Chapter 3.

Additionally, by integrating persistent data into environments, the environment can be made live as discussed above in Section 2.2. This requires significantly less effort for end-users to manage data, at the expense of making it harder to make explicit distinctions about data sources – for example, connecting to a development or production

database. We expect environments to have such advanced distinctions built in where they are necessary.

Finally, enabling users to manage and process their data requires that the user can specify the structure of their data. By this, we mean that if the user has a collection of facts, they must produce some kind of description of the type of facts they are collecting in order to enter them into a computer. Obviously, a user could just enter the facts as plain text (in fact, they could write them on paper) but unless they are structured in a way that makes sense to the machine, they cannot do any useful processing on the data. This then gives our definition of structured data: data that can be processed by the machine. Of course, we now need to define *processed*. By process we mean run computations, do calculations, summarize, classify, mail-merge, reformat or any other syntactic or semantic transform that is applicable to the domain of the data. Note that this definition of structuring is useful because it tells us how much structure needs to be applied to the data – enough to process it in the ways that the user might want to process it.

Most database systems require users to define the structure of the data before the data itself can be entered. This presents an additional problem for end-user programmers, who may not be equipped for this kind of abstract, computational thinking (Blackwell et al., 2008). It also causes a problem which we look at briefly later – what if the data is already structured in a way that is unsuitable for the process the user wishes to perform?

Most end-user data systems that have been successful have enabled users to enter data without first giving it a structure. For example, Excel does not require the creation of tables in order to input data in the way a database system does[3]. Wikis and PIMs with wiki-like semantics such as Popcorn (Davies et al., 2006) allow users to enter textual data without any specific structure. Wiki-like tools also enable users to connect data items together using hyperlinks, which we discuss further below. The Hypercard system allowed users to collect structured data without necessarily having a global design. Each of these tools allows users to evolve the structure of their data as more data is collected.

One final problem with this kind of unstructured data is that it does not tell the environment how to store *additional* data. For example, inserting a new row in a table in Excel may break formulas that are visually associated with that table but will now have the wrong bounds; or creating a number of different cards in Hypercard does not help the user to create a new card which is similar to one or more of the existing ones.

As an aside, there are also various database systems termed *NoSQL* which have reduced the amount of structure that needs to be entered up-front, but have not changed the overall table structure of the database. Since NoSQL systems are aimed more at scalability and the needs of developers rather than at reducing complexity for end-users,

[3]Whilst Excel does provide tools for formatting tables, these have no semantic meaning and represent the worst possible sort of secondary notation – namely where the secondary notation is the only part of the notation that is visible and the primary notation of the semantics is not actually visible at all. This is like using a block structured language where indentation is not significant but the tokens that define blocks are invisible unless the mouse is pointing at them.

they do not solve the problems users have with structuring data. Thus, despite the surface similarity in simplifying database schemas and allowing schemas to evolve, NoSQL systems are not a solution to the problems we are discussing.

Some user data systems give the user predefined or narrowly customisable data structures to put their data into. Address books, mail-merge tools and customisable forms are examples of this kind of data system. Unfortunately, such systems often cannot model the data the user actually has. Additionally, they are generally not designed for processing or combining data and so are not suitable for the purposes we are talking about. We will not discuss such specific solutions further.

Traditional relational databases have been available to end users for a long time, for example in the form of Microsoft Access (Microsoft, 2010a). These have not caught on for end users for three reasons. Firstly, as already noted, having to define the structure ahead of time can be a problem for users. Secondly, although tools like Access provide a view of relationships between tables, they do not actually aid users in creating and specifying those relationships, for example by allowing users to directly draw lines between tables or draw boxes of inclusion between entities to indicate their relationships. Tools like DabbleDB could be better in helping end-users to use the relational model but no such tool has yet made the mainstream or been tested scientifically with end users. This brings us to the final point: the relational model is hard. It pays off for users who understand it and can normalise their data, but otherwise there is no benefit to the relational model, and the downside is that it appears to naïve users to have the same functionality as Excel but with much less flexibility. As an informal example, end users are not likely to ever think of introducing an intermediate table to represent many-to-many relationships. A better data model is one priority for helping end users to structure their data, and one thing it should support is scaling relationships within the same framework – so one-to-one, one-to-many and many-to-many relationships can be created, accessed and refined in the same way.

The relational model is also a bad fit for some of the data users wish to store, in particular hierarchical data. A tree-structured model like XML provides a better structuring for hierarchical data at the expense of making it harder to normalise correctly. Because XML is tightly tree-structured, its expressiveness is limited for many-to-many relationships, which then require messy indirections and thus still require the user to understand the relational model.

Other models, such as those suggested by the semantic web movement aim to do processing on relationships between data. There are several data models such as RDF which emphasise the relationships between entities in the data system. However, none of these models is a particularly good fit for end-users either. RDF is more expressive than is necessary for the sort of data users create and is more focused on providing mechanisms to integrate many disparate but structured data sources.

As we noted above, often users have data before they have devised the structure of the data. As each piece of data is collected, it and the rest of the data must be made

to agree in format. Aiding this refactoring of existing data could be a profitable avenue for research. Sometimes this refactoring does not happen immediately, so there is a lot of data collected in arbitrary formats that do not match. For example, Wikipedia adds infoboxes (which contain tagged, machine readable information) to articles that already contain the same data in order to get that data into a consistent format. More directly, database-like wikis are being developed which may enable users to merge and combine data types as they go (Buneman et al., 2011). Again, automatic tools for aiding these kinds of refactorings would be a fruitful line of research, but is not something we consider further.

The sort of user data we are talking about is often referred to as *semi-structured*. Semi-structured data are like values in dynamically typed programming languages: each data item can be examined and given a type, but the type of data items cannot be determined statically. These types can also evolve, similarly to prototype-based or dynamic-record based object-orientated programming languages like Javascript or Ruby. We think it would be useful to provide approximate typings to this kind of semi-structured data, to aid the user in collecting, categorising and ultimately processing their data.

Unfortunately, there are no general and well-founded techniques for type inference in semi-structured data. Existing approaches for type inference are unsuitable for the kinds of structure end-users create. However, some of these approaches could be combined to inform a useful technique. We examine these approaches in the next section.

2.10 Data type inference

There are several existing approaches to inferring the types of data. Obviously, if the data is statically typed, inference like Hindley-Milner (Hindley, 1969; Milner, 1978) will give exact types. However, in the absence of static types this technique cannot work, so we need more flexible techniques for user data.

Ad-hoc techniques for type inference on semi-structured data have been suggested. For example, ad-hoc inference on spreadsheets (Cunha et al., 2010) has given useful results for the problem of inferring entity-relationship models from spreadsheets. Markov clustering on spreadsheet formulas can be used to group similar cells automatically (Kankuzi and Ayalew, 2008). Work has also been done on inferring the units used in spreadsheets (Abraham and Erwig, 2006) in order to reduce the errors resulting from incorrect combinations of units, but this work could also be used to help categorise data.

There has been a lot of work in converting between structured data representations. This work is not directly relevant to the inference we suggest in Chapter 5, but provides a background to some of the other work we use, so we will examine it in the following two sections.

View updating The obvious starting point is the extensively studied area of SQL view updating. In an SQL view update the type of the view is well defined and the data in a view is derived from other well-typed tables. The problem is then to translate updates in the view into the correct set of updates in the source tables. This problem has been solved for SQL, although it cannot work in all cases since there is often more than one possible update or insufficient information to do the update. The Lens work begun by Pierce gives a better way to express views that makes it possible to handle these cases of excessive or insufficient information systematically. Lenses are also more general than the SQL view update problem, and have been applied to text files (Foster et al., 2008), databases (Bohannon et al., 2006) and tree-structures (Foster et al., 2007).

Lenses and views use programmer-defined mappings to match data from one source to another. Systems have also been developed to generate mappings between schemas automatically.

Schema Matching Berlin and Motro suggest a technique for using machine learning to match schemas based on probabilistic models about the source data (Berlin and Motro, 2002).

Doan et al. use multiple learning techniques which are then combined to give a meta-learner for matching entities between schemas (Doan et al., 2003). They also used integrity constraints, feedback from users and the structures within the data to improve matching and demonstrate these techniques work on matching real-world data from databases.

A matching technique for diagrams based on Bayesian reasoning (Mandelin et al., 2006) could also be applied to the schema matching problem, since a schema can generally be drawn as a diagram and the same matching techniques based on relationships, name matching, and connectivity would apply.

As we are more interested in structuring a single database of user data, we do not look at schema matching further, except where it presents techniques that are relevant to our work. We do however note that schema matching would be useful for further work in matching user data with external data source (and external data sources with each other) in order to enable users' applications to import and export data.

Having explored the matching of disparate schemas for databases holding similar data, we now return to the original problem of discovering a schema for an existing database without one.

The TREC series focused on directly mining structured data from semi-structured and unstructured sources. Modern web search engines like Google extract structured data from unstructured or natural language sources. Kosala and Blockeel made a wide survey of web mining techniques (Kosala and Blockeel, 2000). These techniques are useful as a last resort for extracting data, but it should be possible to make use of the local structures within data to create a better overall structuring.

Ad-hoc techniques Wikipedia has been used as a source of semi-structured data. A variety of different projects have combined it with structured data to create a larger database of structured data (Suchanek et al., 2007; Wu and Weld, 2008; Wu et al., 2008). Most of these systems rely on ad-hoc heuristics and are specialised to the particular domain of extraction.

Other work has extracted schemas from semi-structured data, typically using matching heuristics and exhaustive search of the schema space based on the source data. Lots has been done in rediscovering schemas, for example in generating a schema for HTML documents that are generated from databases with nullable fields (Yang et al., 2003), or in recovering XML schemas for documents that are well-typed but not well-documented (Bex et al., 2007).

Various techniques have been suggested for converting formatted HTML documents into valid XML data (Chung et al., 2002; Mukherjee et al., 2003; Fu, 2004). All of the techniques rely on heuristics for extracting data labels from HTML and do not provide general technique for typing semi-structured data.

Papakonstantinou and Vianu suggest how DTDs can be inferred for views of XML data (Papakonstantinou and Vianu, 2000). They show that the DTDs are not a particularly strong mechnism for creating schemas. Their method focuses on recovering typings from well-typed XML documents; they do not address the issue of variation so this is not a useful technique for end-user programming.

Bex et al. suggest a technique for recovering certain types of XML Schemas from sets of XML documents (Bex et al., 2007). They also present an algorithm which can handle incomplete data sets; again however this technique is ad-hoc in basis and could be improved upon by a more principled technique.

Nestorov et al. produced the first major work on creating schemas for truly semi-structured data (Nestorov et al., 1998). They represent schemas as monadic datalog programs on data that is represented as labelled, directed graphs. They use a heuristic method to group together similar types and a k-means style clustering to choose a set of types. By using k-means clustering they avoid the difficult problem of selecting model size. A statistical technique gives more straightforward ways to select appropriate models.

The above approaches tackle the problem of type inference for semi-structured data. However, the main problem with these approaches is that they rely on ad-hoc heuristics to choose the best types and to unify the types of values that are not exactly equal. A smaller, secondary problem is that despite being ad-hoc, these approaches attempt to be complete, trying a large number of model combinations. Several of the approaches are NP-complete or worse in terms of complexity, and one of the approaches even notes that it is impossible to infer the type in the type system they initially suggest with only positive examples of values. Because these techniques define their search space based on the input data, outliers may be responsible for a disproportionate blowup in the amount of extra computation because their complexities are exponential in the number of variations in the input data.

All of these techniques are intended to find structures in data that is already well-structured, whereas a system for end-users would also have to work with badly structured data. Three other techniques have been suggested which are closer to the inference we are suggesting.

Statistical techniques Garofalakis et al. suggest a way to infer document type definitions (DTDs) for XML documents using the minimum description length (MDL) principle (Garofalakis et al., 2003). They target XML DTDs which gives them a relatively powerful data model. They principally use MDL in order to detect repetition within XML documents but the approach is also able to deal with added and removed attributes. The MDL technique is based on using compression to give an upper bound on the amount of information contained in a description. The schema with the smallest compressed size is considered the best fit.

Abiteboul et al. suggest a technique for creating sets of XML documents that conform to a schema with the same statistical properties as a collection of sample documents (Abiteboul et al., 2012). They suggest this technique could also be used to evaluate schemas by testing how well the generative model suggested by a generated schema matches a collection of documents.

Cozzie et al. suggest a technique using unsupervised learning to find data structures in memory for virus detection (Cozzie et al., 2008). Their technique is useful in identifying structures within noise which suggests a statistical approach could also work for user data. They use Occam's razor to penalise additional model elements.

Our approach Based on a combination of these approaches, a contribution of this thesis is a technique for inferring data types that is useful for end-user programmers. Our approach uses a well-founded statistical technique to evaluate the quality of types. Because of the enormous state space of possible types already identified, we use a heuristic search technique to generate the types that can then be evaluated on a systematic basis. Our technique could be applied to a wide variety of structuring methods, including typed records, tree structures and relational data. We define our approach in detail in Chapter 5.

2.11 Summary

This dissertation investigates creating a web-based end-user programming language for handling data. We draw three themes from the literature cited above which we tackle in the following chapters: using web as a platform for end-user programming, creating usable end-user programming environments, and aiding users in structuring data within programs.

The web provides a platform for client-server applications with several unusual properties: heterogeneous client capabilities, a continuation-based evaluation strategy, distributed concurrency and high scalability. Programming languages have evolved to handle

the complexities of the web execution model. However, there are no general paradigms that support end-user programming languages within concurrent platforms like the web. Chapter 3 introduces a programming language execution model that is suitable for end-user web applications.

Programming languages are more than just the syntax and semantics, and there are alternatives to text. Several attempts have been made at creating an end-user language for the web. We detail the general approach and unique features of our system in Chapter 4. End-user programming languages are rare, but possible. They are focused around strong, concrete environments with live data. We evaluated our system in relation to these other systems in Section 4.4.

Data storage and persistence is an overlooked area of programming environments, especially for end-user programming languages. It would be useful to help users add structure to their data, and to enable machines to comprehend data that lacks explicit structure. In order to do this, a general and well-founded techniques for data type inference in semi-structured data would be helpful. We therefore suggest such an inference technique in Chapter 5, and show how this technique could be used to improve end-user programming environments.

Chapter 3

A new paradigm for programming languages: separating control and data flow

> "It is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail."
>
> *The Psychology of Science*
> Abraham H. Maslow (1966)

Programming languages often concentrate on uniformity at the expense of clarity. This uniformity needs to be tempered so that different concepts in users' programs have different representations in the programming language in order to avoid Maslow's above "hammer problem."

Current programming languages tend to have multiple overlapping sequencing mechanisms, for example line-by-line execution, threads, processes, events and timers, but they do not clearly identify dependencies between operations sequenced in different ways. We wish to distinguish between causally independent operations, data-dependencies and control-dependencies.

We consider programs as blocks of sequential instructions. These blocks are independent from each other and may be executed concurrently except in case of a data dependency or a control dependency between them.

If a block requires some results from another block in order to execute, we say the first block has a data dependency on the second. We define *data dependency* as using the results of another computation. A data dependency occurs when one computation is dependent on (can only be calculated using) the values created by another computation. The minimum, canonical example of data dependency is functional composition, e.g. $g(f(x))$. It is straightforward to distinguish data dependencies from independent operations in a pure functional language. For example, the tuple $(g(f(x)), h(y))$ contains

two independent computations ($f(x)$ and $h(y)$) and one data-dependent computation (g applied to $f(x)$). Some programming languages only have data dependencies, for example, the data flow language Lucid, pipeline-based processing tools such as Toolbox, and graph-based computations like Excel. However, as already discussed in Section 2.8, these languages tend to be limited or unwieldy. The issue is therefore how to add control dependencies in a modular way.

If a block only executes when some condition is met by another block, then there is a control dependency from the second block to the first. A *control dependency* occurs when a program takes a different execution path depending on the *status* of processing some input or data. By status, we mean a boolean value, flag, type or other value drawn from a predefined, finite set and which relates to the outcome of an operation or some predicates about the state of the world. The best canonical example of a control dependency is waiting to receive a message in the communicating sequential processes model of computation[1]. Another good example of control dependency is the use of the IO monad in Haskell programs to order side effects (Peyton Jones and Wadler, 1993). The IO monad models sequential composition, which is not normally a control dependency unless it is composition of externally visible operations, which is exactly what the IO monad sequences. Note that although there is only one possible status (that the operation is now finished), there is an implicit waiting status in the case where the operation has not yet completed. Many parts of ordinary sequential programs without external visibility do not have control dependencies, since they are parallelisable.

In many languages there is an overlap between data and control dependencies. It is often clear where there is a dependency between computations, but not whether the dependency is a control or data dependency.

One problem is what appears to be a control dependency inside a block of code may not be observable from outside that block, and so becomes a data dependency. For example, code to filter a list will probably have a statement to remove an item or add it to a new list based on a predicate on each value in the list. There is therefore control dependency between the predicate on each item and the removal/addition of that item. However, viewed as a whole, filtering the list with a predicate has no control dependencies, only a data dependency between the input and output lists, because the control dependencies are no longer observable. This is why we consider Lucid not to contain control flow: although it has expressions with data dependencies, it has no concept of explicit, global control flow, so there is no way for part of a Lucid program to unilaterally affect the rest of a program in the way an imperative language can (for example, by jumping to the entry point for a different program entirely).

On the other hand, sometimes the flow of control may depend on some properties of the input data. For example, showing an error message if an input list is empty, but

[1]Note the message could contain data, which then leads to an additional data dependency, but here we intend some kind of flag in the message that the computation needs in order to select the next instruction to execute.

displaying a report otherwise. In this case we are lifting a value (length of the input list) into a status (empty/not) and the computation executed depends on that status, thus this is a control dependency. Without this lifting of a value to a status, it is reasonable to assume variables are not responsible for control flow. For example, Sajaniemi identifies nine different roles of variables in novice imperative programs (Sajaniemi, 2002). Only 1% of the variables were of the type *one-way flag* which was the only type of variable which had a direct effect on control flow in their classification.

As a final example, throwing exceptions from a function that normally returns a value gives us a way to express a computation that has both a data and control dependency in a succinct way. Obviously, exceptions can be modelled by returning a sum type from the function. However, the semantics of exceptions in programming languages are generally sufficiently different from the semantics of a sum type to make the distinction worthwhile. This distinction fits nicely into our separation of dependencies since an exception is a computation status and thus obviously causes a control dependency. While an exception can contain data in the same way a return value is data, and there is a data dependency between the exception and the receiver (and between the return statement and the caller), there is an additional control dependency from block that can throw the exception since it can lead to an entirely different piece of code executing.

Two computations can be said to be independent if there is no control or data dependency between them. Two sequential statements in a typical imperative language are independent if the first does not change the flow of control and the second does not rely on any values produced or state changed by the first. For example, the statements `a = x + 1` and `b = y + 2` are independent, i.e. they can be reordered without affecting the output of the program.

Now we have defined data and control dependencies, we return to considering whether typical programming languages represent them clearly. A sequential language cannot easily express independence, and conflates data and control dependencies. The most extreme example is a language with higher-order functions and `if` statements. A language with a variety of constructs for looping is more distinguishable, but most languages allow an uneasy mixture of data and control flow.

For example, take the admittedly obfuscated but classic C string copy loop:

while(∗d++ = ∗s++);

This loop has an independent component (the order of individual character copies is irrelevant), a data dependency (write to d after reading from s) and a control dependency (do this to each character, then do something else), yet only the data dependency is clearly captured with the equals sign. Independence is missing from the code and the control dependency is hidden in various syntactic tokens throughout the program. This program is also subtly buggy: if d points to a character in s, then the copy will become an infinite loop, trashing the whole of memory with a repeated substring until stopped by some memory protection or overwriting its own code (which, if the substring copied can be controlled, is then a remote code execution vulnerability as well). A similar but

clearer program might state $\forall i \,.\, 0 \leq i < length(s)$, $set\, d_i = s_i$ but this precision often scales badly in real programs that have side conditions and other awkwardnesses. It does however capture the intention of the programmer, whilst avoiding the kind of subtle error that is in the C program.

Functional languages augment recursion with operations on data structures like map, filter and fold. These operations help separate the flow of the program from data processing, but they are generally insufficient. For example, writing a complex fold is often harder than writing the equivalent recursive functions. However, the fold is more likely to be correct, so it would be helpful if we refactor the recursive function into the fold, or make it easier to write the fold in the first place. Other syntactic structures like *list comprehensions* and *for comprehensions* provide aspects of restricted control flow, but these are insufficient to completely separate control and data flow because they are merely optional extra constructs, not a mandated part of the core language. These more advanced techniques are helpful for expert programmers, but they are not widely used by average programmers and as add-ons are certainly insufficient to tame programming languages for novices.

We propose a new paradigm for programming languages called CD-SEP[2]. We are particularly focusing on end-user programming languages. As a consequence, we wish to emphasise clarity over expressibility. There are programs that cannot be expressed in our paradigm, for example, Ackerman's function[3]. We argue that this lack of expressibility is an advantage – if all the programs a user might wish to write can be expressed, any extra expressibility is a waste and since increased expressibility typically leads to less clarity, it is of negative worth.

CD-SEP separates control flow and data flow. Languages in CD-SEP have two levels – a pure level which functions as a terminating data flow language, with all of the attendant benefits of reasoning ability via referential transparency and explicit dependencies, and a control level where side effectful actions happen. Our language can be visualised as a graph of control flow nodes, which may have input which are fed by graphs of data flow nodes. Flow in both levels is restricted to be acyclic, except through special top-level trigger control nodes. The acyclic restriction prevents recursion, which means data processing must be done using library functions which operate on collections such as lists, sets, maps and tables in order to process variable amounts of data. Our execution model is outlined in Section 3.1. We define a simple language that implements our CD-SEP in theoretical terms and explain its semantics in Section 3.2. We then discuss how concurrency is handled automatically and optimistically in CD-SEP in Section 3.3.

[2]Pronounced seed-sep.

[3]There are probably simpler functions that are not expressible. Since we do not have recursion, even factorial would not be natively supported. Instead of looping, it would be necessary to generate a list of numbers from 1 to n, and then multiply that list together. Fibonacci would be harder but possible, since you can easily create an input list of size proportional to the number of steps required to calculate the answer. However, for a function that explodes like Ackerman it is definitely not going to be possible to create an input list proportional in size to the number of computations, and thus it is inexpressible.

The semantics of CD-SEP are similar to but not the same as Haskell with control dependencies represented by binds on the IO monad, Erlang, functional reactive programming, and some other existing paradigms. Others have also proposed restricting programming languages to be non-Turing complete, in particular, Turner suggested total functional programming which can only express primitive recursive functions (Turner, 2004). The exact restrictions and differences between CD-SEP and other modern programming languages and paradigms are discussed in Section 3.4. We then conclude and discuss how this paradigm would be useful for end-user programming in Section 3.5.

3.1 Execution model

Figure 3.1 shows a simple CD-SEP program. Programs in a CD-SEP language consist of a graph of nodes, which are divided into data nodes and control nodes. In the figure, the rounded nodes in boxes 2 and 4 are data nodes; rectangular nodes in boxes 3 and 5 are control nodes; and the triangle in box 1 is a trigger node, as shown by the key. Data dependencies are shown as thin solid lines and control dependencies as bold dashed lines.

A data node can participate in data dependencies, but cannot participate in control dependencies. A control node can participate in control dependencies, and additionally can act as a sink to data dependencies. We use *data flow* to refer to edges carrying data from data nodes to other data or control nodes. A *control flow* is an edge between one control node and another. There can be no edges from control nodes to data nodes.

Execution occurs by a *node pointer* (analagous to an instruction pointer in a processor) starting at a trigger node and then moving along control flows. As the pointer arrives at a node, its data dependencies are evaluated, using a lazy, pull data flow semantics. Once its dependencies have been resolved, any side effects are executed based on the calculated data and then, based on the result of those side effects, a descendent control node is selected to be executed.

For example, in Figure 3.1, execution begins at the trigger node, *Click*. *Click* is a control node, and can activate zero or one of the control nodes it is connected to: in this case *AddPost*. *AddPost* needs to fulfil its data dependencies before it can execute, so *MakeRow* is activated next. *MakeRow* in turn activates *GetForm*, which has no dependencies so it can return a value. *MakeRow* then processes this value from *GetForm* and returns it to *AddPost*. Now all the dependencies of *AddPost* have been fulfilled it can be executed. In this case, *AddPost* is presumed to have some side effect like adding a row to a certain database table. *AddPost* can now activate a control node it is attached to. *ShowList* then executes its dependencies in box 4 in a similar way before executing its action (showing the list of posts from the database). *Highlight* can access the value of *MakeRow* previously calculated since the pure data flow language can be memoised. *ShowList* has no successors, so execution terminates here.

As already mentioned, when the node pointer reaches a node, before any side effects

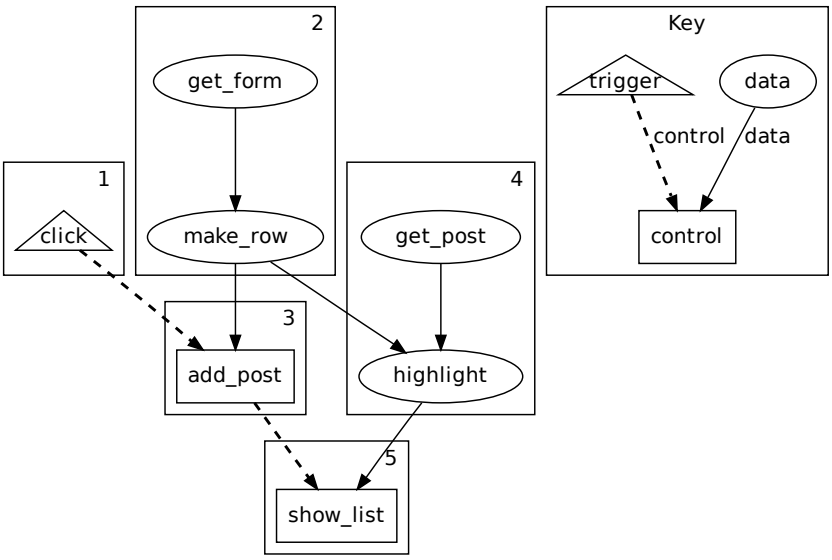


Figure 3.1: A simple program in CD-SEP

occur, all of the data that flows into that node is requested. This request propagates up the data flows until it can be fulfilled; data then flows down, into the node that initiated the request. This means that data flow cannot be cyclic (so the data flow graph must be a DAG), and that each data node must produce output (so it must terminate).

Therefore, each control node is guaranteed to terminate, and since the control nodes cannnot form a cycle either, this guarantees termination of each execution. A control node may have a side effect which creates new trigger nodes. In this way, a program can show user interface elements and have them trigger new executions. This means that something like a read-eval-print loop could be built in our language, since a trigger can be fired each time the user enters a line of code to run, even though an infinite loop without user interaction cannot be expressed.

In order to create a useful language in CD-SEP, it is necessary to augment the simple language with constructs for processing data and performing actions in a domain, in order to create a *domain-specific language* (DSL) that is an instance of CD-SEP. For example, in web application programming, there will be specialist elements for HTML pages, form elements, databases, data processing like sorting and filtering, e-mailing and URL routing. Special elements can be divided into four types:

- Sources, which store persistent data or provide inputs to programs. They are data nodes with no predecessors, like *GetForm* above. As data nodes, these nodes are idempotent.

- Processors, which are all other data nodes that take some data input and provide some data outputs, e.g. *MakeRow* above.

- Triggers, which start programs based on external events or inputs. They are control nodes with no predecessors, such as *Click* above.
- Actions, which are control nodes which can perform side effectful actions. They have predecessors and can have successors, for example *AddPost* above.

An action that displays some user interface or carries out some irreversible external action (for example, launching the missiles) may optionally not have any successors, since the rest of the program is irrelevant at that point. Otherwise, each type of control node has an associated set of statuses that may result from executing that node. These statuses are used to control which sucessor node to activate. Opportunities for concurrency and handling of external side effects are discussed further in Section 3.3.

We design and build an instance of CD-SEP which is a DSL for web applications in Chapter 4, where we also discuss issues relating to the usability of CD-SEP for programmers, particularly novices.

3.2 Theoretical basis

In order to discuss the exact semantics of CD-SEP, we now describe a symbolic form for CD-SEP programs. We then give the typing rules and reduction rules of the symbolic version in order to explain the semantics.

3.2.1 Syntax

Converting a visual CD-SEP program into symbolic form requires two steps: naming each node and then writing out an expression for each node. Since CD-SEP programs form a forest of directed acyclic graphs (DAGs), we write out expressions by making a depth-first traversal from each of the trigger nodes. We now investigate each part of the grammar in turn and show how it relates to the visual example. Grammar rules are written as ⟨*rule*⟩ and rules are defined using standard BNF syntax with the extension that ⟨*rule-list*⟩ is parsed as a comma-separated list of zero or more ⟨*rule*⟩ elements. Concrete syntax elements are written in a fixed-width font like `token`.

A program is defined with the following grammar rule:
⟨*program*⟩ ::= (⟨*data-node*⟩ | ⟨*control-node*⟩ | ⟨*trigger-node*⟩)∗

This means a program is made up of a list of data (including source and processor nodes), control (action) and trigger nodes, each listed after their predecessors. These can occur in any order, but forward references are prohibited. This will occur automatically if a program is written out by a depth-first traversal as described above.

Data nodes are defined by the ⟨*data-node*⟩ rule and associated rules:
⟨*data-node*⟩ ::= `data` ⟨*ident*⟩ `=` ⟨*expr*⟩
⟨*expr*⟩ ::= ⟨*value*⟩ | ⟨*ident*⟩ | ⟨*built-in*⟩

⟨*built-in*⟩ ::= ⟨*ident*⟩`(`⟨*expr-list*⟩`)`

Data nodes are syntactically simple; they define a named node to be equal to an expression. Expressions can be either values or the results of evaluating other data nodes or of calling built-in functions from the domain. The following statements correspond to the data nodes in Figure 3.1:

```
data form = get_form()
data row = make_row(form)
data posts = get_post()
data highlighted_posts = highlight(posts, row)
```

Control nodes are defined by the ⟨*control-node*⟩ rule as follows:
⟨*control-node*⟩ ::= `control` ⟨*ident*⟩ `=` ⟨*action*⟩⟨*map*⟩
⟨*action*⟩ ::= ⟨*ident*⟩`(`⟨*ident-list*⟩`)`
⟨*map*⟩ ::= {⟨*mapping-list*⟩}
⟨*mapping*⟩ ::= ⟨*status*⟩`->`⟨*ident*⟩
⟨*status*⟩ ::= ⟨*ident*⟩

When a control node is activated, it completes some kind of built-in action identified using the ⟨*action*⟩ rule. It is a requirement that any arguments to the action are identifiers that reference data nodes. A control node contains a map, which decides which control node to activate next based on the status of the built-in action. Each built-in action will define an associated set of possible statuses which may be the result of activating that action as part of its type. The following pair of statements correspond with the control nodes in Figure 3.1:

```
control add = add_post(row){ok -> show}
control show = show_list(highlighted_posts){}
```

Trigger nodes are defined similarly to control nodes, except they are not named and can only take constant parameters:
⟨*trigger*⟩ ::= `trigger` ⟨*ident*⟩`(`⟨*value-list*⟩`)`⟨*map*⟩

The identifier in a trigger node names a trigger function. The constant parameters of a trigger node are used to configure the exact conditions under which a trigger node activates. When those conditions are met, the trigger function activates one of the control nodes in its map in exactly the same way as a control node, except the status comes from the trigger rather than the status of some operation. Only concrete values can be passed in the ⟨*trigger-node*⟩ rule. Since trigger nodes are constantly waiting for some trigger condition to be met, it does not make sense to allow a calculation to affect the trigger conditions, since this would then necessitate constantly re-evaluating that expression in order to know when the trigger should fire. This does not mean triggers cannot activate in

response to changes in external data; the data source to watch is specified as a constant and the implementation of the trigger node is responsible for getting notifications or polling. Since triggers have a map in the same way as control nodes, it is possible for a trigger to start different executions depending on some status generated by the trigger. For example, a trigger node representing a switch could generate two different statuses "on" and "off" depending on whether the switch had been turned on or off. This is no more powerful than simply having multiple triggers, but can be more convenient and allows a single trigger node to correspond directly with a user interface element even if the user can interact with it in multiple ways. The following statement corresponds with the trigger in Figure 3.1:

```
trigger button("Add"){click -> add}
```

We give the full grammar for reference in Figure 3.2 and show the complete example corresponding to Figure 3.1 in Figure 3.3.

⟨*program*⟩ ::= (⟨*data-node*⟩ | ⟨*control-node*⟩ | ⟨*trigger-node*⟩)∗

⟨*data-node*⟩ ::= `data` ⟨*ident*⟩ `=` ⟨*expr*⟩
⟨*expr*⟩ ::= ⟨*value*⟩ | ⟨*ident*⟩ | ⟨*built-in*⟩
⟨*built-in*⟩ ::= ⟨*ident*⟩`(`⟨*expr-list*⟩`)`

⟨*control-node*⟩ ::= `control` ⟨*ident*⟩ `=` ⟨*action*⟩⟨*map*⟩
⟨*action*⟩ ::= ⟨*ident*⟩`(`⟨*ident-list*⟩`)`
⟨*map*⟩ ::= {⟨*mapping-list*⟩}
⟨*mapping*⟩ ::= ⟨*status*⟩`->`⟨*ident*⟩
⟨*status*⟩ ::= ⟨*ident*⟩

⟨*trigger*⟩ ::= `trigger` ⟨*ident*⟩`(`⟨*value-list*⟩`)`⟨*map*⟩

Figure 3.2: The grammar of CD-SEP

```
data form = get_form()
data row = make_row(form)
data posts = get_post()
data highlighted_posts = highlight(posts, row)
control show = show_list(highlighted_posts){}
control add = add_post(row){ok -> show}
trigger button("Add"){click -> add}
```

Figure 3.3: A simple program in CD-SEP as text

3.2.2 Type checking

Given this syntax, we then check the types of the program. While doing this, we also check that the graph formed is acyclic.

Typing judgements are given in the usual syntax of $\Gamma \vdash e : \tau$, which means that an expression e has type τ in environment Γ. Γ is the environment of identifier-type pairs in the program. Data node identifiers in the program are mapped to their type by Γ. Control node identifiers are mapped to the special type κ (for control) by Γ.

Firstly, we consider the types of data nodes and expressions. Figure 3.4 gives the rules for this. The types are part of the domain that CD-SEP is specialised in. We do not support passing functions as parameters, so all expressions are of a basic type. Expressions may refer to other expressions by name, as long as that does not form a cycle. All invocations of built-in functions require checking the correct number of arguments of the correct types.

Lit The rule *Lit* states that values have the type of the constant, in any environment.

Var References to other data nodes are checked that the named node existed in Γ by rule *Var*. This rule assigns the type of the other data node to this expression.

App Built-in functions are checked to ensure they exist and that they are passed the correct number of arguments of the correct types by rule *App*. The expression is given the type of the return value of the built-in function.

Data Data node definitions do not have a type but instead update the type environment for all subsequent definitions using rule *Data*. In this way, cycles can be prevented by simply disallowing forward references, since a DAG is always linearisable.

$$\text{Lit}\ \frac{v \text{ is a constant of type } \tau}{\Gamma \vdash v : \tau}$$

$$\text{Var}\ \frac{x : \tau \in \Gamma}{\Gamma \vdash x : \tau}$$

$$\text{App}\ \frac{\begin{array}{c}\mathit{builtin} \text{ is a function of type } (\tau_1, \ldots, \tau_n) \to \tau \\ \Gamma \vdash e_1 : \tau_1, \ldots, \Gamma \vdash e_n : \tau_n\end{array}}{\Gamma \vdash \mathit{builtin}(e_1, \ldots, e_n) : \tau}$$

$$\text{Data}\ \frac{\Gamma \vdash e : \tau}{\Gamma \vdash \texttt{data}\, x = e}\ \text{adds } (x : \tau) \text{ to } \Gamma$$

Figure 3.4: Data flow typechecking

To check the control level, we need to check three things: nodes do not form cycles, action functions are called with values of the correct types, and that for each action the map from statuses to nodes only mention statuses defined for that action function. The rules for checking the control level are given in Figure 3.5.

Action Action functions are checked to ensure the correct number and types of arguments are passed in by rule *Action*. The rule *Action* also checks that the status to node map only contains statuses that are in the set of possible statuses for that action function and that each status is either unmapped or mapped to a single other control node. The action definition does not have a type of its own, but instead updates the type environment for subsequent declarations, again to avoid cycles.

Trigger Trigger functions are checked similarly to action functions by rule *Trigger*. Since triggers are anonymous nothing is added to the environment by rule *Trigger*.

$$\text{Action}\ \frac{\begin{array}{c}\mathit{action} \text{ is an action function of type } (\tau_1, \ldots, \tau_n) \to \Sigma \\ \Gamma \vdash x_1 : \tau_1, \ldots, \Gamma \vdash x_n : \tau_n \\ \{s_1, \ldots, s_m\} \supseteq \Sigma \\ \Gamma \vdash c_1 : \kappa, \ldots, \Gamma \vdash c_m : \kappa \\ \forall j, k \,.\, j \neq k \Rightarrow s_j \neq s_k\end{array}}{\Gamma \vdash \texttt{control}\, c = \mathit{action}(x_1, \ldots, x_n)\{s_1 \to c_1, \ldots, s_m \to c_m\}}\ \text{adds } (c : \kappa) \text{ to } \Gamma$$

$$\text{Trigger}\ \frac{\begin{array}{c}\mathit{trigger} \text{ is a trigger function of type } (\tau_1, \ldots, \tau_n) \to \Sigma \\ \Gamma \vdash v_1 : \tau_1, \ldots, \Gamma \vdash v_n : \tau_n \\ \{s_1, \ldots, s_m\} \supseteq \Sigma \\ \Gamma \vdash c_1 : \kappa, \ldots, \Gamma \vdash c_m : \kappa \\ \forall j, k \,.\, j \neq k \Rightarrow s_j \neq s_k\end{array}}{\Gamma \vdash \texttt{trigger}\, \mathit{trigger}(v_1, \ldots, v_n)\{s_1 \to c_1, \ldots, s_m \to c_m\}}$$

Figure 3.5: Control flow typechecking

3.2.3 Semantics

Our semantics are defined as reductions on a configuration. Configurations are made up of a state and an expression to be reduced. Each execution (which corresponds to a node pointer and is started by a trigger node) has a separate state Δ, which is distinct from the type environment Γ. The state acts as a cache of evaluations of data flow nodes, in order that each data flow node is evaluated at most once per execution. The state starts out as an empty map over the domain of data flow node names and range over values of the type of the data flow node in Γ, augmented with a π value to record in-progress evaluations.

We describe a small step operational semantics showing how expressions can be reduced with the relation:

$\langle \Delta, e \rangle \to \langle \Delta', e' \rangle$

As well as yielding a new expression to be reduced, a reduction may also update the state to give a new state, which we have typically named Δ'. We define each reduction

rule in the usual way, with the reduction consequent occurring when the assumptions are satisfied, as long as any side conditions are met:

$$\text{Name}\frac{\mathit{Assumptions}}{\mathit{InitialState} \rightarrow \mathit{ReducedState}} \text{ Side conditions}$$

We take all the declarations in the program as assumptions which may appear as antecedents of reduction rules. The semantics of our data flow language defined in Figure 3.6 are slightly interesting in order to fit with our concurrency model and memoisation scheme. In this part of the semantics, declarations of data nodes appear in the assumptions of the rule *Var2*. We now describe the semantics of the data flow part of the language. It should be noted that the semantics of this language are non-deterministic but confluent.

Var1 Any evaluation of a named expression first checks the state to see if this expression has already been fully evaluated. If it has, the previous value from the state is reused by rule *Var1*. If evaluation has begun but is not yet finished (that is, $\Delta(x) = \pi$), no reduction of x is yet possible.

Var2 Otherwise, we use the assumption of the declaration of that data node in the program to get the expression that is bound to that named expression in rule *Var2*. Once we have reduced this expression, we will want to store it into the state for future use. We therefore tag the expression with its name so that the memoise rule can add it to the state later. We also make an initial entry into the state to show that evaluation has begun for this data node.

EvalI We can reduce inside parameterised brackets using rule *EvalI*.

$$\text{Var1}\frac{v = \Delta(x)}{\langle \Delta, x \rangle \rightarrow \langle \Delta, v \rangle} \text{ if } x \in \mathit{dom}(\Delta) \wedge \Delta(x) \neq \pi$$

$$\text{Var2}\frac{\texttt{data}\, x = e}{\langle \Delta, x \rangle \rightarrow \langle \Delta + \{x = \pi\}, [e]_x \rangle} \text{ if } x \notin \mathit{dom}(\Delta)$$

$$\text{EvalI}\frac{\langle \Delta, e \rangle \rightarrow \langle \Delta', e' \rangle}{\langle \Delta, [e]_x \rangle \rightarrow \langle \Delta', [e']_x \rangle}$$

$$\text{Memoise}\frac{}{\langle \Delta, [v]_x \rangle \rightarrow \langle \Delta + \{x = v\}, v \rangle}$$

$$\text{EvalE}\frac{\langle \Delta, e_i \rangle \rightarrow \langle \Delta', e_i' \rangle}{\langle \Delta, \mathit{builtin}(e_1, \ldots, e_i, \ldots, e_n) \rangle \rightarrow \langle \Delta', \mathit{builtin}(e_1, \ldots, e_i', \ldots, e_n) \rangle}$$

$$\text{Apply}\frac{v = [\![\mathit{builtin}]\!](v_1, \ldots, v_n)}{\langle \Delta, \mathit{builtin}(v_1, \ldots, v_n) \rangle \rightarrow \langle \Delta, v \rangle}$$

Figure 3.6: Data flow semantics

Memoise Once we have reduced a tagged expression to a value, we store the value in the state for later use and reduce the expression to that value with rule *Memoise*. This binding is assumed to replace the temporary binding of the data-node name to π by rule *Var2*. Together these rules ensure that each data node is only evaluated once per execution.

EvalE We represent expressions which are calls to built-in functions as $builtin(\dots)$ in the semantic rules. We reduce functions in the normal way, first reducing their arguments using rule *EvalE*. Note our evaluation rule does not provide an ordering on evaluation of arguments, so any order is permissible, including parallelisation of independent reductions. We later show that this leads to the same results, even in the presence of memoisation, as long as all built-in functions are idempotent.

Apply We refer to calling a built-in function from the domain as $[\![builtin]\!](v_1, \dots, v_n)$ and call it with the reduced arguments in order to yield a value with rule *Apply*. Since this rule does not affect the state, it can always be parallelised.

We now look at the semantics of the control flow part of the language in detail, which are defined in Figure 3.7. Expressions in the program are evaluated with the data flow semantics we described above. A CD-SEP program begins executing when a trigger node is activated. When a trigger node activates, it spawns a new thread of execution with a new, empty state. This explains the slightly odd form of the rule *Trig* which has an empty initial state. The rule *Term* is also odd in having an empty reduced state. This is because execution terminates after the rule *Term* is applied so there is no subsequent state. Each execution runs in a separate thread and is isolated from other executions until it terminates, as described further in Section 3.3 below.

Lookup The rule *Lookup* describes how a status and a map from statuses to identifiers can be reduced to a new control node, using the definitions of the control nodes in the program as assumptions. This rule only fires when the status is mapped to a control node, as checked by the $status \in dom(M)$ side condition.

Term The rule *Term* shows how execution terminates when no successor control node is linked to the resulting status of a control node. The environment is destroyed at this point, and any concurrency commitment occurs as described in Section 3.3 below.

Trig The node pointer is started with a new, empty state with rule *Trig*. This rule evaluates the status returned by the trigger function and then reduces to the control node in the trigger's node map for that status via rule *Lookup*. We use $[\![trigger]\!](v_1, \dots, v_n)$ to mean the execution of the trigger function in the domain with the values given as arguments. The trigger definition in the program is taken as an assumption. For example, the earlier definition `trigger button("Add"){click`

`-> add`} might mean a trigger node which is associated with the button named "Add". When the button is clicked, this trigger activates with the status `click`: that is, when this rule executes $[\![button]\!](\text{“}Add\text{''})$ is equal to *click*.

EvalN The evaluation of expressions passed as parameters to action functions proceeds exactly as for parameters passed to functions in data nodes using rule *EvalN*.

Step Once the parameters to an action have been fully reduced, the action function is evaluated with rule *Step* and a new status is returned. This status is used to choose a new node to execute or to terminate the program using rule *Lookup* and rule *Term* respectively, in the same way as for trigger nodes. We use $[\![action]\!](v_1, \ldots, v_n)$ to mean the execution of the action function in the domain with the values given as arguments. The action function may have some side effects and returns a status based on its operation. For example, the earlier definition `control add = add_post(row){ok -> show}` might mean a control node which adds a value to a database table. When this row is added successfully, the control node will have a status such as `ok`: that is, when this rule executes $[\![add\_post]\!](row)$ is equal to *ok*. However, if the row is not added successfully, a status such as `fail` might be returned instead, enabling the program to handle the failure.

These semantics show that data flows are run before the action flow side effects occur, since the action function can only run once all of the inputs have been reduced to values. We ensure separation between activations since for each activation of a trigger node, a new empty state is generated, which is entirely separate from any other execution's state. As we discuss further in Section 3.3, we use optimistic concurrency control to keep executions separate from each other so each thread sees a consistent view of the world. As already discussed, data flow nodes are memoised in the environment, so data flow nodes are only

$$\text{Lookup}\ \frac{\begin{array}{c} n = M(status) \\ \texttt{control}\ n = action\texttt{(}x_1, \ldots, x_n\texttt{)\{}M'\texttt{\}} \end{array}}{\langle \Delta, M(status)\rangle \rightarrow \langle \Delta, action\texttt{(}x_1, \ldots, x_n\texttt{)\{}M'\texttt{\}}\rangle}\ \text{if } status \in dom(M)$$

$$\text{Term}\ \frac{}{\langle \Delta, M(status)\rangle \rightarrow}\ \text{if } status \notin dom(M)$$

$$\text{Trig}\ \frac{\begin{array}{c} \texttt{trigger}\ trigger\texttt{(}v_1, \ldots, v_n\texttt{)\{}M\texttt{\}} \\ status = [\![trigger(v_1, ..., v_n)]\!] \end{array}}{\rightarrow \langle \emptyset, M(status)\rangle}\ \text{when a trigger activates}$$

$$\text{EvalN}\ \frac{\langle \Delta, e_i\rangle \rightarrow \langle \Delta', e_i'\rangle}{\langle \Delta, action\texttt{(}e_1, \ldots, e_i, \ldots, e_n\texttt{)\{}M\texttt{\}}\rangle \rightarrow \langle \Delta', action\texttt{(}e_1, \ldots, e_i', \ldots, e_n\texttt{)\{}M\texttt{\}}\rangle}$$

$$\text{Step}\ \frac{status = [\![action(v_1, ..., v_n)]\!]}{\langle \Delta, action\texttt{(}v_1, ..., v_n\texttt{)\{}M\texttt{\}}\rangle \rightarrow \langle \Delta, M(status)\rangle}$$

Figure 3.7: Control flow semantics

evaluated once. However, if the program needs to evaluate the same expression again after some control node has executed, it can do so by defining a freshly named date node that evaluates the same expression.

Since control nodes form an acyclic graph, data nodes are similarly acyclic, and reduction of expressions usually leads to a smaller expression, it is fairly obvious that the execution resulting from a trigger node activating is guaranteed to terminate. We could prove this more systematically by induction on each rule, showing it either makes the expression smaller, or accesses or activates another node (data or control respectively), which reduces the scope for expressions to expand further in the future. Specifically, once each node has been visited, expressions cannot grow any larger since the only rules that expand expressions have an unvisited node in their assumptions. Therefore, in the worst case we visit every node once and then reduce the resulting expression with strictly shrinking rules.

3.3 Concurrency

No explicit concurrency within a program is possible – node pointers (which correspond roughly to threads of execution) cannot be manually spawned or forked. This simplifies the execution model and the programmer's understanding. Instead, node pointers are spawned in special trigger nodes, which are control flow nodes that interact with the user or the environment. Trigger nodes spawn a node pointer whenever the event they are watching for occurs. This means that having multiple simultaneous node pointers, corresponding to overlapping triggerings of the program, is possible. There is no special handling in the case of having multiple trigger nodes connected into the same control node – each trigger node activation creates a new independent thread of execution which is isolated from all others. To give a concrete example, each time a user of a web application requests a new page a new node pointer is spawned. Node pointers do not interact, except through an external data source or other external state. This is similar to the idea of a continuation-passing web server, first introduced by Queinnec (Queinnec, 2000), but is simpler than continuations, since no state can be carried between one node pointer and another.

One big advantage of CD-SEP is that this implicit concurrency lends itself to easily and automatically implementing optimistic concurrency control (OCC) (Kung and Robinson, 1981). For example, in the web application case, after a user has made a change to some data and pressed save, we can first check which version of the data they received and ensure no intervening modifications have occurred. This can be done easily by the system since the data flows can be statically analysed, so data which needs to be unchanged can be automatically identified. In the case that the data has changed, two solutions are possible. If the data changed in the course of this flow execution, then we rollback any side effects that have happened during this execution and then restart the execution with access

to the updated data. This approach corresponds to running concurrent programs with software transactional memory (STM) (Knight, 1986). Primitives that access external resources mean we either need external transactions to rollback external side effects after failures, or we need external side effects that can provide a compensation, which reverses their effect, as described by Hoare (Hoare, 2010). This compensation or rollback is used if the flow has to be restarted. If neither of these ways of reversing external side effects is available, then any internal primitives which access the side effects must themselves provide a way to reverse this side effect. If we cannot reverse the side effect internally or externally, then we have an irreversible side effect. If we have at most one irreversible side effect, and this side effect is not observed during the execution (that is, nothing that depends on it happens, or we have a way to pretend it happened internally), we can work around the irreversible side effect by deferring it to the end of the execution, and rolling back all other side effects if it fails. With multiple irreversible side effects, we have to accept a loss of some of our concurrency control on external services, which may not be rolled back when they should be. Note we cannot delay all side effects because the flow of execution may depend on the statuses resulting from those effects.

If the input to the flow execution depends on data which has changed since it was retrieved, then we can cause the part of the flow execution with the dependency to fail. This can then be transparently treated as an error in that part of the execution (and can additionally be reported to the end-user as having failed due to stale data). The normal error handling in the program can then be used to present the end-user with the ability to reattempt the action based on updated data.

The separation of control and data flow will enable this kind of analysis far more easily than current systems. It will also aid partitioning, for example, pushing filters and sorts up to a database server, since the data flow part of the program has no side effects it can have more aggressive optimisations applied to it than otherwise might be possible.

3.4 Comparison to other paradigms

These semantics can be neatly compared to the semantics of a pure call-by-need language with limited side effects, for example, Haskell. The evaluation strategy of our data flow language is exactly the evaluation strategy of Haskell. However, Haskell without side effects can still recurse, which we explicitly disallow.

Haskell uses the IO monad to thread side effects through the program, as proposed by Peyton-Jones and Wadler (Peyton Jones and Wadler, 1993). The programmer cannot create an instance of the IO monad, and so is required to pass an instance created at the outermost-level throught the whole program, thus threading control flow through the program and making any dependencies explicit. In the same way, in our system, only our action level has primitives for accessing external state, and it is impossible to get to the action level from the data level (the proof of this is obvious by case analysis on

the data-level constructors.) There is therefore a correspondence between our data and control flow separation and pure Haskell functions and Haskell functions that are tainted with the IO monad in the type signature.

However, the semantics of a program in our system as a whole are slightly different from Haskell. In our system, the firing of multiple triggers causes multiple threads of execution to run with separate local state. These threads are independent except for any shared access to global state which we discussed in Section 3.3. In contrast, the IO monad in Haskell generally forces the whole program into sequential order, which does not mesh well with interaction with other systems. Alternatives such as the STM monad give other concurrency choices but do not allow Haskell to integrate with external systems.

In addition, Haskell requires that even idempotent reads from external state are threaded through the IO monad. This forces lots of what would otherwise be pure computations into the sequential IO path and confuses side effects with state. In contrast, programs in our language can be viewed as "striped" – each side effectful action forces a break in pure functions, but between side effects access to state is unrestricted. Colouring each data node with a colour based on the first control node that is connected to it would result in the program having "stripes" corresponding to these unrestricted read zones. This makes programs more easily parallelisable than Haskell.

Haskell also permits side effects to occur at the data level (using a primitive called performUnsafeIO). In contrast, we prevent all unsafe actions by having no similar escape hatches. These are necessary in Haskell in order to make it a useful general purpose language; our system can enforce more safety in exchange for being less useful for more advanced programs.

Restricting programming languages to be non-Turing-complete is a common technique in end-user programming. Most of these attempts are either data flow languages, which we consider below, or languages with ad-hoc restrictions that excessively limit their expressibility, for example macro languages with no branching or recursion. These languages are typical domain-specific configuration languages or macro recordings. We will not discuss these restricted languages further, since a language without conditionals is simply a list of instructions which cannot be considered as programs, since programming is usually about details and edge cases. The ability to create a process that is just a simple list of instructions should be part of any end-user programming language, but a programming language is too restricted if it does not have the ability to do anything more complex. One interesting area of restricted programming languages is total functional programming, suggested by Turner (Turner, 2004). Total functional programming (TFP) restricts functions in a functional language to be total by removing the possibility of exceptional errors or unrestricted recursion. Instead, recursion can only be done on syntactically identified sub-components of parameters. Turner also suggests the use of corecursion[4] on codata

[4]This is just recursion on codata, but with the added restriction for TFP that the right-hand side mention of the codata is larger than the left-hand side, i.e. that the output grows. This is the dual restriction to total recursion, which requires the right-hand side to be smaller than the left, i.e. the

to represent infinite computations, for example, receiving and responding to events in an event-driven system. This separation is similar to our data/control separation: total functions on data corresponds to data dependencies between data nodes; and corecursion on a stream, with a terminating process occurring for each stream element, corresponds to our system of triggers causing executions which are guaranteed to terminate. In this way, both systems are unable to generate non-termination, but are able to compute indefinitely on infinite input.

Our restrictions on recursion are even more restrictive than the restrictions of TFP to primitive recursion on data. Our lack of recursion is made up for by libraries which support powerful operations, e.g. filter and fold, on data structures. Note a DSL containing fold and map is already quite powerful and capable of implementing something like a fuel-limited interpreter. Programs in CD-SEP are automatically embedded in a corecursive environment, which has the same properties as the corecursion on codata possible in TFP.

The use of controlled mutable state also increases the power and expressiveness of our language. Persistent mutable state makes it simple to handle long-running computations and user interaction without having to resort to codata. Persistent mutable state also permits greater parallelism than storing state as part of the codata input, which by its nature requires the program to be sequential. We believe that CD-SEP is closer to user mental models than a total functional language. In particular, the stylistic restrictions imposed on the language by the need to be able to prove syntactically that computations terminate can make programs unwieldy. Coupled with the purely functional nature of the language, we argue this means TFP is unsuitable for end-user programming.

The data flow level of our language can be compared to several other data flow-based paradigms. Many pure data flow languages are stateless. For example, Excel can be seen as a data flow language. In the same way as us, pure data flow does not allow circular dependencies, since there is no clear way for a such a program to be evaluated. Interaction in such a pure data flow language is generally limited to either batch-processing, for example in an image processing pipeline (Strandgaard and Hansen, 2008) which uses a graph of modifications to an input image to create an output image, or to provide an interactive environment, again, like Excel. Interactive environments are good for exploring solutions and simple data processing, but tend to be unwieldy for larger scale data processing. Many interactive environments also layer a scripting language on top of the environment, e.g. VBA within Excel. This is awkward, and typically loses the advantages of the data flow language such as user friendliness. In contrast, CD-SEP adds principled control flow on top of the data flow language itself.

Batch data flow is more scalable to processing a variable collection of data, providing the program can be written at the granularity of processing a single element of input. Batch data flow can also be extended to infinite streams of input and output, for example,

argument shrinks.

Unix line-ordered utilities. CD-SEP distinguishes between long lists of data, which can be processed in one go, and the creation or arrival of new data, which can be recognised with a trigger and processed individually.

The Lucid language adds a concept of discrete time to the data flow paradigm. In Lucid, each update to the world is discrete, so there is no requirement for programs to be acyclic. Instead of cycles causing non-termination of the data flow computation, each element is updated based on the current values of its dependencies. This can lead to inconsistencies and does not guarantee that an element converges to particular value, or even stabilises at all. This makes more advanced computation possible at the expense of making it harder to reason about programs. Interaction in Lucid can be handled by making a stream dependent on some external data (e.g. keyboard input), and by making some external data dependent on a stream (e.g. printable output.) Our approach is stronger than Lucid's since Lucid still has the classic programming language problem – forcing too many types of dependency into one construct. Lucid is the opposite of most programming languages, forcing the user to do control flow with data flow.

Functional reactive programming (FRP) (Elliott and Hudak, 1997) typically adds infinite streams to a functional language (Cooper and Krishnamurthi, 2006). Most FRP languages also add events. Events happen at a discrete time, triggered by some update to a stream. Because FRP events can trigger arbitrary other FRP events, FRP is Turing-complete even without being embedded in a Turing-complete language. In contrast, we place a strict restriction on cycles which prevents our programs from being Turing-complete.

Some interactive data flow languages permit cycles, as long as the graph is made linearisable by fixing the value of an input node. For example, the Fabrik language (Ingalls et al., 1988) provides a UI toolkit with data flow constructs. It is possible to make two sliders that are both set in relation to each other (for example, Celsius to Fahrenheit temperature conversion and vice versa.) Normally this cycle is not evaluated, but if one slider is moved manually, the cycle is broken and the other slider can move automatically. In general, while bidirectionality often appears neat for small examples and limited domains (for example Lenses (Bohannon et al., 2006; Foster et al., 2007) make good use of restricted bidirectional programming in a narrow domain), in general it requires programs to be isomorphisms which is very difficult to ensure in large-scale programs. Thus, although neat, we do not support any bidirectional dependencies, instead preferring to have two separate control flows which handle changes in either slider by updating the value of the other.

Many other programming languages use a flow-like analogy, especially coupled with a visual environment as we describe in Chapter 4, for example, LabView. However, existing flow languages do not make a distinction between control flow and data flow. At the most extreme, some languages use "enable signals", which are data flow, to simulate control flow (Leff and Rayfield, 2007). These languages are very similar to hardware, where a

control line is just another type of data line[5].

The Erlang language is an implementation of the Actor model, where independent *actors* have their own thread of execution and communicate by sending message asynchronously (Hewitt et al., 1973). Erlang has complex, structured signals between independent nodes. Within each node, Erlang is purely functional, which is similar to our data flow language. Between nodes Erlang allows unrestricted, asynchronous message-passing. This gives a good separation between data and control flow, but makes the control flow layer overly powerful. Erlang places no restrictions on how messages propagate, allowing non-determinism and branching, whereas we demand a predictable and linear ordering of program operations. This makes Erlang powerful and expressive at the expense of ease of use for smaller programs.

The Scratch end-user programming environment described earlier (Maloney et al., 2010) has similar semantics to our system. Scratch has control nodes and triggers that function in the same way as CD-SEP. Scratch has a data model based on simple variables and animation sprites with stored properties; this data model could be fitted within CD-SEP. However, Scratch has several control blocks which surround other control blocks and can cause them to run repeatedly, including an explicit infinite loop and conditional loops which could be infinite through user error. Scratch also allows the programmer to broadcast messages that can trigger one or more other executions. These features mean that programmer error can easily cause Scratch programs to not terminate. Because Scratch programs can intentionally run in infinite loops (for example, using a loop with a delay in it to animate an object) there is no way to isolate different parts of the program from each other with automatic transactions as we describe in Section 3.3. This forces users to consider concurrency explicitly, and this is generally a repudiated technique even for professional programmers. In contrast, by having isolated, terminating subprograms, CD-SEP makes reasoning about concurrency purely local.

The WebRB system for end-user web programming (Leff and Rayfield, 2007) has somewhat simpler and more restrictive semantics than CD-SEP. WebRB uses a similar automatically transactional concurrency system. WebRB makes no distinction between control and data dependencies, which significantly weakens the operations a WebRB can carry out. Because of the pure data flow semantics of WebRB, which uses flags to select side effectful actions to perform, only one or zero side effects are permitted in each execution, which are carried out after the execution is complete. This causes a second problem: there can be no control dependencies on the status of a side effect. In contrast, CD-SEP gives a well-defined way to manage multiple side effects and to act based on the status of side effects.

[5]On the subject of hardware comparisons, clocked registers in hardware description languages like Verilog behave very similarly to Lucid, although access to history must have special hardware synthesised and typically other types of control can be layered on top, e.g. reset signals. Asynchronous circuitry has no direct software parallel, since the handshaking mechanisms necessary to connect separate asynchronous circuits make even less sense in software.

3.5 cd-sep: A new paradigm for end-user programming languages

We have described a non-recursive, two-level language paradigm that is a novel way of structuring programming languages. We argue that the philosophy of restricting the language to a level of expressiveness and abstraction which is appropriate to the users of the language represents an effective approach in programming language design. CD-SEP is related to monadic IO; data flow programming; functional reactive programming; and the actor model, but hits a sweet spot of expressiveness and simplicity. CD-SEP explicitly separates and handles control flow, making it particularly suitable for event-driven systems that may have multiple concurrent operations occurring. Because of these features, CD-SEP is especially suited to end-user programming in event-driven systems.

However, CD-SEP is only a paradigm and it is hard to demonstrate or evaluate its effectiveness without a more concrete implementation of the paradigm. Chapter 4 now shows how this paradigm could be implemented in the area of programming web applications. As we discussed in the introduction and Chapter 2, the web is an ideal platform for end-user programmers but there are few appropriate tools. A tool based on CD-SEP would have all of the benefits of termination, parallelism and simple reasoning for end users that we have discussed. We additionally consider how these concepts fit in with a visual environment that improves on the state of the art described in Chapter 2.

As a programming paradigm CD-SEP does not particularly constrain the data model, apart from requiring support for parallelism and transactions. We combine CD-SEP with the relational data model in Chapter 4. While powerful and straightforward to implement, this is probably too complex for end-users. We therefore suggest a more suitable data model for end users and discuss how it fits with CD-SEP and our visual programming environment in Chapter 5.

Chapter 4

Visual web programming

> "A favorite subject for Ph.D. dissertations in software engineering is graphical, or visual, programming – the application of computer graphics to software design. Nothing even convincing, much less exciting, has yet emerged from such efforts. I am persuaded that nothing will."
>
> *No silver bullet*
> Frederick P. Brooks (1987)

Syntax is a large barrier to end-user programmers. For programmers learning their second, or tenth, or hundredth language, a new syntax is at worst an irritation, especially as languages almost all follow similar conventions of structure and reading order. However, for a novice learning their first language, syntax is a big barrier. Freeform text input is good for experts, like using a cello bow, but for novices something like a piano keyboard, with only two variations of input (which key and how hard) is preferable. In fact, I would argue for something even simpler. To extend the piano analogy further, since most pieces are written for a key signature[1], the piano should disable the notes which fall outside the key signature[2].

By restricting the programmer to direct manipulation of program elements, syntactically incorrect programs can be avoided, making a visual language better for novices. One of the problems with visual programming languages has been it is hard to scale up

[1] For non-musicians, a key signature is which of the notes in a scale need sharps or flats. An octave usually contains 12 equally spaced semitones, but a particular piece of music usually uses just 7 unequally spaced notes from each octave.

[2] Actually, this is done for beginners since many easy pieces are written in C major, whose 7 notes are just all the easily accessible white keys.

as programs get bigger. I address this by restricting the visual layout severely (allowing only for horizontal rearrangement of unrelated nodes.) This, coupled with the splitting of programs into control and data flow makes even large programs manageable. Control flow is mapped onto the horizontal dimension, and data flow onto the vertical dimension. This means data always flows downwards and control to the right, so it is easy to see how execution might proceed. This is in contrast to current visual languages where layout is completely freeform. Petre's review of visual programming (Petre, 1995) showed that experts stick to conventions without help, but novices appeared ignorant of convention. By enforcing convention, we hope to make beginners function as well as experts, at least in this area.

Despite much research and many commercial systems such as Microsoft Access and Hypercard, most users keep data in spreadsheet applications like Excel or Google Docs. This data is often structured or semi-structured, but users lack suitably powerful tools for sharing and processing it. Many systems have been proposed to mix or "mash-up" existing data, or to help skilled programmers access databases more easily, but no new paradigms for end-user database programming have emerged. We believe there is a need for a data management and programming system that can be used by all computer users. In this chapter, we make the following contributions:

- We describe how the novel separation of control and data flow described in the previous chapter can be used in a visual programming language. This separation can be shown by layout, colouring and other visual effects. We believe this separation makes it easy to follow and reason about programs. This separation also facilitates the separation of reading and writing from persistent databases, again making reasoning easier.

- Useful visual tools for building functional programs over collections. We believe Turing-completeness is a bug, not a feature, in end-user programming languages because complex loops are hard to reason about.

- A live, web-based, WYSIWYG environment for web development. We believe installation is a significant barrier to entry. By running on Google App Engine, our application provides a scalable cloud-based service.

- A user study demonstrating that such a system is usable. Although we used computer scientists as our study participants, we were impressed with their success with the system.

4.1 Description

The Flows language is an implementation of the CD-SEP paradigm described in Chapter 3. We refer to the restricted control flow in the Flows language as *action flow* because, from

a user's perspective, control flow is all about the sequencing of actions by the user and the system. Programs in the Flows language are referred to as *flows* throughout.

The Flows language is embedded in a visual programming environment we call VisualWebFlows. The environment functions in two modes: *view* and *edit*. In the view mode the site is rendered in a web browser as a normal, functioning website. The default installation, in view mode, is shown in Figure 4.1.

Figure 4.1: A simple web site

The programmer can also view the same website in edit mode. In edit mode, the site is also rendered in the web browser, but it is annotated with buttons to allow the programmer to edit its content and functionality. Figure 4.2 shows the same default installation in edit mode.

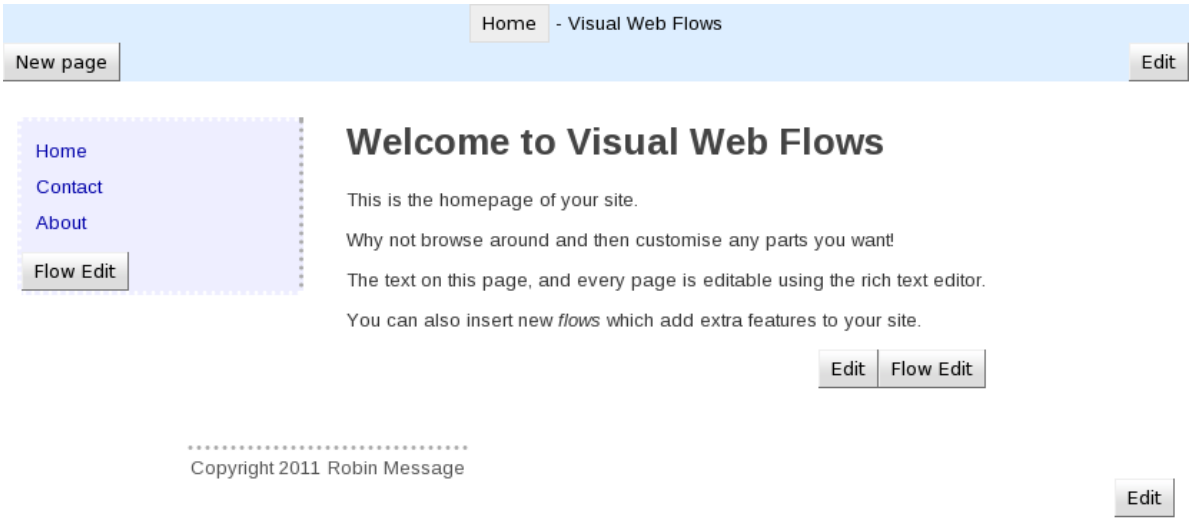


Figure 4.2: Editing a simple site

This remainder of this section describes the system design. We look at how data is stored together with a description of the type system. We describe the data flow operations we support and then discuss how the Flows system fits into the CD-SEP paradigm. Finally, we look at how our web system binds the execution of flows to URLs and how such flows generate HTML suitable for display on the browser.

4.1.1 Data types

Our type system is built at two levels: *primitives* and *tables*. Primitive types are used to describe simple datatypes such as integers, strings, HTML text and dates. Whilst our implementation does not currently support many datatypes, it could be extended to support a richer set of primitives, including such things as e-mail address and location. New primitive types could be added using a system like Topes (Scaffidi et al., 2008).

User-defined types are called *tables*, which are similar to named records and aim to build on user experience with spreadsheets or SQL. A table has one or more columns, and each column has a name and a type; the name of a column is unique within the table. All tables have a column called `id` of primitive type ID, whose values are required to be unique (if not provided by the programmer, numeric IDs are generated.) Each table also has an ordered list of tuples called *rows* whose contents match the types specified by the columns. Below is a simple example table type with three columns:

`id`:ID	`full_name`:Text	`age`:Integer
`rhm31`	Robin Message	`25`
`arb33`	Alastair Beresford	`32`

The system has a persistence mechanism which associates a system-wide unique table name with the contents of the table. These persistent tables are backed by Google App Engine, giving end-users scalability. New rows can be added to persistent tables, and existing rows can be retrieved, updated and removed by referencing their ID value.

4.1.2 Data Flows

We first consider flows that only contain data flow; we refer to these as *data flows*. The user creates a flow visually in the web browser by placing the nodes of the graph, called *blocks*, and joining the nodes with edges, called *connections*.

All blocks output a new table except for a special output block: instead of outputting a new table, it displays its input rendered as HTML which will be displayed to the user on the website. The output of each block is rendered as part of the block in the visual environment, in order to aid programmer understanding of the result of the current flow. In the case of ordinary blocks, this means a scrollable table, and for the output block, the actual HTML rendering of the output as it would be seen on the website.

Blocks may have zero or more inputs and an output from one block can be wired to any number of inputs, but each input can only accept a single output.

The output block can be configured to display output in one of four different ways: (i) *plain,* this output style renders its input without any formatting; (ii) *list,* this configuration renders the value of each row in the input as an HTML list; (iii) *table,* this output style displays the input table as an HTML table, with the column names as a header row; and (iv) *report,* this configuration displays each row of the table input according to an HTML template. The HTML template can be edited using a WYSIWYG interface. Values from

cells in the current row can be displayed using mail-merge style grey boxes in the HTML template. A detailed example using this feature is presented in Figure 4.6 of Section 4.2.

The output block could easily be extended to support other output types, such as graphs or maps. This is not something the end-user could be expected to define, but it should be possible to add mappings to existing libraries to a VisualWebFlows system for these types of output.

We considered making it possible to nest other flows inside a report. Whilst potentially useful, this feature seemed excessively powerful. Instead we would like to provide a mechanism for adding buttons to reports that support contextualised triggering. The action flow for these buttons would be editable from the report editor and would have a special data flow input which would contain the row that the button that was pressed was on. Such buttons would be useful for, for example, deleting a row from a table, or switching to a more detailed view of that item of a report.

Blocks other than the output block can be divided into two categories: *producer blocks* which have no input and therefore merely provide data; and stateless *processor blocks* whose output is a strict function of inputs.

Producer blocks

There are four types of producer blocks that take no input: (i) *form,* a row of the values containing all the HTML form elements on a page; (ii) *page,* a row of values representing the arguments found in the URL. Further information on this input block is described in Section 4.1.4 as part of our URL processing scheme; (iii) *text,* produces a piece of static text. This text can be edited from within the flow editor; and (iv) *table,* loads a named persistent table from the system.

We would add a block that can import data from other web applications dynamically. One problem with such a block is converting the input into our data types. Converting a particular, identified table on a web page would be fairly easy to do, and we could provide a WYSIWYG GUI for the user to select which table to import from a page. Access to structured or semi-structured data sources would depend on our ability to convert that data into our table format, which we do not in general have a good way to do. For things like RSS feeds and simple query methods from web services that return two dimensional data it would be fairly easy to import these as tables.

Processor blocks

All processor blocks have one or more inputs and a single output. These blocks offer simple processing steps which are similar to SQL and spreadsheet functions, such as *where* (select only those rows in a table which have a specific set of values), *order by* (re-order the rows in a table) and *limit* (only output the first n rows). These blocks are similar to the features provided by the Yahoo Pipes system (Yahoo!, 2007). Our system also supports an *equi-join* block which implements the SQL equi-join feature for tables,

and an *aggregate* block which supports operators including sum, count, minimum and maximum on a particular column.

Finally, we have a *link* block which accepts a table as input and combines this with the special *controller* table (described later). The block then outputs a column of URLs suitable for generating clickable web links in the rendered HTML output of the output block. The full operation of the link block is described in Section 4.1.4 after we have described URL handling and the "system" tables.

As an example data flow, consider the flow that puts the name of the current page in the web browser title bar. Pages within VisualWebFlows are also stored in a persistent table, and flows are used to display them similarly to any other part of the program. The program which generated the name of the current page in the title is shown in Figure 4.3.

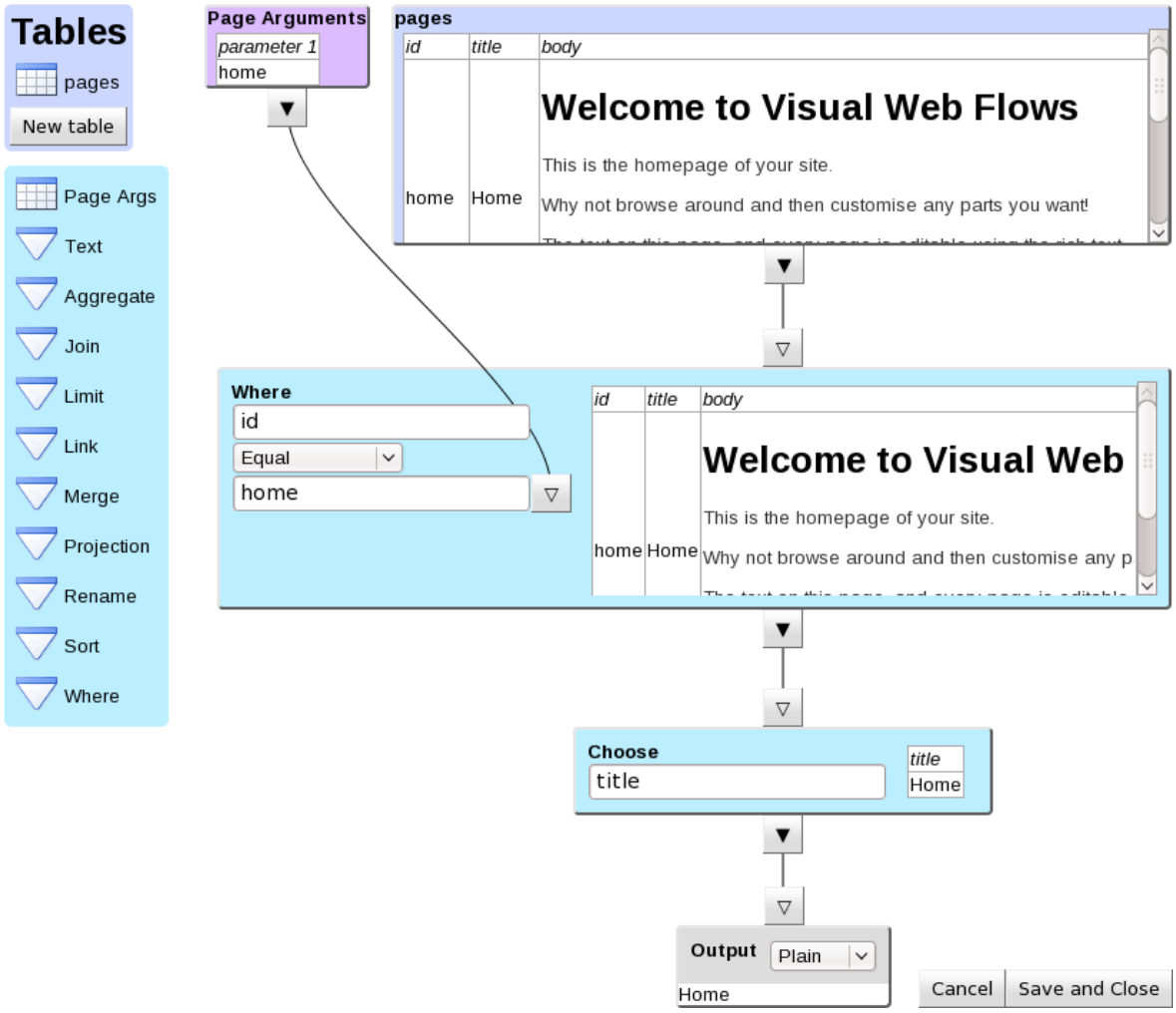


Figure 4.3: Page title in flow editor

The program written in Figure 4.3 is installed in the default installation and represents a simple data flow. On the left-hand side is a selection palette from which the user can select data sources and processing blocks. In the centre of the screen at the top are two blocks, one representing a portion of the page URL labelled "Page arguments" (in this case with the value "home"), and the other representing a persistent table stored in the

system (in this case the table containing all the pages of the website). These two blocks are wired into a processing *where* block, which selects a single row from the pages table. Finally, the *choose* block selects the title column from the output of the *where* block; this is connected to the output block at the bottom of the screen and is then displayed in the browser title bar.

4.1.3 Action flows

We now consider flows that contain control flow in addition to data flow. These flows are called *action flows* but may also contain data flow blocks. An action flow is only created when the state of the server needs to be modified, for example by the submission of data contained in a web form; the action flow then allows the programmer to modify the state of persistent tables and cause other side effects to occur. Action flows are represented by a DAG of *action blocks* rooted at a single special *start block*, like data flows are rooted in an output block, but with the arrows in the opposite direction, so action flows out of the start block into only one subsequent block, and action may flow into a block from multiple other blocks. The use of DAGs prevents loops of control being formed, which prevents a variety of programming errors. A block can be triggered by multiple other blocks to allow sharing of code between operations, e.g. redirecting to a certain page whether or not an action succeeds. Data flows can also be rooted in an action block. The precise semantics are based on those described in Chapter 3 and summarized below.

Every normal action block has exactly one trigger input, and at least one trigger output; in addition, zero or more data flows can be connected to an action block. No action block has a data flow output.

An individual action block starts processing when it receives a trigger event on its trigger input and fires exactly one trigger output when processing is complete. In this way, processing of an action flow begins at the root of the action tree, represented by the start block, and follows a single path through to a leaf node (i.e. an action block with nothing connected to its output trigger).

Currently, the only start block we support in an action flow is the clicking of a submit button on a web form. Other start blocks could be triggered by, for example, timed events, updates to external data sources or e-mail messages received. These start blocks would be managed through a separate trigger administration area, since they are not part of the user interface of the site in view mode. Where external data sources do not have a notification mechanism, the VisualWebFlows could be configured to poll data sources like RSS feeds and trigger a flow when new items are added. Asynchronous messaging systems like e-mail, twitter or XMPP would be easy to add to the system. However, these triggers would need a special mechanism to get the content of the new message. Web applications that can call callbacks could also be supported through auto-generating callback URLs for callback triggers.

In the context of a web application, a web form submission carries out two tasks: (1) it (possibly) modifies the state of the server, and (2) displays a new page to the user. By default, the VisualWebFlows system re-displays the same page the user came from (i.e. the one containing the form submitted) after executing the action flow. This is useful for a variety of applications, such as writing a search page, or providing simple data entry. It also enables the programmer to return a user to a form if there is an error acting on it, so that the user may adjust their submission and try again. In more complex applications, the programmer can attach a *redirect* action block at the end of an action flow to control the page the VisualWebFlows system will return to after the action has been processed. If the programmer wants to display the same page but with any form controls having their default values, they can just redirect to that same page.

By convention, action blocks are arranged from left to right across the bottom of page, while ordinary blocks, describing a data flow, are arranged from top to bottom of the page. In this way an action flow resembles a timeline of events which begins at the start block and proceeds along a single path through a set of action blocks. Also, as mentioned earlier, data flows can be connected to action blocks. Since action blocks may modify the state of persistent tables, it is important to define when any data flows are evaluated as their contents may be updated as the action flow is processed. In the VisualWebFlows system, any data flow connected to an action block is evaluated immediately before the action block is executed. In particular, connected data flows are evaluated *after* the execution of the preceding action block that triggered the current action block.

Our current implementation supports three action blocks in addition to the start and redirect blocks already mentioned. The *insert* action block adds one or more new rows to a persistent table. It has two output triggers, labelled "success" and "failure", which fire under the obvious circumstances. In addition, the insert action block accepts a single data flow input which provides the values for the new row or rows to be added to the persistent table. The *update* action block is similar to the insert action block but has a second data flow input to provide the `id` values of the rows to update. A *delete* action block removes one or more rows from a table. It takes the `id` values of the rows to remove from the table.

We could also have action blocks that are the opposites to the trigger blocks discussed above for messaging services. An e-mail block would be similar to an output block in report mode, but would have an additional input to select which column contains the destination e-mail addresses.

We need an if-block, which enables a user to choose between alternatives, for example for data validation. Such a block would have a similar interface to the where block, but would activate a true or false trigger based on the condition on the input data. A block more like a switch statement might be useful but would require us to have types that are drawn from sets in order to give a usable semantics.

Action flows are designed to hide the fact that web applications are made up of separate pages and instead give a more direct representation of data processing. In particular, the

user does not have to worry about form submission URLs, since all forms submit to the page they are from and are then processed by the system. These properties have been chosen deliberately to provide a simple interface for programmers. This is an improvement on the HTTP programming model of having forms and the code which handles those forms separated, which is something that even experienced programmers can find complicated. This mechanism will also support AJAX-based forms, which could execute asynchronously without making any changes to the flow language itself.

4.1.4 System tables and URL handling

Every installation of VisualWebFlows contains system tables to control URL handling, rendering of HTML, and to provide storage for static content. URLs are handled in the following way: The domain name is removed and the path is split on slashes into a list of strings. For example, `http://www.example.com/pages/home` becomes `[pages,home]`. The first element of the URL is used to look up the *controller* to use from a special system table. A controller provides a layout for the page (so pages can have consistent formatting and menus) and a block of HTML that is used as the main body of the page. This HTML may contain flows. For example, the built-in *pages* controller just returns the body of the row specified by the second URL argument in the pages table. The current URL, represented as a row, is made available as a producer block in every flow the programmer writes, and can therefore be used by the programmer to control the execution of flows on any page.

The combination of controller, layout and pages system tables allows users to quickly create static web pages, and also provides a place to attach the output of flows which utilize new, user-defined tables, into the URL address space of the site. When a new table is created, controllers to add and edit rows from that table are autogenerated as an aid to users. These generated controllers can be edited in exactly the same way as built-in and user-created controllers.

Now that we have described the controller table we can provide a better description of the flow language *link* block mentioned earlier. The link block expects its input to have a single `id` field, which came from a table. If there is more than one `id` field, the user must select which one they want to link to. If the `id` field did not come from a table, no link to it can be made, so the link block fails. The link block then examines the controller table to find which controllers can render the table the `id` came from. The first of these is selected by default and the user is offered a choice of controllers if there is more than one for that table.

4.2 Example application

In this example application, we show how a blogging system could be added to a VisualWebFlows site. We demonstrate the utility of the system, and how it is used to build

applications.

Firstly the user creates a new page that will contain the blog, or chooses an existing page to incorporate the blog into. New pages can be created by clicking the "New Page" button, which is always available within edit mode. The user is asked to give a title for this page, which is then displayed in edit mode.

The programmer can use the HTML editor to add any titles or other information to the new page. The next step is to insert a new flow which will show the latest posts of the blog. Newly inserted flows just display the text "Default" and can be edited by clicking on them. The outputs of flows are displayed with a grey background in the HTML editor, as shown in Figure 4.4, to distinguish them from editable text. These features mean that flows can be combined with HTML code and formatted as the user desires.

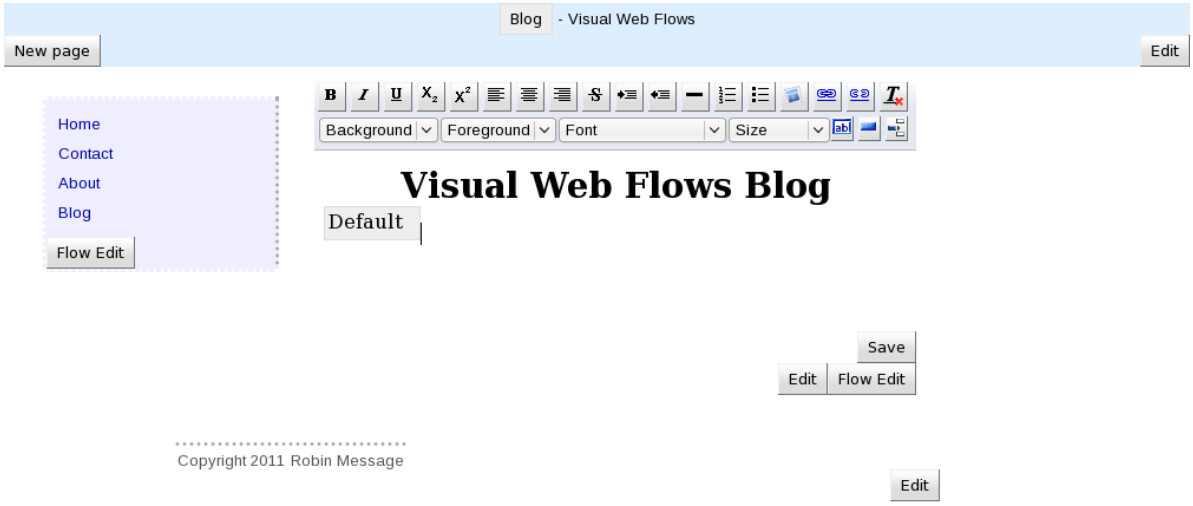


Figure 4.4: HTML editor on the home page

The user edits the new flow to create a view of the latest posts. Three flow elements are needed: a table to store the posts, a sort block to arrange the posts in reverse chronological order, and an output block to display the posts.

From the palette on the left (Figure 4.5), the user clicks the "New table" button (marked 1). The user is then taken to the table editor where they specify the columns needed. In this example, we want a title, some body text, and a date "posted at" column for each post. The user can also add any rows to the table; in this example the user has added a couple of posts.

The new table then appears in the palette of the flow editor. The user can add the new table to the flow and see its contents (marked 2 in Figure 4.5.)

The user adds a sort block to the output of the posts table (marked 3) and sets it to sort its input by the "posted at" column, in descending order[3]. Next, the user connects the output of the sort block to the output block.

[3]We do not yet have a primitive date type, so we have cheated and used ISO formatted dates where lexicographic sorting is also temporal sorting.

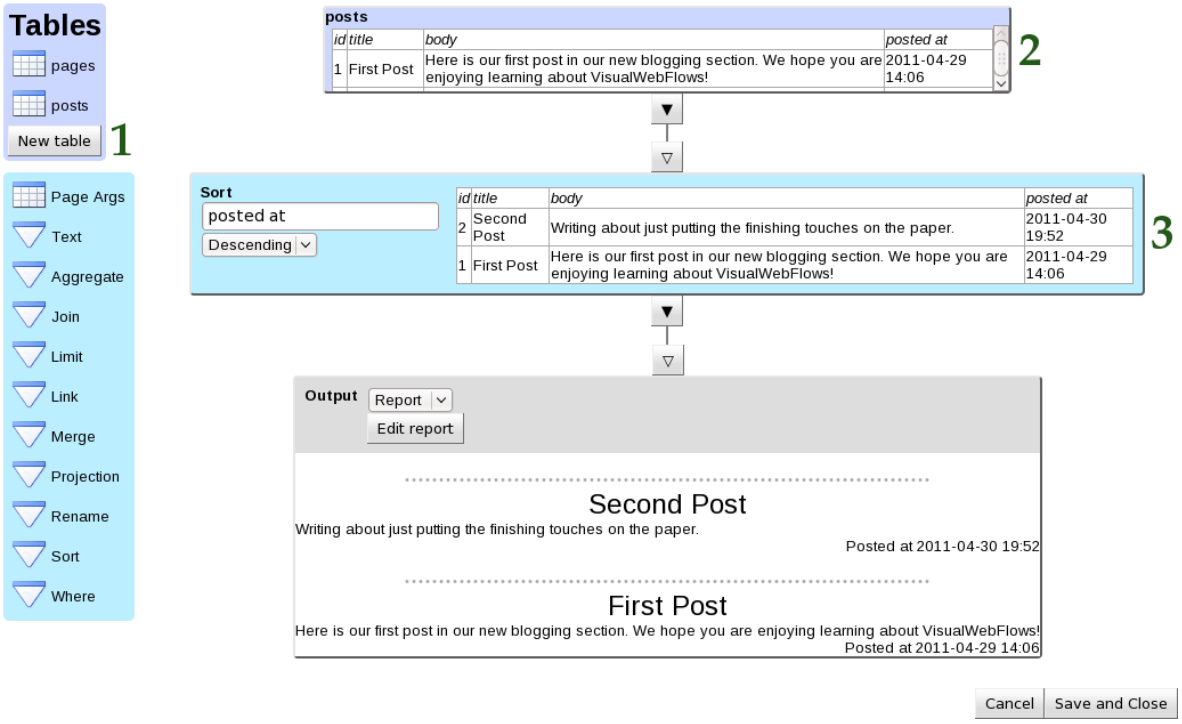


Figure 4.5: Latest posts flow

Since we want to format each element of an entry differently, the user switches the output block to report mode and clicks “Edit report”. In report mode, each row of the input is displayed according to a template, which the user can now create. Figure 4.6 shows the report format editor for this report. The report editor enables the user to insert output fields into a rich text editor, using the drop-down menu and insert button on the top right. The editor also enables the user to manipulate and format any static text and output cells. The user inserts three fields, “title”, “body” and “posted at”, and formats them so that the title is be displayed centered, followed by the body of the post and the right-aligned date. The user also adds the text “Posted at ” before the date field.

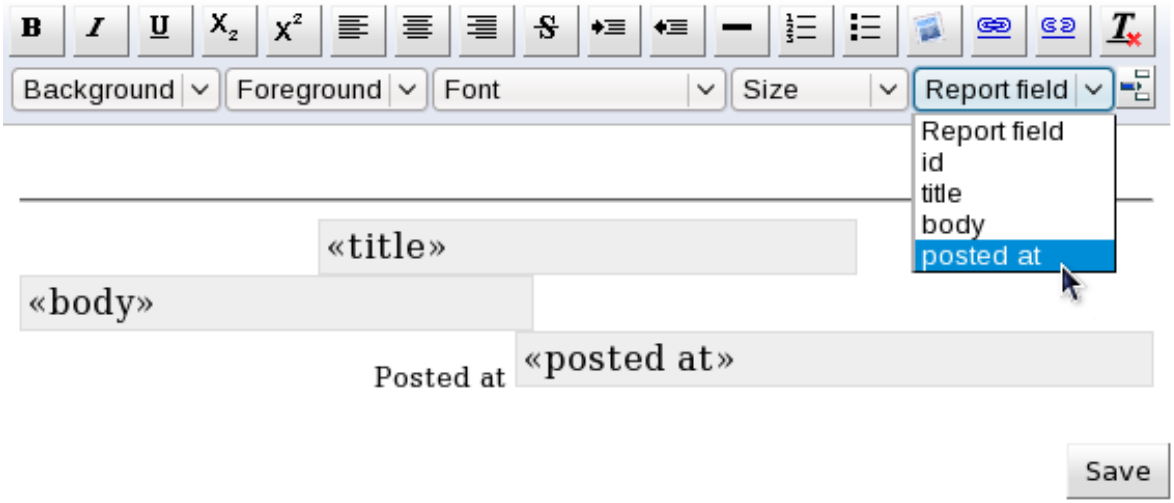


Figure 4.6: Report editor for the blog flow

We will now look at an example of an action flow in the context of editing a blog post. Creating a new table usually implies the need for a method to add and edit entries in the table on the site. As explained in Section 4.1.4, the system auto-generates two new controllers for this purpose. The view of the edit controller generated for the posts table is shown in Figure 4.7.

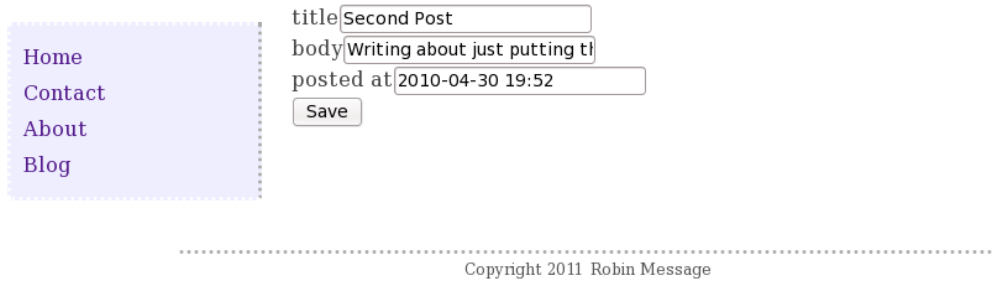


Figure 4.7: Editing a post

Automatically generated controllers and flows can be edited in exactly the same way as user created ones. For example, the default behaviour after the "Save" button is pressed is to return to the same page. Figure 4.8 shows how the action flow for the "Save" button in Figure 4.7 could be modified to redirect the user back to a list of all posts after a modification is saved successfully.

The action flow editor has two additional sections in its palette compared to the normal flow editor – form elements and actions. Form elements enable the user to get the values of any controls on the page when the button was clicked. In this example, the automatically generated code pulls in each of the form elements on the page and merges them to give a row suitable for adding to the "posts" table.

We can see how data flows downwards and action flows left-to-right. The "Save" node on the bottom left runs when the save button is clicked. It causes the row specified by the page arguments in the "posts" table to be updated with the values taken from the form elements.

Figure 4.8 shows a modification to the generated action flow. The generated flow stops after the update table block, so the user remains on the edit posts page after an update. The user adds a redirect action to the update success trigger, which means the user is taken to a list of posts after a successful save. If the update fails, the user stays on the same page so they can try submitting their changes again. A more advanced implementation might display an error message to the user explaining the reason for failure.

4.3 User study

In order to assess the suitability of the Flows system for end user programmers, we decided to do a preliminary user study to see if people could use the system to create simple web applications. We recruited computer science students to participate in the study. Whilst

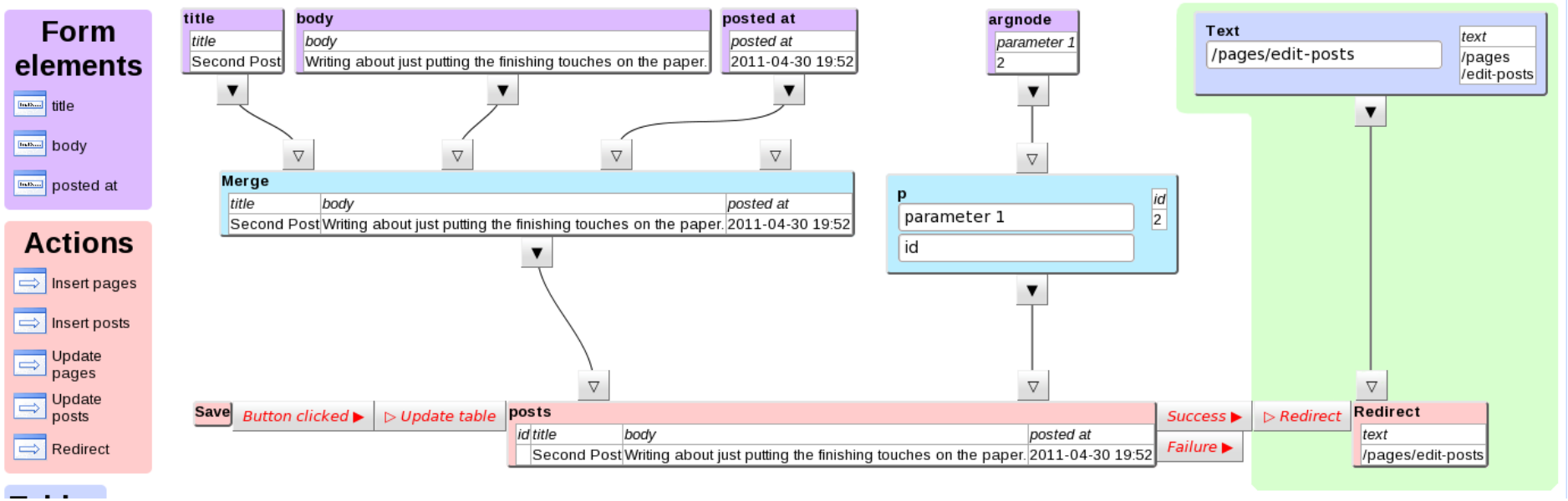


Figure 4.8: Save action flow – programmer modifications on the right highlighted by the green background

our system is aimed at end-user programmers, we felt computer science students would be a good baseline – if they could not understand the system, there is little hope for end-users. We set study participants the task of building a simple web application in 30 minutes, and measured whether they were able to complete this task successfully in the time allotted. We also used a follow-up interview to gather qualitative feedback, and assess their understanding of the Flows system. We found that 7 out of the 8 students completed the task in the time allowed and all of the students showed a good understanding of the Flows system. Many of them agreed the system was quicker than using a conventional programming language for the kinds of tasks assigned. The next step for this research would be to repeat the same study with non-computer scientist participants in order to ensure beginners can also understand and use the Flows system. We now examine the participants, goals, results and evaluation of the study in more detail.

4.3.1 Participants

For ease of recruitment we found 8 computer science students to participate in the study, all male and between 18 and 25 years old. They had a variable amount of experience, averaging about 3 years of programming knowledge. Their exact experience can be seen in the answers to question 1 of the interview.

4.3.2 Goals

Participants were shown a ten minute training video which demonstrated the Visual-WebFlows system. They were then asked to solve the following problem: *Starting with a new, blank application, please create a new page for people to sign up to an impromptu five-a-side football match. The page should show a list of who is signed up for the match. People should be able to add their names to the list. People should also be able to remove their names from the list.* The full instructions given to participants are reproduced in Appendix A.

We assessed the outcome of the study in multiple ways. We had a simple pass/fail cut-off after thirty minutes to see if they could complete the assigned task in that time. We observed the participants working to try and identify any problems with the system that could be fixed. We interviewed participants after they had attempted the task to get qualitative feedback on what was good and bad about the Flows system, and to ask them some questions to test their understanding of the Flows paradigm.

This assessment was designed to test the usability and understandability of the Flows system, and to gather feedback that could improve the system and the study. We also set an extension problem for the students if they finished the main task in less than 30 minutes: *1. So as to be fair, ensure players show up in the order they add themselves. 2. Show the first five players as* Team 1*, the next five as* Team 2 *and the rest as* Substitutes. This extension problem was designed to test the data handling capabilities of the system.

4.3.3 Results

The full results of the study, including details on the participants and notes on their answers to the interview questions, are given in Appendix B. Here we discuss the results in relation to the goals of the study. Most importantly, although some students were delayed by bugs in the prototype implementation, seven out of eight participants completed the task in 30 minutes, and most participants attempted some of the extension tasks.

All of the participants showed a good understanding of the nature of flows in their answers to the interview questions. Additionally, four of the eight answered the more tricky question "Is a form control a flow?" correctly.

The qualitative feedback was good, with many positive comments and suggestions for how the tool could be improved. The overall idea was considered good by several participants, one of whom explicitly commented that it was quicker than using a programming language. The flows concept was commented on by several participants who thought it was "expressive", "quite good" and "intuitive".

Negative comments fell into three main categories. The rename, merge, and delete blocks were commented on as being hard to understand; the pages table and mechanisms associated with it were "confusing", "[too] magical", and fragile (one participant broke their instance of VisualWebFlows completely); and the environment lacked supportive features, such as copy-paste and undo, and was inconsistent in places, for example, in the naming of blocks.

Feature requests were mostly obvious things, such as extra form controls like checkboxes and select boxes; the ability to add controls to reports to do things like deleting a certain row; and being able to have multiple output blocks in a single flow.

As we observed participants, it became obvious that their computer science training actually hindered them in certain cases, for example, as they searched for a way to add abstraction to their programs, and looking for ways to do more advanced things with the output of flows like adding buttons to rows and splitting the output into multiple parts.

Most participants attempted the extension tasks, but they struggled to structure their data in a way that would allow them to complete the tasks within the constraints of the VisualWebFlows system.

4.3.4 Evaluation

The system was useful and usable for students with varied amounts of programming knowledge and experience. Whilst many students had issues with bugs and inconsistencies in the prototype implementation, the idea of a flow-based programming language appeared to be appealing to the study participants, and was well-understood by them.

The biggest problem participants had with the system, particularly in the extensions tasks, was with structuring and managing data. We consider how this could be improved in Chapter 5.

Because we used computer scientists as study participants, this unfortunately weakens the claims we can make about the suitability of our system for end-users. However, these students, some with limited expertise and experience, were able to quickly understand and effectively use the system, which are least eliminates the possibility that it is completely incomprehensible and gives us some confidence that end-users will be able to pick the system up. Additionally, even computer scientists might be quicker using the Flows system than a conventional programming language for some tasks; although not the original goal, this would still mean the Flows system is useful for some users. Due to a lack of time and resources we were not able to carry out a further study with non-computer scientists. Because of this, in the next section we carry out a systematic assessment of our environment in order to answer the question of whether it is a suitable system for end-user programmers.

4.4 Cognitive Dimensions of Notations Analysis

In this section we use the Cognitive Dimensions of Notations framework (Green, 1989) to analyse the usability of the system we have designed. We make comparisons to Excel, as our standard of end-user programmability, and a standard web programming language like PHP that might be used instead of our system. We first compare these three systems on each dimension separately. Figure 4.9 gives an overview of where each system falls on each dimension[4]. We then discuss where we have improved end-user usability compared to existing systems, and identify areas for future work that would improve a system like ours further.

Abstraction gradient Our notation requires the user to work at a fairly low level of abstraction. Crucially, there is no procedure for packaging up a collection of nodes in a graph as a reusable node, unlike how a function can be created in most programming languages. This abstraction-hating is close to the level of abstraction possible in Excel, where formulas must be copied if they are to be used repeatedly. We do support structured data types as tables which, when compared to Excel, are an abstraction over multiple cells. The amount of abstraction required by the user seems acceptable compared to Excel, and less than the programming language.

Closeness of mapping The notation maps quite well to the problem domain. In particular, our WYSIWYG editor enables the user to put programs directly into web pages. The use of tables as the pervasive data structure forces a tight mapping between the notation and the possible problems that can be expressed. This could make it much

[4]Note that these dimensions are not orthogonal, so a change in one dimension will affect other dimensions. Additionally, whilst the dimensions are not intrinsically good or bad, we organise them according to the preferred direction of each dimension for end-users, for example, low abstraction and high visibility are considered good.

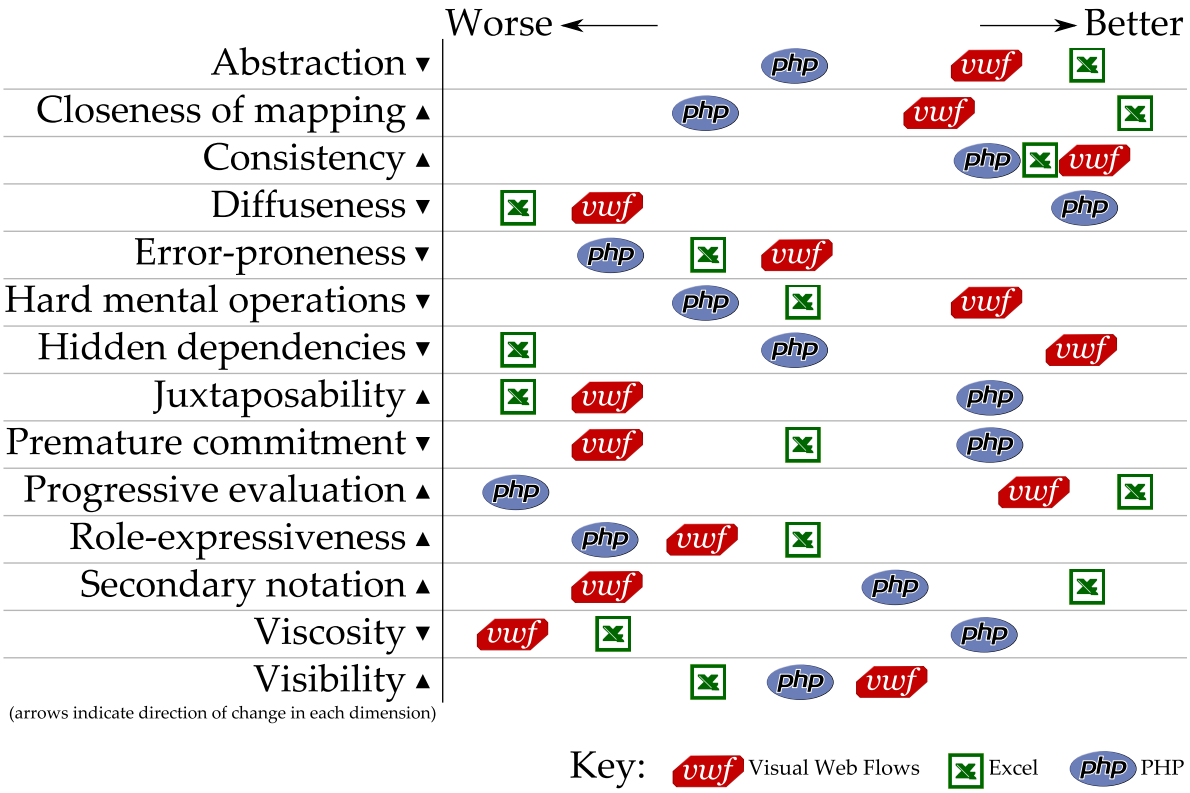


Figure 4.9: Overview of where each system falls on each dimension

harder to work on other data structures. For example, handling tree structured data would be better done by adding new primitives to the language than by attempting to force trees into tables, but for an end user having to handle tree structured data is likely to be awkward.

Consistency There is a high degree of consistency between the flow operations. The user would need to learn about the distinction between data and control flow. This is the biggest inconsistency in the system (although deliberately so). In our user study (admittedly of computer scientists), users had generated excellent hypotheses about the workings of flows, suggesting a good degree of consistency. One problem area is that the operation of each flow node is unique and specific, requiring the user to consult the manual to be sure of the exact operation of each type of node. This requirement to search for and understand operations is worse in Excel and PHP which both have many more operations and many operations that are only provided for legacy reasons, but are not hidden from new users.

Diffuseness / terseness The use of simple flow building blocks makes the language quite verbose. This is a common problem in visual languages compared to textual ones like PHP. However, an improvement we have made is to use a WYSIWYG environment to link the various parts of the program to their related user interface so that any particular part of the program can easily be found and displayed. This modularity enables users

to build large programs, as long as the parts of those programs are still small enough, avoiding some aspects of the scaling problem (Burnett et al., 1995). We also improve on Excel by having structured data, so that the display size of a collection is not proportional to the number of elements as it is in Excel.

Error-proneness The lack of static type checking makes it more likely a mistake by the user will not be picked up by the environment. The previews of the output of each flow element are designed to mitigate this, enabling the user to try test values and observe the effect on the program, helping avoid mistakes. We currently do not provide good feedback to users on what the table operation control blocks will do with the inputs they are given. Excel has live feedback which avoids this problem, but despite this, errors in Excel spreadsheets are pervasive (Powell et al., 2009) due to the hidden nature of formulas and reliance on copy and paste.

Hard mental operations The user has fewer hard mental operations in understanding a particular flow than Excel[5] or PHP. However, understanding how side effects occur and how one part of the program may affect another is hard, as it is in full programming languages. Our use of optimistic concurrency control and automatic retrying means that users do not have to think in order to handle concurrency correctly. In contrast, a language like PHP requires many hard mental operations to reason about multiple simultaneous users.

Hidden dependencies Within a single flow, most dependencies are very visible, more so than Excel or PHP. The dependencies between database operations are hidden both within a flow and between flows. This kind of dependency is also hidden in PHP and Excel; it is hard to see how it could be shown in any environment.

Juxtaposability Similarly to Excel, it is not possible to view multiple parts of the notation at once. This is mostly a restriction to simplify the interface, but is weaker than most programming environments.

Premature commitment The system requires the user to design data tables before they can be used. If a user structures data in the wrong way, they might have to rewrite the whole application to recover. This is a common problem in all programming languages and so is usually overcome by methodology – primarily systems analysis and reducing coupling. VisualWebFlows is weaker than Excel and PHP in requiring too much premature commitment due to weaknesses in the environment.

[5]Because of the environment of Excel, it is time consuming and error prone to manually trace cause and effect. Excel comes with special tools for highlighting dependencies but they are insufficiently powerful and not well-known. In contrast, our graph based approach makes tracing cause and effect trivial.

Progressive evaluation Within a flow it is very easy to get feedback because of the preview feature. It is also possible to build and use parts of a program separately. Overall, similar to Excel and better than PHP.

Role-expressiveness It is easy to see the role of components within our flow system, since they show previews of what they do. However, choosing which component to use to achieve a particular goal is more difficult for users. This is a common problem in programming languages, so we are no worse than PHP, but Excel is better in providing searchable help and advice about the role of functions within the environment.

Secondary notation We provide the opportunity to use layout as a secondary notation in our visual editor. We do not provide any comment ability which is weaker than both Excel and PHP.

Viscosity The lack of functional abstraction means some changes to the structure of data may require multiple repetitive changes. This is compounded by our relatively weak environment – we do not have features like copy/paste or autofill that make this less of a problem in Excel. Overall, localised changes are very easy but more dramatic changes have noticeable viscosity.

Visibility When not in the flow editor, although it is possible to identify which parts of the page are flows, it is not possible to see how those flows function. This is no worse than Excel, where cells display their output instead of the formula used to generate that output, or PHP, where a function call tells you the name of the function but not how it actually functions.

We will now elaborate on what we believe are the important differences between our system and Excel and PHP, before considering areas where our environment could be improved according to our analysis.

According to our analysis, we believe we have managed to remain fairly similar to Excel on most cognitive dimensions.

In the area of secondary notation, we are weaker than Excel. Excel is what you might call a "notational playground", allowing arbitrary mixing of primary and secondary notation within a sheet. This makes Excel very powerful for exploration as a task, and enables it to be used in ways that were almost certainly not intended[6]. In contrast, our tool is more structured and lacks this ability to use secondary notation so powerfully.

We particularly improve on Excel in the area of hard mental operations and hidden dependencies. One of the main hard mental operations in Excel is tracing the dependen-

[6]The author's father designed a garden in Excel, including a hedge maze, by resizing the columns so the cells were square and then colouring the cells to represent the plant in that area. The only missing feature was the ability to count how many cells were of a certain colour, which would have helped him buy the correct amount of gravel for paths.

cies, which are hidden. By making dependencies visible, we aid the user in doing this. The same argument applies to comparisons with other non-graph-based languages.

We think we have improved on PHP (which we use as representative of a simple programming language for web applications) in two key areas for end-user programming. By providing the ability to see the results of programs as they are written (progressive evaluation) we make it easier for users to develop programs and self-correct as they proceed. Our modelling of web applications in our new paradigm enables more consistency in how operations occur and makes the mapping between the domain and the language closer.

However, there are a number of areas where our system would hold back more experienced programmers. The lack of tools for abstraction would lead to the attendant problems of copy-paste coding and is likely to be irritating to more advanced users. We considered adding the ability to define new blocks based on other blocks but felt it did not fit well with our aim at end-user programming[7]. This lack of abstraction ability is also the cause of some of the viscosity in our system, since without abstraction, common parts of programs are repeated, necessitating multiple, spread-out edits. Our environment is more diffuse than a typical programming environment, showing about equivalent to one method in the space of several methods.

This analysis has caused us to identify several areas where our environment could be enhanced to support users better without changing the notation. The lack of juxtaposability in our environment is unrelated to the notation. A windowed system for opening more than one flow at a time would be easy to implement and would solve this problem.

However, the diffuseness of our representation means that it will never be possible to show as much at once as with a more compact representation. A more compact representation (perhaps based on the syntax in Chapter 3) would be useful for power users as an alternative and completely compatible representation.

Some action blocks do not demonstrate their operation to the user in an intuitive way, and so use of these blocks can be error-prone. A better display on these blocks would help users avoid errors.

Our environment forces some viscosity due to a lack of features. Copy/paste could be added easily, as well as multiple selection. The use of basic block coalescing and automatic layout would make it much easier to rearrange flows and add new flow elements, which reduces viscosity at the expense of slightly weakening secondary notation. Because the flows language has various constraints on the types of connections between nodes, it would be possible to automatically lay flows out in a systematic and helpful way. In particular, data flows could always go downwards and action flows could always be to the right. These constraints would ensure that the layout follows the semantics of the flows language and would work well with an online layout system like that described by He and Marriott (He and Marriott, 1998). Given that secondary notation such as laying out graphs is often

[7]Note that Excel still does not have user-defined functions, despite research into how this could be implemented (Peyton Jones et al., 2003).

done badly by novices (Petre, 1995), we think this reduced expressibility could be a good trade-off.

A simple idea to improve secondary notation would be to add free text blocks that could be placed anywhere and contain uninterpreted comments. However, as with comments in programs, it would be easy for these to get out of date and to get left in inappropriate places. Therefore, comments should be attached to specific nodes, edges or groups of nodes, in order to force them to be connected to the program. This is another case where weakening the secondary notation to be less expressive makes it more useful in practice.

Overall, the Flows language improves the notation for beginners from an existing programming language like PHP on almost every dimension. Additionally, it is as good or better than Excel on most axes, which suggests it would be well suited to end users. Further work to improve the environment would remove most of the remaining disadvantages.

4.5 VisualWebFlows: A new platform for end-user web programming

We created the VisualWebFlows system to showcase the semantics described in Chapter 3. This chapter has explained the workings of this system and demonstrated how visual languages can be used for data processing tasks. We have shown how the novel separation of control and data flow in CD-SEP can be translated into a real programming language, and how the visual environment can support this separation through syntactic features such as layout and colour changes. We have also demonstrated a technique which allows users to observe the dynamic operation of programs statically through the preview tables we show next to each block in the environment. Flows is a scalable, web-based system which allows end-users to create distributed programs in a familiar online environment without software installation. We have also addressed aspects of the scaling problem for visual languages by separating out parts of the user's program and linking each part to the interface they are creating.

We evaluated the system through a user study and using the cognitive dimensions of notations framework. Our user study was small-scale and relied on computer scientists as study participants. Although the participants were not the target users of our system there are still some useful conclusions that can be drawn from the study. Firstly, study participants with a variety of experience and exposure to different systems found VisualWebFlows to be usable, and most of them successfully completed the study task. Secondly, many participants commented on the usefulness and effectiveness of the system, which suggested that even for computer scientists it might still fill a gap in the available programming languages for simple data gathering and processing tasks. A further user study with non-computer scientists would be necessary to validate these conclusions and ensure the system is usable for end-users. A more polished system, which could take into

account some of the feedback from study participants and conclusions drawn from the cognitive dimensions analysis, would be needed to make a full evaluation.

We used a cognitive dimensions of notations analysis to make up for some of the weaknesses of the user study. In most areas our system improved on programming languages for beginners and was closer to Excel, which is considered a successful end-user programming language. We also identified areas where we significantly improved on Excel, such as minimising hard mental operations and having fewer hidden dependencies. In several areas our prototype environment is understandably weaker than a commercial product, such as in secondary notation, juxtaposability and viscosity.

The main area that did not work well was the relational data model. Even technically savvy users struggled with how to structure their data, and the cognitive dimensions analysis revealed this to be primarily a problem of premature commitment. In the next chapter we consider how users could be aided in structuring their data by allowing them to restructure data after they have gathered it, and suggest how this data structuring technique could be integrated with the VisualWebFlows environment.

Chapter 5

Inferring types from data

> "All problems in computer science can be solved by another level of indirection."
>
> David Wheeler

> "...except for the problem of too many layers of indirection."
>
> *Unknown*

This chapter describes an inference technique which helps users to structure and restructure their data. Users need help structuring data because, while humans are good at identifying patterns, they are relatively poor at doing so over large data sets and at unifying related patterns. It is also helpful to aid users in restructuring data because end-users are relatively poor at abstract planning, so early choices may need to be changed in order to avoid premature commitment problems like those identified in the VisualWebFlows system in Chapter 4.

We expect users to be able to work with elements of data that have some structure, and to use our technique to create a unified structure over these elements. Many existing information systems contain data that is neither fully structured nor entirely unstructured, so called *semi-structured data*. The study of semi-structured data has mainly focused on structured records that contain unstructured fields. However, our inference must focus on the opposite problem – organising untyped records of typed data.

Some examples of data organised like this are:

- Key-value databases
- Badly normalised databases with many NULL values and multi-purpose fields
- Objects within dynamically-typed programs

In each of these cases, any particular value plucked from the data is structured, but there is no overall, predictable structuring on the data, making type checking, error detection or optimisation difficult or impossible. This may happen because the structuring has been lost, in which case we are reconstructing it, or that no overall structure ever existed, so we are constructing one. A further example is e-mail, which (from a semantic point of view) is an unstructured list of semi-structured records.

We use records (a record being a map from textual keys to primitive values) as the basic element within a database system for end-users because they fit well with user's understanding of paper filing systems, where each record is a self-contained unit of data, and computer filing systems, where again each file is a self-contained document. Records were used very successfully as the basis of Hypercard (Apple, 1998), one of the most popular and successful end-user database systems. We want to enable users to store data in records without thinking too much about how those records are structured, but to then be able to have programs act on sets of related records.

To give a concrete example, consider a key-value database. This database contains records and each record is made up of key-value pairs. For example, we might have three records {Processor:"3GHz", Memory:"4GB"}, {Processor:"2GHz", RAM:"1GB"}, and {Benchmark:"Memory copy"}. The ideal structuring would be into two sets of records, one of type {Processor, Memory/RAM} and another of type {Benchmark}. This structuring reveals the two types of data within the database and identifies the variation within one of those types (although this relies on an ontology to equate Memory and RAM). An acceptable and more feasible structuring would be {Processor, Memory, RAM} and {Benchmark}, which identifies the two datatypes, but does not fully categorise the former. A poor structuring would be {Processor, Benchmark}, which does not separate the two datatypes. An absurd structuring would be {Clowns}, {Chickens} and {Cowboys}, which bears no relation to the input data.

We infer a good structuring of the user's data by using a statistical clustering technique. We discover the types within the set of records created by the user in a principled and robust way. We do this by building a simple trained simulation of the user's preferences about matching of records and by then combining these matching judgements into an evaluation function for a set of types using standard Bayesian techniques. We then use a search technique with this evaluation function to find the best set of types for the user's data. The technique attempts to match records that the user would consider related and tries to also minimise the number of different types generated. Because of the statistical approach, it is robust to minor variations between records. As well as finding records that are related to each other, this technique also generates types that could be used by the user as templates for creating new records.

Section 5.1 begins by giving an overview of the statistical principles used. We describe how we formalise our intuitions about user preferences and how we can combine judgements about individual types to give an overall structure. In Section 5.2 we describe how we calculate similarity between records and types; and how we build this into a statistical

evaluation of a set of types for a set of records. Section 5.3 shows how we use this statistical evaluation measure to generate and select the best set of types for a particular data set. We compare different search techniques for checking a manageable number of models before settling on simulated annealing as most suitable. In Section 5.4 we then compare the techniques described to existing techniques such as K-clustering, minimum descriptor length, ad-hoc analyses and others. Section 5.5 discusses some possible applications for our technique and looks at whether it is suitable for those applications. In Section 5.6 we show how these data structuring techniques could be integrated with the VisualWebFlows system described in Chapter 4 in order to reduce the premature commitment problem it has. Section 5.7 concludes and discusses how this work fits into other areas of computer science.

5.1 Overview of algorithm principles

In this section we consider how we can formalise our intuitions about how users consider types (and whether there is a match between a record and a type) into a statistically-sound evaluation. We then show how these statistical evaluations can be combined to give a measure of the match between a set of records (*evidence*) and a set of types (a *model*). We then define some notation and terminology which is used throughout this chapter.

5.1.1 Statistical typing of records

Since we are making a system for end-users, we want the structuring that our system imposes to resemble the intuitions of users about the similarity and differences between types. We treat the eventual user as an oracle that may or may not agree that a record has a certain type. We therefore create an algorithm that simulates that oracle in order to estimate the likelihood of a type being acceptable to the user.

What does it mean for a type to be acceptable to the oracle? And what does it mean for our algorithm to provide the type of a set of records? To answer the second question, the mapping from each record to a type is similar to a classical type environment, but it maps values instead of variables. A classical typing would provide a type for a set of records by providing a set of types (a model) and a mapping from each record to a type in the model. Such a classical environment can be written as a mapping Γ of type $v \to \tau$. We can rewrite such an environment as $v \to \mathcal{P}(\tau)$ which removes the restriction that each variable is of exactly one type. This could be written as $v \to \tau \to \{false, true\}$. We can then lift the restriction that a value either has a type or not by defining an environment Δ of type $v \to \tau \to [0, 1]$, which maps a value onto a function from types to probabilities. This shows how each value may be considered to have multiple types, each with a specified probability of being accepted. Note we can create a classical-style value environment $\Gamma(v) = \arg\max_\tau \Delta(v)(\tau)$ which chooses the most probable type for each value. However, what we are most interested in is the range of Γ: that is, the set

of preferred types is what we will call the model, and the mapping Δ is implicit[1]. We first consider the mapping of individual values to types, and then show below and in Section 5.2 how these individual mappings can be combined to give an overall evaluation of how well a particular model fits the evidence.

To return to our earlier question, *"what does it mean for a type to be acceptable to the oracle?"*, we measure our estimate of whether the oracle accepts a type as a probability, which encompasses both the uncertainty of the oracle accepting a type[2] and our algorithm's uncertainty about what the oracle will accept. Obviously, for any particular record, there may be multiple types that are acceptable to the oracle with equal probability. Equally there may be an infinite number of types that are at least somewhat acceptable.

An exact match between the record and its type would obviously be accepted by the oracle with a very high probability and an arbitrary but unrelated type would be accepted with a very low probability. We can therefore use these probabilities comparatively to choose the type most likely to be accepted by the oracle; and we can also combine them to find the probability that the oracle accepts a set of types.

Because our typing judgement ascribes a probability instead of a boolean, a value may be considered to have a type that is not an exact match classically. For example, a value that does not contain an entry for a label in its type could just be considered to have a null value for that field (database-like semantics). On the other hand, a value containing an entry not found in its type can just be considered as a subclass of the type given (object-orientated semantics).

These different semantics may also be applied differently depending on the number of values of a certain type, because, like many statistical calculations, these preferences are not linear. A small number of values that are variations of one type implies the object-orientated semantics, where those values are subclasses of the type, because the variations are rare in the evidence so do not support the same variations in the model. Whereas, a large number of values that are variations of one type implies the database-like semantics, where those values merely have fields missing, because a large number of examples in the evidence supports a variation in the model. As an analogy, getting 3 out of 4 heads after flipping a coin you believe to be fair does not suggest the coin is biased, but 750 out of 1000 heads certainly would. The exact workings of our oracle estimator are described further in Subsection 5.2.1.

[1] Δ is fully determined given the set of types and the evaluation function that takes a type and value and returns a probability, so there is no need to specify it as part of the model.

[2] This is the Bayesian view that a probability is a single measure of uncertainty of any and all kinds. From a frequentist perspective, the uncertainty of the oracle can be interpreted as asking the oracle repeatedly and measuring how many times it accepts the type.

5.1.2 Combining typing judgements with Bayes' theorem

We need a way to combine the above idea of statistical typing judgements about individual types in order to create an evaluation function of the whole model. However, for our generated models to be useful, we need to balance match quality with model complexity. On the one hand, we can create a perfectly matching (but useless) model that has one type per value. On the other hand, a model consisting only of the empty type is simple, but does not explain the evidence well and is equally useless. We can see there are two opposing forces on the model, one trying to add elements and the other trying to remove them, and our evaluation function should reflect that. Trying to calculate model complexity and match quality and then combine these on an ad-hoc basis is unprincipled and difficult. We use Bayes' theorem to evaluate the model in a way that enables us to consider model complexity as well as closeness of match. In particular, *we wish to find the probability that a particular model M is acceptable given the evidence E.* This is denoted by $P(M|E)$, but unfortunately we cannot calculate it directly from our typing judgements since they are based around the acceptability of evidence given a certain model. Instead, we need to turn our estimates of the likelihood of the oracle accepting that a certain value has a certain type into a conditional model probability.

Bayes' theorem shows $P(M|E) = \frac{P(E|M)P(M)}{P(E)}$. We have already discussed how we will calculate $P(E|M)$ by combining probability estimates of the acceptability of types from the model for each value in the evidence. We show how $P(M)$ can be calculated on a similar basis in Subsection 5.2.3. From the formula above, $P(E|M)P(M)$ is proportional to $P(M|E)$ if $P(E)$ is constant, which it is for fixed evidence, so our evaluation function for assessing models simplifies to $P(E|M)P(M)$. Note that these two terms are affected by the size of the model in opposite directions and therefore correspond to the two opposing forces on the model that we anticipated our evaluation function would contain.

We calculate the closeness of the match $P(E|M)$ by looking at the match between each element of the evidence and each element of the model. We describe this further in Subsection 5.2.2. A good model will have few self-matches as these represent overlaps between types. Therefore we evaluate the complexity of the model $P(M)$ similarly by looking at the match between each element of the model and every other model element. This will be explained in Subsection 5.2.3.

5.1.3 Terminology and typing model

We create the *candidate types* (types that could explain some of the evidence and denoted t) by examining the values (v) in the evidence multiset (E). A *candidate model* (denoted M) is a set of candidate types that together might explain the evidence.

As a simple initial way of describing and comparing types, we consider evidence which consists of a collection of values that are records with fields of type unit[3], e.g. `{A:unit,`

[3]We use unit since our algorithm does not examine the type or value of record fields. We consider how to handle more advanced data types in Subsection 5.3.3.

`B:unit}`, {`C:unit`}. Records could have fields of other types, e.g. strings or integers, but our inference does not look at these types so we treat them as unit. A type can therefore be unambiguously represented as a set of record labels. We write types in our text as {`A,B,C`} and we express values in the evidence in the same way, since with unit values the only distinguishing features of records are the labels. The evidence may contain multiple values of the same classical type. In that case, we represent that multiple evidence using a multiplication sign. For example, evidence containing 5 records of type {`A,B,C`} is written as $5 \times$ {`A,B,C`}. The empty type {} is written as $\bot$. The set union of the classical types of each of the records in the evidence (that is, the type with all of the labels that appear anywhere in the evidence) is called $\top$.

5.2 Statistical model evaluation

Evaluating a model requires two steps – assessing the closeness of match between the model and the evidence $P(E|M)$, and assessing the complexity of the model $P(M)$. As discussed above, our final evaluation score for a model is $P(E|M)P(M)$ which, by Bayes' theorem, is proportional to the probability a particular model could have been the source of some evidence $P(M|E)$. This gives us a way to rank models and compare them quantitatively.

We show how to estimate the probability a user accepts that a record has a particular type in Subsection 5.2.1. We then consider how we can combine these probability measures to calculate $P(E|M)$ and $P(M)$ in Subsections 5.2.2 and 5.2.3 respectively.

5.2.1 Lifting similarities to probabilities

As discussed in Subsection 5.1.1, because we want to create typing judgements that a user would agree with, we need to simulate the user. We denote the probability that a user accepts a type for a particular value as $P(v|t)$. Since all the user has available to consider are the labels in the value and in the type, we presume that any similarity function on these labels would give a good estimate of the likelihood of a user accepting a typing judgement. We could just use a similarity function that varied between 0 and 1 as a probability, despite this being unprincipled and technically incorrect. However, in order to create a more principled approach, we use a conditioning function on the similarity measure to convert it into a probability. This approach has the added advantage that it gives us a straightforward way to combine different similarity measures and also to incorporate measures that do not vary between 0 and 1. The function we use to lift similarity measures to probabilities will be based on a set of training data from users on whether they accept typings with different similarities. We do not anticipate doing any kind of curve fitting or non-parametric modeling; instead we propose choosing a simple probability distribution that fits with the similarity measure being considered, and then using linear regression to fit the parameters of that distribution to the training data.

Whether we use a conditioning function or not, we first need to identify some possible measures of similarity. We have investigated several different similarity measures. We need similarity measures that are fast to calculate and not overly dependent on the types of things we are comparing since we are trying to develop a general technique. The two most promising ones are total overlap and the Jaccard similarity coefficient. Total overlap between labels $O(v,t) = |v \cap t|$ gives us a measure of similarity that weights a larger amount of evidence of overlap more highly. Total overlap is useful since a large number of overlapping labels is suggestive of similarity, even if there are also many labels that do not overlap. However, overlap is not constrained to the $[0,1]$ range, so it cannot approximate a probability directly. The Jaccard similarity coefficient $J(v,t) = \frac{|v \cap t|}{|v \cup t|}$ is symmetric in addition or removal of labels, which gives no bias to the OO-like or database-like semantics for outliers and variations (Jaccard, 1901). An interesting extension might be to use either string similarity measures or an ontology such as WordNet (WordNet, 2010) to match together non-equal record labels, but we do not pursue that any further here.

As we mentioned, a simple, unprincipled approach would be to use the Jaccard similarity coefficient directly as an estimate of the match probability since it ranges between 0 and 1. As a slight enhancement, we could clip it to between some ϵ_1 and $1 - \epsilon_2$, to include the intuition that even a very poor match is not impossible and a perfect match might not always be considered acceptable by a user[4].

Instead of (mis)using a similarity coefficient in this way, we will estimate a probability of an acceptable match based on some distribution function on the similarity coefficient. The distribution function will return an estimate of the probability that a particular value came from a particular type in the model, based on the output of some similarity function. We define a function Ψ on each similarity coefficient which converts the result of that similarity measurement to a probability estimate. This is the probability that a user accepts that type for that value, according to that similarity measure. Since we need a different Ψ function for each similarity measure, we refer to the similarity measure with a subscript on the Ψ, i.e. for the Jaccard similarity measure, we refer to Ψ_J and for total overlap we use Ψ_O. We can then combine similarity measures, for example using both total overlap and the Jaccard similarity coefficient, by combining these probability estimates using the naïve Bayesian assumption[5]. Each similarity probability is treated independently and the outputs of the different Ψ functions are simply multiplied to give the overall probability estimate.

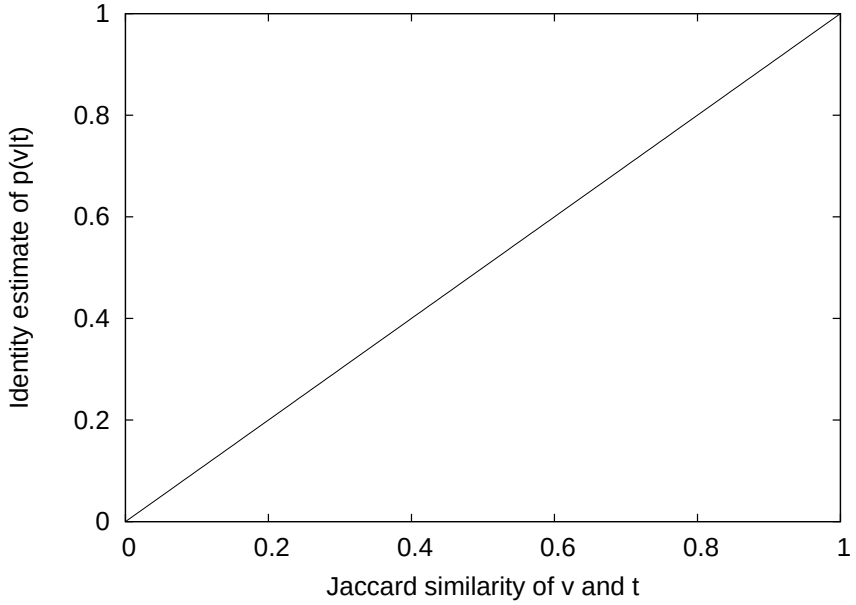
[4]As an example of a perfect match not being acceptable, consider the record of type {`length,height, wadth [sic]`} – most users would consider the typing {`length,height,width`} more acceptable.

[5]The author has been unable to find who first coined this term. Lewis' survey paper on the assumption, *Naive (Bayes) at forty: The independence assumption in information retrieval*, identifies two papers by Maron and Kuhns that make the assumption from 1960 and 1961 but they do not name it. Russell and Norvig suggest in *Artificial Intelligence: A Modern Approach* that either Duda and Hart, or Robertson and Spärck-Jones coined the term in 1973 or 1976 respectively. In any case, it refers to the treatment of all variables, even obviously dependent ones, as independent in order to simplify the analysis.

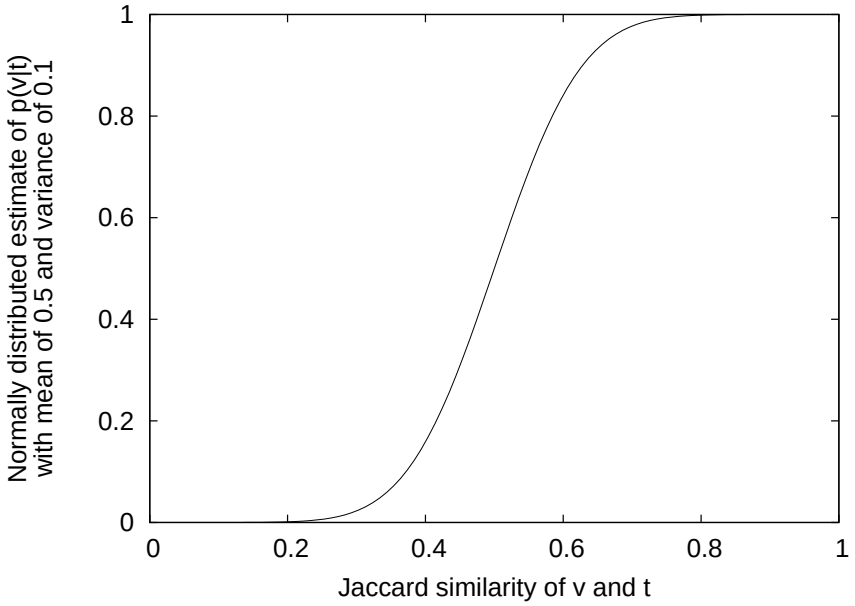
We expect each Ψ function to have a range of $[0, 1]$, and to be monotonically related to the similarity measure, so that more similarity leads to higher probability. We do not expect the exact values of a Ψ function to make a big difference in most cases; it only affects the results of the algorithm in borderline cases. We now discuss some examples of the effect of different Ψ functions.

Effect of different Ψ functions We wish to choose Ψ functions which give us an appropriate estimate of the actual probability based on each similarity measure. We consider some possibilities for different Ψ functions below.

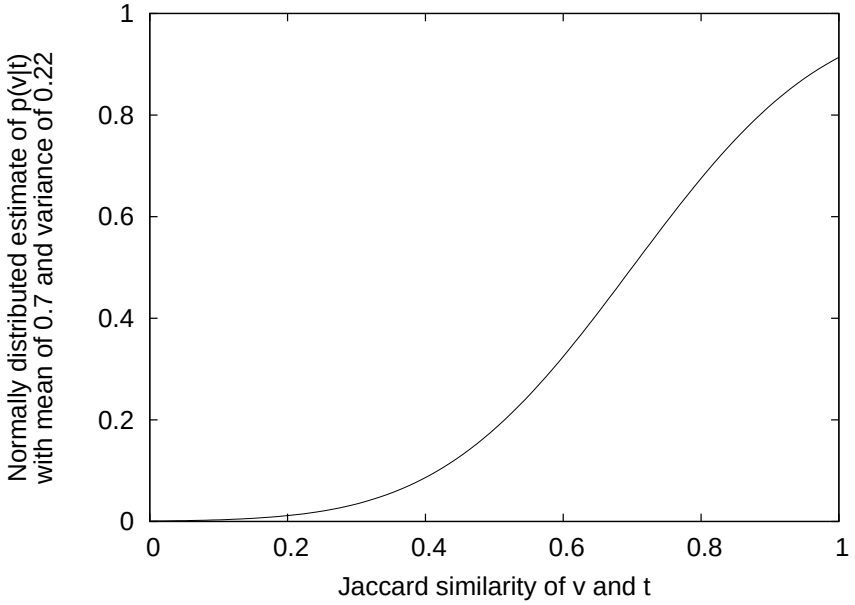
If we directly use J as a probability, that is the same as making our Ψ_J function the identity:



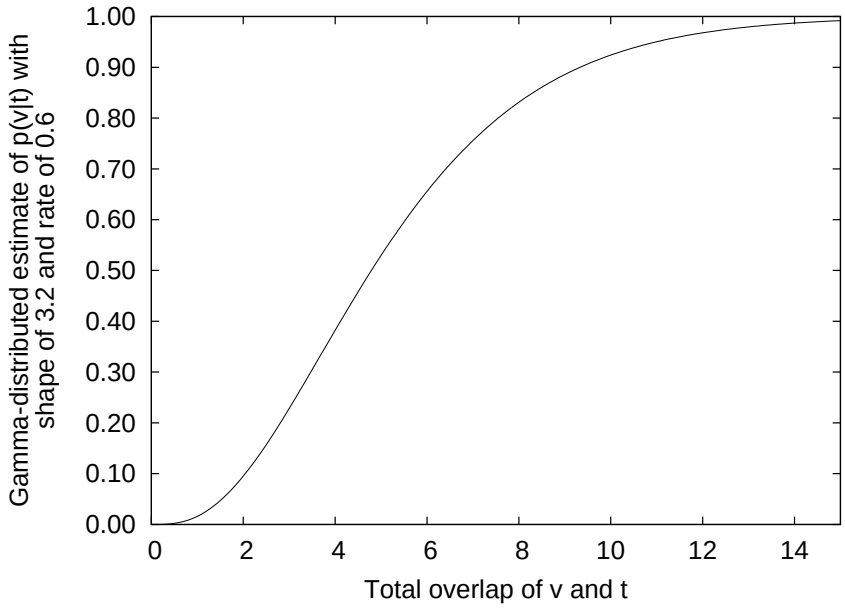
We might expect a sharper cut-off, and would like a way to vary the Ψ functions parametrically. We choose a probability distribution to generate the functions that have properties appropriate to the similarity function we are using. For example, the normal distribution is a straightforward parametric distribution that is probably suitable for Ψ_J. Taking arbitrary values for mean and variance of 0.5 and 0.1 respectively, we get the following function:



In order to choose suitable parameters for each distribution, we use a set of training data. Note this training is not complex or non-parameterised fitting, but instead selecting a small number of parameters to affect the match probability distribution. We give more details on the training process below. In this case, we might expect training to lead to a Ψ_J function like the one below:



Turning now to the total overlap similarity function, we might expect a distribution which starts low when there is no overlap and then tends to 1 as the number of overlapping labels increases. The Gamma distribution is probably a suitable parametric distribution for the Ψ_O function like so:



These mapping functions will not affect type mapping in the obvious cases, when there is no overlap between types, but in the case of some overlap, the functions serve two purposes. They provide a real probability estimate of the likelihood that a particular value came from a particular type. They can have the properties we expect, in particular, never reaching 1, which makes sense since even if the types match exactly, the value could be a variation of some other, similar type. They also allow us to condition the response to a low degree of matching, so that (as shown in the latter two example functions) poor matching leads to almost no probability that the type is the source of the value, which again makes sense. Since the output of the trained functions is still somewhat similar to the identity function, we would expect them to only make a difference in borderline cases.

Using training to set Ψ parameters In order to create a Ψ function for each similarity measure, we need some kind of labelled training set of examples for that similarity measure. We want to create our function Ψ such that it closely matches the points in the training set, which includes both values for the similarity measure and for the probability of a match. We choose a probability distribution such as a normal distribution that has a small number of parameters and draw a random variable from that distribution for each Ψ function, e.g. $X_J \sim N(\mu_J, \sigma_J^2)$. We define our probability function (Ψ_s) as the probability that a number from that distribution is less than the similarity value: $P(v|t) = \Psi_s(v, t) = P(X_s < s(v,t))$. Note that Ψ gives us a cumulative probability estimate, not an estimate of the probability density for that similarity.

Finally, we use linear regression to choose the parameters of the probability distribution (e.g. μ and σ) that give the best match between the training probabilities and the output of the probability function. Note we are not using a large training set to create the Ψ function as a point-wise curve-fitting; instead we are using a small number of examples

to train the small number of parameters used to control the distribution behind the Ψ function.

5.2.2 Bayesian evaluation of evidence given a model

Now we have an estimator for $P(v|t)$ we need to construct an estimate for $P(E|M)$. We do this in two steps. Firstly, we again use the standard naïve Bayesian assumption and treat each value in the evidence independently, so $P(E|M)$ is $\prod_{v \in E} p(v|M)$. If the same value occurs multiple times in the evidence, e.g. $10 \times \{\texttt{A,B,C}\}$, we include the probability that many times in the product, so in this case we include a $p(\{\texttt{A,B,C}\}|M)^{10}$ term in the probability.

Secondly, since we do not know which type a value has come from (and finding out is part of the process), we must calculate the probability a value has come from each of the types in the model and then combine these. We can only reject the notion that a model gives an acceptable typing for a value if none of the types in the model are acceptable typings for that value. For a model consisting of a single element t, the probability $p(v|M)$ equals $1 - (1 - p(v|t))$ which is obviously just $p(v|t)$ as you might expect. In the case of a model of two elements, $t, u \in M$, the value could have come from either t or u. Therefore, the probability $p(v|M)$ must be the probability that either t and/or u explains the evidence. This is just the negation of the probability that neither t nor u explains the evidence, giving us $1 - ((1 - p(v|t)) \times (1 - p(v|u)))$. This formula generalises with $p(v|M)$ given by $1 - \prod_{t \in M} (1 - p(v|t))$. Our overall estimate of $P(E|M)$ is therefore:

$$\prod_{v \in E} \Big(1 - \prod_{t \in M} \Big(1 - p(v|t)\Big)\Big)$$

5.2.3 Bayesian evaluation of models

We evaluate the complexity of the model by looking at the match between each element of the model and all its other elements. The justification for this is as follows. Supposing a model contains types t_1 and t_2, and that a value of classical type t_1 could be generated by a variation of t_2, then it is likely that the model could do without t_1, since if t_2 can generate values of type t_1 then it is likely that any values generated by t_1 could be generated by t_2 instead. It is also possible that we could do without t_2 instead and so the exact decision will depend on the evidence through the $P(E|M)$ term. For example, if the evidence contains values that are very unlikely to have been generated by t_2 but could be generated by t_1, this is good evidence for including t_1 and will outweigh the model evaluation's preference for t_2 over t_1. We therefore calculate $P(M)$ similarly to $P(E|M)$, which also allows us to leverage the same similarity measures.

In the model, we are concerned with penalising self-similarity. A good model will have few self-matches, so we compare the model against itself, in a similar way to how we

compared the evidence against the model, but with the scoring inverted, so a good match makes the model improbable and a bad match makes the model likely. For a two element model, t and u, the probability $P(M)$ is $(1 - p(t|u)) \times (1 - p(u|t))$. This generalises so $P(t|M)$ is equal to $\prod_{u \in M, u \neq t} (1 - p(t|u))$, which is essentially the negation of $P(v|M)$, just taking both elements to be compared for similarity from the model, instead of one from the model and one from the evidence, and excluding the case of comparing a type against itself. $P(M)$ is calculated in exactly the same way as $P(E|M)$, that is, $\prod_{t \in M} P(t|M)$.

Instead of using $1 - P(t|u)$ as the probability of a model containing both t and u as types, we could create an estimator specifically for models. This would improve our model evaluation by creating a separate set of Ψ functions for evaluating whether a user would expect two types to appear in the same model. These could be trained in exactly the same way as the ones described in Subsection 5.2.1, but on pairs of types instead of types and values.

However, we would again expect a specially trained estimator for models to only have an effect in marginal cases, so we keep the original $1 - P(t|u)$ formulation. Our estimate of $P(M)$ is then:

$$\prod_{t \in M} \prod_{u \in M, u \neq t} \Big(1 - p(t|u)\Big)$$

which gives an overall evaluation function of:

$$\left[\prod_{v \in E} \Big(1 - \prod_{t \in M} \Big(1 - p(v|t)\Big)\Big)\right] \left[\prod_{t \in M} \prod_{u \in M, u \neq t} \Big(1 - p(t|u)\Big)\right]$$

5.3 Model generation and selection

Now we have a way of evaluating models we need a way of generating candidate models in order to find the one with the highest score. A simple way to do this would be to generate a list containing all possible models and then select the highest scoring one. In order to generate all possible models we must first generate a list of all possible types (which we can create by taking the powerset of $\top$) and then take all subsets of that list to get the set of all possible models (the powerset of the powerset of $\top$). We might compare this algorithm to the permutation sort algorithm: generate all permutations of the input list, then return the one that scores highest with an evaluation function that rewards ordering[6]. This is clearly an inefficient way to sort. Listing all of the possible models made up of all of the possible types and then selecting the best one is similarly inefficient.

Since this method generates a powerset of a powerset, the set of candidate models is intractably large for even small collections of evidence. Therefore, in the same way better sorting algorithms try to generate only more-sorted lists as they proceed, we wish to make our algorithm more tractable by generating only high-scoring models.

[6]That is, return the permutation that is sorted.

We improve the two subset-generating steps differently. Firstly, we reduce the number of candidate types by applying heuristics to generate them instead of forming the powerset. Secondly, we search the space of candidate models more intelligently instead of brute force. Note this still does not change which model is selected by the algorithm overall, so long as the algorithm encounters the model that the evaluation function considers best at some point. We designed our heuristics to generate all of the types that are even slightly likely to appear in the best model and therefore our search will be able to find the best model.

5.3.1 Fast heuristic type generation

We first describe in detail the powerset method of candidate type generation as a basis for two improvements: forming a lattice only of types that combine whole other types, and only forming the parts of that lattice that have similar members in the evidence.

Some types in the evidence may not appear in the model. This would typically happen when those types are rare variations of more common types. As we discussed in Subsection 5.1.1, this breaks down into two cases. Where there are rare values with overlapping types, for example, $1 \times \{\texttt{A,B,C}\}$, $1 \times \{\texttt{A,B,D}\}$, $1 \times \{\texttt{A,B,E}\}$, these might be best modelled by a type that covers their common elements, in this case $\{\texttt{A,B}\}$. Where there are many values with many fields in common, we might generate a type that incorporates all of the fields, including those that appear optional. For example, $100 \times \{\texttt{A,B,C}\}$, $100 \times \{\texttt{A,B,D}\}$ might be best modelled as $\{\texttt{A,B,C,D}\}$[7].

In order to generate these types that do not appear in the evidence, we take the union of the types in the evidence (considering them as sets), to create the type $\top$, here $\{\texttt{A,B,C,D,E}\}$ (i.e. $\top$ is the set of all record labels used in the evidence). $\top$ can represent any value in the evidence, albeit with some fields missing or considered to have default values. Similarly, the type called $\bot$ (always $\{\}$) corresponding to the empty set can represent any value if we consider that value to be of the empty type with some extra fields.

It never makes sense for the model to contain a type with a record label that never appears in the evidence. Because of this, any useful type must be a subset of $\top$ in the set representation. Therefore the collection of candidate types is the set of all subsets, the powerset, of $\top$, written as $\mathcal{P}(\top)$.

We can eliminate many of the types in $\mathcal{P}(\top)$ since they do not correspond to any sensible type in the evidence. For example, if the evidence is $100 \times \{\texttt{A,B}\}$ and $100 \times \{\texttt{C,D}\}$, then the types $\{\texttt{A,C}\}$ and $\{\texttt{B,D}\}$ are unlikely to be useful. We create only useful types by forming a lattice of the types that exist in the evidence. Our lattice operations are set union and set intersection over the set representations of the types[8]. This already improves our runtime since the lattice is formed by union and intersection on existing types, which will mean it potentially has far fewer elements than $\mathcal{P}(\top)$. Specifically, if

[7] We later consider variant types that take into account exclusion between properties, i.e. forming $\{\texttt{A,B,C+D}\}$ (where `+` is a sum type) in this example.

[8] This explains the origin of naming of the $\top$ and $\bot$ types.

the types in the evidence do not overlap, then the lattice will only consist of combinations of entire types, whereas $\mathcal{P}(\top)$ will contain partial combinations of types. For example, if the evidence contains $100 \times \{\texttt{A,B}\}$ and $100 \times \{\texttt{C,D}\}$, the powerset of $\top$ will contain $2^4 = 16$ elements[9], but the lattice only has four members – the original types $\{\texttt{A,B}\}$ and $\{\texttt{C,D}\}$, and additionally $\{\texttt{A,B,C,D}\}$ and $\{\}$.

We can improve on the lattice method further by building a sparse lattice of the types found from the values in the evidence, and only adding types to the lattice that are suggested by a heuristic. To do this, we first define a type as being *supported* if it is in the evidence or suggested by it. The union of two very common types with a large overlap is obviously supported by the evidence, whereas a variation of a common type in the evidence that has nothing in common with anything else in the evidence is unsupported.

We then assign weights to the lattice and retain only the non-zero elements. Initially, we assign a weight to each element in the type lattice according to the number of occurrences of that type in the evidence and zero weight to types not occurring in the evidence. We then apply a blurring kernel to the lattice repeatedly until it stops changing. This takes each pair of elements in the lattice and checks if they have more than one label in common. If they do, we add weight to the lattice at their union and intersection equal to the weight of the heaviest of them divided by two, as long as that weight is at least 1. To prevent an endless increase in weight, once a type has been compared against all other types, it is not used as a source again. Types with non-zero weight after this process are considered as candidates.

To give an example, consider the evidence: $4 \times \{\texttt{A,B,C}\}$, $2 \times \{\texttt{A,B,D}\}$, $2 \times \{\texttt{D,E}\}$, and $1 \times \{\texttt{E,F}\}$. Our first stage of blurring would generate the following additional types (we write the weight of these types as if extra values existed): $2 \times \{\texttt{A,B}\}$ and $2 \times \{\texttt{A,B,C,D}\}$ from combining the first two values; $1 \times \{\texttt{D}\}$ and $1 \times \{\texttt{A,B,C,D,E}\}$ from the second and third values; and $1 \times \{\texttt{E}\}$ and $1 \times \{\texttt{D,E,F}\}$ from the third and fourth values. Next we would run the blurring again on these values, discarding any types already discovered: $1 \times \{\texttt{A,B,C,D,E}\}$ from the second and fourth new values; and $1 \times \{\texttt{A,B,C,D,E,F}\}$ from the second and sixth new values. Because all the new values have a weight of 1, no more blurring is possible, so we stop there, having generated 12 of the possible 64 types in the powerset.

The idea of this algorithm is to spread the weight of support from defined elements in the evidence, which are obviously supported since they are in the evidence, to types which are not in the evidence but are similar to those types. This heuristic is designed to create the types that we need to form the best model with high probability whilst creating a set of candidate types that is more tractable than $\top$.

[9] The powerset of a finite set of n elements contains 2^n members.

5.3.2 Model generation and search

We then create combinations of these candidate types to make candidate models. A model M is a set of types (and an implicit mapping of each element of the evidence onto one of those types[10]). As discussed, the simplest way to generate candidate models is to take the powerset of all candidate types.

Although our set of candidate types is smaller than a powerset, evaluating every model from the powerset of these types is still impractical since there are still $2^{|T|}$ candidate models, where T is the set of candidate types. Given that we expect a model to contain relatively few types, a simple way to make this more tractable is to restrict the number of types to some k and consider all models containing k or fewer types, which gives us $O(|T|^k)$ to consider.

However, this is still intractable for non-small integer k, and requires us to select an appropriate value for k. Instead of attempting to generate all possible models and evaluating them, we can achieve greater efficiency by lazily searching through the space of possible models using the evaluation function to guide our search. A simple greedy search would work well in some cases by adding the type that gives the biggest improvement to the model until no improvements can be found. This algorithm has an attractive $O(|T|^2)$ run time, but in some cases it would precommit to types that are too broad and then be unable to discard them. For example, given values $100 \times \{\texttt{A,B,C}\}$ and $100 \times \{\texttt{A,B,D,E}\}$, the first type selected is likely to be $\{\texttt{A,B}\}$, which will then inhibit having $\{\texttt{A,B,C}\}$ or $\{\texttt{A,B,D,E}\}$ in the model, preventing us from reaching the model containing only those two elements ($\{\texttt{A,B,C}\}$ and $\{\texttt{A,B,D,E}\}$), which seems like the best model in this case.

Most improvements on best-first search, for example A* search, require some kind of distance metric and/or some kind of estimator of how close we are to 'success'. Unfortunately, our model evaluation function is not a distance metric and we have not found a way to create a useful distance metric from it. Additionally, metrics are less suitable for use on high-dimensional spaces. We also lack a good way to estimate how close we are to 'success' in the search.

Therefore, an optimisation method is more suitable for this task than search algorithms. Gradient-based methods are of no use since our model evaluation has no usable gradient because our models are defined in a discrete space of $\{0, 1\} \times |T|$ – that is, once a type has been added to the model, finding that it has improved the evaluation does not help improve the model further, since it cannot be added again.

One way to look at our evaluation function is to consider it as a measure of the energy of the model, where similarity between model elements and evidence has an attractive force; and similar model elements feel a repulsive force. Because of this, simulated annealing makes sense as an algorithmic technique for minimising the energy stored by these forces.

[10]The mapping tends to be implicit as we map each value onto the type that is the best match for that value, but it is important formally. If there are equally good matches, we arbitrarily select a mapping for all values of that type.

We simulate annealing by making random adjustments of adding or removing a type from the model. When these changes improve the score, we accept them unconditionally. Otherwise, we accept them with a probability that decreases as the algorithm proceeds. As the algorithm proceeds we keep track of the best model found so far. Once we have finished the predefined annealing schedule (the schedule of how the acceptance probability decreases), we return the best model found. This method is robust against local maxima and effective for quickly finding good models whilst the unconditional acceptance of model improvements encourages the best model to appear.

5.3.3 Handling more data types

We now show how the same approach could support more advanced data structures. In particular, these techniques could be expanded to handle distinct primitive types, sum types, recursive types (tree structures and DAGs), and mutually recursive records (cyclic graph structures). With these four features it would be possible to handle all of the current popular formats of semi-structured data. Calculating match probabilities would not be any more difficult with these data types, but further work would be needed to efficiently generate models with these characteristics. We now briefly explain how each of these features could be implemented.

Simply typed values Up to now, we have considered record types simply as a set of labels. However, classically, a record type is a mapping from a set of labels to a set of other types. We could extend our model to cover records of this kind. As well as covering primitive types like strings, integers and unit, we could also support richer types such as postal codes or email addresses using Scaffidi et al.'s Topes system (Scaffidi et al., 2008).

In order to infer a model for these records it would be necessary to handle the case where the values of matching record labels have different primitive types. We would use training data to create a matrix of similarity probabilities between each primitive type. This would be combined with the existing probabalistic similarity measures by multiplying the label match probability for a value and a type with the similarity probabilities between the primitive types of each matched label. For example, matching {`A:"foo",B:2,C:true`} with {`A:string,B:integer,C:integer,D:boolean`} would mean multiplying $p(\{\texttt{A,B,C}\}|\{\texttt{A,B,C,D}\})$ with $p(\text{“}foo\text{” is a } string)$, $p(2 \text{ is a } integer)$ and $p(true \text{ is a } integer)$.

We also envisage a synthetic type that represents the union of all primitive types. It would be included in the matrix of similarity probabilities and generated in candidate models where the same label is used for a variety of different primitive types in the evidence.

Disjoint typed records These allow us to express choice inside records, for example, showing that a record representing a person could contain either a date of birth or an

age. A record type would no longer be a simple map, but instead a structure of sums (disjunctions) and products (conjunctions) on label to type mappings. We write the conjunctions with commas as before; the disjunctions as pluses; and use parentheses for grouping, giving types like {A,B,(C+D,(E+F))}, which means the type with labels {A, B,C}, {A,B,D,E} or {A,B,D,F}. We find the similarity of these records by walking down the record structure, trying each branch crosswise in the case of disjunctions, and taking the best match probability. For example, matching {A+B} with {B+C} requires matching A with B, A with C, B with B, and B with C.

Creating models containing these new types is straightforward – in addition to the union and intersection operations we used before to form a lattice we also consider a disjoint union operation ($\uplus$) which forms a sum of the dissimilar labels between the two types. For example, {A,B,C} $\uplus$ {A,B,D} = {A,B,C+D}.

Recursive types We can handle recursively typed records relatively easily by first identifying leaf records which do not have any record children, typing them, and then working up the structure. Starting from level zero, we assign types using the above algorithm to all records at that level. Since level zero contains no child records, the above algorithm works without modification. However, we need to refine the algorithm to handle higher levels. In order to handle level $n + 1$, given level n has been typed, we have two choices. Firstly, we could simply run the inference on records at level $n + 1$. We would calculate the similarity between two records containing lower level records by considering the record types already discovered as possible types in addition to the primitive types. The similarity between record types could be calculated recursively and memoised, so this would not require much additional work.

The second option is to assign types according to the types already discovered for all records at level n and below, but to rerun the inference on all of the records from level 0 to $n + 1$. This would enable us to recognise structures like organisational charts, where records at different levels are actually of the same type (although there will be an obvious difference between employees, who would be leaf nodes with no children, and managers, who would have descendants), at the expense of running the inference on more records repeatedly. However, this overhead would be minimal for graphs with a branching factor above 1, which would generally be the case.

Mutually recursive records The above technique for structures that are directed acyclic graphs cannot handle mutually recursive records and may require many repetitions to terminate. A better technique that can handle mutually recursive records neatly is to use the second technique for recursive records, but to apply it to all of the records at every step, and then to repeat the analysis, using the types from the previous run to match child records. The first run would give an arbitrary marker type to child records, which would mean all child records have a fixed similarity probability. After the first run, actual types would be used, with the child record types gradually being refined with more

specific types: if all the records referred to by a field are of the same type, then that field can take on the type of the record instead of the generic record type. We expect this technique would give useful results with only a few repetitions and would quickly reach a fixed point. To give an example of how it would proceed, consider the data structures shown in Figure 5.1.

We have four classical types: {`name:string,teaches:record list`}, {`name:string, dob: date, classes: record list`}, {`name: string, lecturer: record, attendees: record, assistant: record`}, and {`name: string, professor: record, attendees: record list`}. At the first stage of the algorithm, none of the types would be joined together but the annotations on types would become more precise as follows: C has type {`name: string,teaches: record list`}$_1$, B and E have type {`name: string,dob: date, classes: record list`}$_2$, A has type {`name: string, lecturer:` `record`$_1$`, attendees: record`$_2$`, assistant:` `record`$_2$}$_3$, and D has type {`name: string, professor:` `record`$_1$`, attendees:` `record`$_2$}$_4$.

We are using subscripts on the record types to indicate specific other record types in the model. The second stage of the algorithm might now tip over into unifying types `record`$_3$ and `record`$_4$ now that the lecturer and professor labels are more clearly the same type: C has type {`name: string, teaches:` `record`$_3$ `list`}$_1$, B and E have type {`name: string, dob: date, classes:` `record`$_3$ `list`}$_2$, and A and D have type {`name: string, lecturer/professor:` `record`$_1$`, attendees:` `record`$_2$`, assistant:` `record`$_2$}$_3$.

The third iteration would probably result in the same types, showing a fixed point has been reached. We would not expect more iterations to be required than the length of the longest chain through distinct types in the final structuring. In this case, the longest chain is three records (trivially since we only found three types, but a disconnected set of other records would not have increased the chain length even though there might have

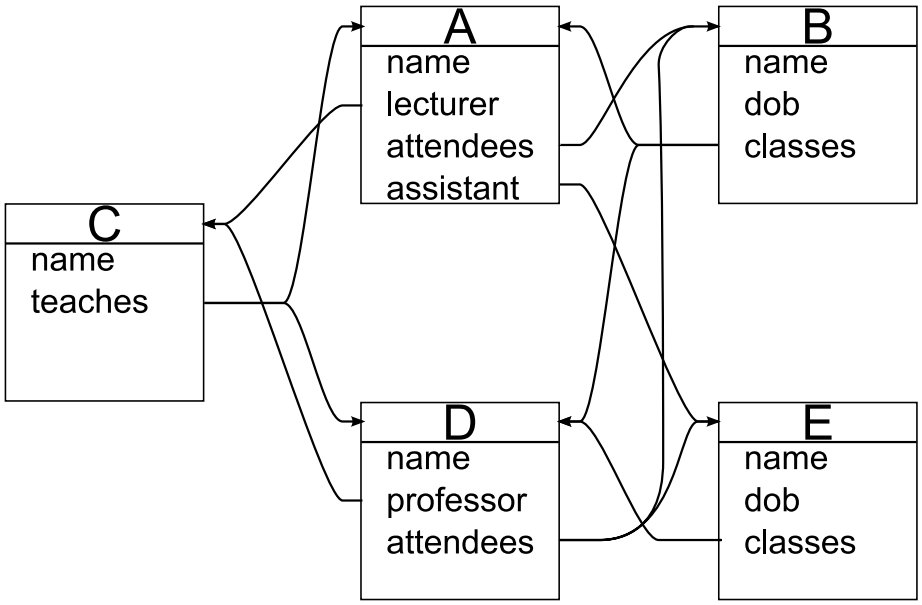


Figure 5.1: A recursive data structure of faculty, courses and students

been many more types) and as expected three iterations were required.

5.4 Comparison to existing techniques

As discussed in Section 2.10, various techniques have already been applied to similar sorts of semi-structured data. These include ad-hoc approaches to extract structured data from certain data sets or kinds of document; clustering techniques such as k-means built on top of similarity functions; using Occam's razor as a straightforward way to penalise overfitting in clustering; fitting generative probabilistic models to document sets; and the *Minimum Descriptor Length* (MDL) approach which uses an information-theoretic approach to decide between structurings.

Ad-hoc techniques for finding data structures can be very successful and achieve a great deal of accuracy. However, they are obviously not suited to discovering structures in new sets of data because the new data may have different properties from the data the technique was designed to work on. They are also weak because they cannot continue to work consistently and accurately as the structure of the data evolves over time.

Clustering techniques such as k-means can be used to find the kinds of structurings our technique can be used for. The biggest problem with the k-means algorithm is selecting the correct value for k, something the algorithm merely takes as an input. A low k value gives a very simple model that may have an unacceptably high variance. On the other hand, we can create as many clusters as there are types in the evidence, which gives a total variance of zero, but a very complex model with no predictive power. Our evaluation function acts like a repulsive force between the k centres, so if the centres are too close together the model is given a less favourable evaluation. This enables us to choose the optimal number of data types at the same time as choosing what those types are. Occam's razor (the principle of minimising the number of additional entities in an explanation) is a reasonable principle, but, similarly to k-means, does not give a way of deciding between a better fit and a smaller model.

The generative probabilistic approach suggested by Abiteboul and colleagues fits a generative model to a set of documents (Abiteboul et al., 2012). The main aim of that work is to create a generator of sample documents with similar properties for testing purposes. However, they comment that the fit between their generative model and the set of documents can be used as a quality measure of the model, and thus they can generate good schemas by extracting the schema from the best generative model (a simple process since the generative model is just an annotated schema.) This process focuses on the proportions of different types of node (since they are generating tree structures, this is more interested than for our flat set of records), and so is quite different from our approach which focuses on the probability of a user accepting a schema.

The MDL approach measures the total length of both the structuring and the information needed to reconstruct the input from the structuring (Garofalakis et al., 2003).

This means that, like our approach, it has the two opposing forces on the size of the model. This information-theoretic approach is mathematically equivalent to a statistical approach. However, because the evaluation criterion is the length of the structuring plus the length of the modification needed, a better structuring that fits less well with the input data is penalised. One example of this is a misspelt record label, where the structuring is the same size but the modification needed is longer for the correct structuring. In these kinds of marginal cases, our technique is stronger because the evaluation function is influenced by a simulation of the user's preferences about structure rather than a strictly information-theoretic evaluation.

Overall, the use of a statistical model of the user to infer types provides a simpler and more principled way to balance model size and match quality than existing techniques. Additionally, it allows us to take user preferences into account in marginal cases. It is also robust to changes in the source data and indifferent to the size of the best model.

5.5 Results

This inference technique was originally designed for use within the end-user programming environment described in Chapter 4. The VisualWebFlows environment is designed to allow users to write programs on data stored in an Excel-like system. The focus of this technique is to allow users to write programs that work correctly on data that is not explicitly structured.

We assume that users produce data that is internally consistent (so each record makes sense on its own) but records do not necessarily fit into a predesigned structure. Karger et al.'s Haystack project suggest that users are capable of creating semistructured data by adding arbitrary properties and relationships to records (Karger et al., 2005). Users often use copy/paste/modify to create new records from existing records, often adding relevant fields and removing unused fields in the process. As an example, consider Wikipedia *infoboxes* (records of structured information about particular entities): a user adding a new artist, for example, is likely to take another artist, filling in new field values, removing any that are not relevant, and adding new fields for information that does not fit the existing fields. When users have novel data to record (i.e. creating new records that are not similar to existing types) then they will typically start from a blank record and add the fields that make sense for that data. For example, the first article about a planet to get an infobox probably had the infobox generated from scratch since planets are not very similar to anything else. A further way of creating records is to draw on multiple existing infoboxes, copying many of the fields from each of them and then making modifications. Leonardo da Vinci is a good example: as an artist and an inventor, it might have made sense to pull up infoboxes on both Botticelli and Edison and combine them.

It was our intention to run the inference algorithm on these infoboxes to discover the underlying structure. Unfortunately, our predictions about how infoboxes are generated

were wrong for three reasons. Firstly, infoboxes are not free-form records but each infobox is an instance of a particular infobox template. These templates mean that the data is already structured and this structure is readily available. Secondly, because Wikipedia is intensively curated, incorrect or misidentified data is rare – we postulate much rarer than in private data kept by an individual or organisation. Thirdly, many similar-looking infoboxes share no record labels because, rather than the evolutionary process we described, there was a parallel design process where each template developed field names which were entirely different from those of similar templates.

For these reasons, our inference technique does not work well on infoboxes and we have struggled to find data sets that meet these assumptions about how users create data. Published data sets tend to be curated, so they do not exhibit the properties we would expect of data created by users. Because there are no tools that can act on the sort of semi-structured data users could collect, we postulate that users do not collect this data as much as they would if they could use it.

Therefore, we have been unable to find a data set that lets us make a convincing argument about the suitability of this technique for end-users. Instead, in the next section we show how this technique could be integrated with the VisualWebFlows system of Chapter 4 and thus how it could be used by end-users to structure, refine and process their data.

5.6 Integrating with VisualWebFlows

We created this data structuring algorithm to help end-users structure their data without having to plan types in advance; and to aid them in evolving their types and programs simultaneously. By avoiding having to name and define types, users can instead gather semi-structured data and act on it without explicitly categorising everything. Variations in types can be dealt with by the system and similar structures from different sources can be processed similarly. This technique could also be used in order to join types from different sources that have overlapping but not identical schemas.

In this section we show how the structuring algorithm could be combined with the VisualWebFlows system described in Chapter 4 to create an environment with less premature commitment. We first describe the user interface for viewing and creating data. Users can create and modify records, and see the structuring that has been inferred. Next, we specify operations for creating, fetching, updating and manipulating data; and show how we generate previews of these operations to aid user understanding. We conclude by discussing how types can evolve over time and how manual changes to the inferred types could be made.

The simplest part of the integrated system is a visual record viewer which allows the user to see all of the records in the system and the type that has been assigned to them. The user can filter and group records by type, and edit them in place with feedback on

how any of the edits they are making will affect the type of that record or any other inferred type. In the UI, the inferred types are referred to as *archetypes* to distinguish them from the types of the records themselves. The record viewer would allow the user to create new records, optionally using an archetype as a template. As an additional benefit for end-user database creation, rather than the user having to clone and modify an existing record to create one of a similar type (a prototype-based approach), the archetypes provided by the inference are automatically representative of their class as a whole, and are more convenient to use as a basis for a new record rather than manually searching for an appropriate prototype to clone and modify.

As well as the user being able to view and edit their data statically, the user can write programs that create, modify and delete data. The control nodes within VisualWebFlows would be modified to handle these new operations in the following ways. Firstly, instead of a node to insert a row into a specified table, there would be a node to create a new record and store it in the database. The type of the record would not need to be specified and instead would be inferred from the properties assigned to the record. Next, rather than having table nodes to fetch persistent data, there would be a fetch node which would take a record or an archetype and output all of the records of that archetype or which shared an archetype with the record provided. Because we no longer have unique IDs to identify rows in a table, deletion would be trickier to handle. In order to delete a record, it would be necessary to first retrieve it, and then pass it to a deletion node that would be responsible for removing it from the persistent database. The environment would be responsible for tracking the flow of records through the program in order to know which record to delete; handling this is already well understood as the SQL view-updating problem. Changes to records would be handled similarly, by having an update node which could take a set of records and a set of new field values that would be changed for those records – note this might also change the type of those records. The general filtering, sorting and mapping operations described in Subsection 4.1.2 could operate similarly on lists of records, so no modifications would be needed there.

One important part of VisualWebFlows is the way it gives users previews of operations by showing changes to sample records visually inside control nodes in the environment. We would like this new system to have similar useful previews. For some situations, like retrieving all the records of a certain archetype and then filtering that list, the approach we have currently taken of showing the results with real records would continue to apply. However, for modifications and creating new records, it might be more helpful to show the results in terms of archetypes, particularly if a modification is likely to result in a record changing type. When a user is creating a new record, the system could use the inferred archetype to suggest fields that are in the archetype but missing from the record; and to highlight fields that are in the record but not part of the archetype. Both of these operations are valid, but highlighting and suggesting would warn the user if they had, for example, incorrectly labelled a piece of data (something real users struggled with in the user study of VisualWebFlows).

Because records are not of a fixed type, it is important that programs continue to work even if the types change. Operations that act on a type (e.g. a node that fetches all records of that type) store a copy of that type. When that operation is run, the stored type is classified into an archetype by the system in the usual way. The operation then acts on all of the records with that archetype. In this way, programs are robust to later changes in the types stored. As their data evolves, users may discover that records that should be of the same type are having different types inferred. This may be because the older records are too dissimilar to newer ones. In this case, the user can write a special flow that takes the records of the old type and turns them into records of the new type.

The main problem with such an automated framework is that the inferred types may not accurately match the intentions of the user. Therefore we need a way for the user to manually indicate records that are misclassified or types that are unacceptable. Because this is not a fully implemented aspect of the VisualWebFlows system we have not been able to evaluate the various ways of handling this. The main aim is to allow the user to indicate errors in the inferred types with the minimum of operations, and to do so using concrete examples. For example, a set of records of a certain type could be selected and forced to join another type. Alternatively, a type could be split using examples, by iteratively annotating some records that should stay in the type and some that should be in another type, until the user is happy with the overall separation. Ideally, rather than just overriding the statistical model in these cases, user preferences that certain records belong in the same type or in different types could be added to the statistical model, giving extra weight to models that satisfied user preferences. This would provide a natural and scalable way of influencing the result of the inference.

We have shown how this inference technique could be used by end-users to structure their data. We argue this technique would be a more natural fit for users than existing systems. By not having to make upfront declarations of types, we avoid the premature commitment problems of VisualWebFlows. Our semantics for operations are relatively simple and allow us to handle records in a scalable way, and for programs to evolve over time to suit the data the user is storing. The proposed user interface makes working with records straightforward and helps to guide users into creating consistent types without requiring up-front design. The biggest risk with such a system is it appearing to be too magical and therefore hard to predict, reason about and ultimately understand. This risk would be mitigated by a clear visual presentation of records and archetypes, combined with manual controls for overriding incorrect inferences.

5.7 Conclusion

This chapter has described a novel type inference algorithm for end-users which uses statistical techniques to make typing judgements. We created this algorithm to help end-users to structure and restructure their data. We enable users to avoid premature

commitment problems by not requiring up-front commitment or design of data structures.

This algorithm is general purpose but focused on recovering the overall structure of a set of untyped but structured records. We have taken elements of other algorithms, including standard results in probability and search, clustering techniques, the Minimum Descriptor Length approach, and probabilistic generative models. By using statistical techniques, we have created a generally applicable technique with few special cases or prerequisites. By considering user preferences in calibrating the algorithms, we hope to fit user preferences more precisely than models that use a straightforward mathematical view of similarity.

We have extensively described the statistical evaluation function, and shown how it can be built up from an understanding of how users compare individual types into a fully-fledged evaluation of structurings. We have also shown how this evaluation function can be used to find acceptable structurings tractably. Our informal testing of this technique suggested good results with the sorts of data users might generate; however more work is needed to find or create suitable data sets to test this technique further. We described how this work could be extended to handle more complex data types, up to and including fully recursive records with typed fields. Finally, we showed how this data structuring could be integrated with our visual programming environment in order to make it significantly simpler for users.

Further work would be needed to build the full integration with the VisualWebFlows system. It would also be interesting to locate some data sets that meet the criteria of the technique and demonstrating the applicability of the technique upon them.

Chapter 6

Conclusions

My thesis is that it is possible to create better programming tools for end-users to process their data. To that end, this dissertation has described and evaluated novel techniques for end-user programming and type reconstruction to enable end-users to store, manipulate and process their data.

Our tool for web-based end-user programming demonstrates several novel features. Firstly, the integrated WYSIWYG editing and programming environment aids end-users in creating and styling applications. In particular, the use of preview tables within the VisualWebFlows environment enables the user to understand and reason about the effect of operations on data. Secondly, the CD-SEP paradigm separates data and control flow in a novel way which is useful for end-user programming and makes it easier to reason about concurrent programs. We highlight that Turing-completeness is unnecessary for a wide variety of useful applications, and that without it we avoid a variety of bugs such as infinite loops and off-by-one errors. Thirdly, we conducted various evaluations which demonstrated that, while not perfect, the tool was understandable and filled a niche not covered by existing research.

Through the user study and cognitive dimensions analysis we identified that users need better tools for structuring their data. To aid users in this and in avoiding premature commitment problems, we also proposed a novel technique for type reconstruction which would be useful for end-users with semi-structured data sets. This technique recovers structures from users' data using statistical techniques and enables them to write programs that operate on their data using the inferred structuring. We developed this technique using synthetic data that simulated the data we envisage end-users would create with the tool; however we were unsuccessful in our attempts to find real data sets suitable for testing the technique. We also showed how this technique would fit with the programming environment described earlier.

6.1 Contributions

This thesis makes the following contributions to the state-of-the-art in end-user programming:

- In Section 2.8 we made an analysis of existing programming paradigms with respect to their suitability for end-user web programming and showed that there are no current paradigms with the most desirable set of properties.
- In Chapter 3 we proposed a novel programming paradigm that separates control and data flow within programs in order to make them easier to understand by end-users. This paradigm improves on many existing paradigms including those of Haskell, Turner, batch-processing systems, Lucid, FRP, Fabrik, Erlang, Scratch and WebRB.
- In Chapter 4 we detailed a programming environment for end-users to create web applications that has several novel features, including WYSIWYG integration of code and automatic previewing of the operation of code; a visual language based on our new paradigm; and a sensible solution to concurrency using optimistic concurrency control and the automatic scoping our programming paradigm provides.
- Chapter 4 also includes an evaluation of our end-user programming environment from a variety of perspectives, including a pilot user study which suggested the environment was usable and useful for skilled users; an analysis based on the cognitive dimensions of notations framework which identified some problems with premature commitment but broadly validated our approach and suggested we had achieved our goal of comparable usability to Excel; and comparisons to existing research which showed our environment to be more powerful and usable than other approaches.
- In Chapter 5 we explained a technique for statistical type inference in semi-structured data which is particularly suited to programming environments for end users. We showed that this technique is straightforward to implement and principled. We also showed how it could take user preferences about structuring into account, and how it could be integrated with the visual programming environment of Chapter 4.

6.2 Further Work

This thesis aimed to create an end-user programming environment for web-based database applications. Whilst many aspects of this have been been successful, there are several areas open to further work.

With more resources, a more extensive user study could be designed to test and develop the usability of the system for end-users. In particular, the visual programming environment, while functional, is very much a prototype implementation. A test with

less-technical users would require significant engineering effort to make it more sufficiently solid. It would also be helpful to include some of the improvements discussed from the user study and CDN analysis.

It would also be interesting to integrate our programming environment with a semi-structured data environment that uses the novel type inference technique to make it possible to run programs on user data. Such a system would have a data model similar to Hypercard but would require less data design up front by end users. It would also provide a more suitable basis for integrating with existing web services, for example, by automatically discovering types for JSON feeds from existing APIs.

Appendices

Appendix A: User study instructions

Included below are the information sheets, which was given to participants to describe the study being performed, and includes the post-study interview questions used; the consent form used; and the exact instructions given to users in the study.

Information Sheet

Purpose of the study

To measure the effectiveness of a new software tool for end-user programming. Participants will use the tool to complete simple tasks and their performance and feedback will be measured by the researchers.

Participant requirements

After giving their consent and beginning the study, participants will be shown a ten minute demonstration video of the tool being used. They will then be shown the instructions (attached) and asked to spend 30 minutes completing the task. After that, they will either be interviewed individually or in a group, or asked to fill in a short questionnaire. No personally identifiable information will be collected.

Consent form

See attached.

Study instructions

See attached.

Survey questions

1. Please describe any previous programming experience, in terms of languages known and amount of experience with each language.
2. What didn't make sense about the system?
3. What did you like about the system?
4. How could the demonstration video be improved?
5. What is a flow?
6. What is an action flow?
7. Are form controls flows?
8. Any other comments?

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Visual Web Flows User Study

Welcome to the Visual Web Flows User Study

This study is being run by Robin Message and Alastair Beresford of the University of Cambridge. If you are not here to participate in that study, please leave this page.

This study is designed so we can observe how effective our system is for technical computer users. You will watch a demonstration video for 10 minutes, then attempt a task on your own.

The video will demonstrate some features of the system. You'll be free to watch any of it again if you need to during the task.

We'll then give you a task to attempt on the system. Please don't spend more than 30 minutes on the tasks. As part of the testing there will be a window for you to type any ideas, comments, questions that arise as you complete the task.

Browser

Please use an up-to-date web browser. Visual Web Flows is tested with Mozilla Firefox and Google Chrome. Please use one of these browsers or inform an experimenter if you cannot.

It looks like you're using: Mozilla/5.0 (X11; U; Linux x86_64; en-GB; rv:1.9.1.9) Gecko/20100330 Fedora/3.5.9-1.fc11 Firefox/3.5.9,gzip(gfe)

Consent

The purpose of this user study is to evaluate the design of a web application we?ve developed. As a volunteer in this study, your participation will be anonymous. We may contact you with follow-up questions, but any feedback you give will not be attributed. As you work, you will be observed by an experimenter who may take notes on your activities. You will also be asked to write down any reflections you have on the system as you work on it. The screen you are working on will be recorded. The entire study should take no more than an hour. If for any reason you are uncomfortable with the study, you may end it at any time.

☐ Please check this to indicate you have read and fully understood the extent of the study and any risks involved.

Continue with the study

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Visual Web Flows User Study

The Task

Starting with a new, blank application, please create a new page for people to sign up to an impromptu five-a-side football match.

Please create a new page on the site for people to sign up to an impromptu five-a-side football match. The page should show a list of who is signed up for the match. People should be able to add their names to the list. People should also be able to remove their names from the list.

Open your site in a new window

Notes

Please put any notes, observations, or questions in this area so we can review it alongside your results later.

Extra tasks

If you complete the task in the time allowed, feel free to attempt any of the following tasks, or terminate the experiment.

- So as to be fair, ensure players show up in the order they add themselves.
- Show the first five players as *Team 1*, the next five as *Team 2* and the rest as *Substitutes.*

Finished?

Remember we suggest you only spend 30 minutes on the task. If you finish before then, feel free to attempt any of the extra tasks, or just stop.

Suggested time remaining: 30:00

I'm finished

Demonstration Video

Appendix B: User study survey results

Question 1. Please describe any previous programming experience, in terms of languages known and amount of experience with each language.

3 years PHP, 4 years variety, 1 year PHP, 1 year .net, 3 years variety, 5 years variety, 6 years variety, 5 years variety

Question 2. What didn't make sense about the system?

Cannot edit tables manually, where column selection not a dropdown.

Not clear how to use merge block, cannot work on data except in flows, layouts could be messy.

Renaming block confusing, not sure what is editable.

Cannot undo mistakes, join block unclear even after reading help, unclear which edit/flow edit button corresponds with which part of the page, flows could get crowded.

Heuristic for field matching would be better than rename blocks, edit screen unattractive.

Changing the id in the pages table breaks things, some visual inconsistencies.

Not clear to what extent pages are magic.

Self-hosting of pages cool but confusing, delete block unclear, too much renaming.

Question 3. What did you like about the system?

Interface bugs are annoying but tool could definitely be useful.

N/A

Storing/retrieving data comes naturally, idea has potential.

Flow concept quite good.

Good idea in large niche, flow model is intuitive.

Fairly expressive, good use of drag and drop.

Intuitive for certain tasks.

Quite cool. Nesting is powerful.

Question 4. How could the demonstration video be improved?

Good, made sense.

N/A

N/A

Pace too fast, hard to remember sequence of actions, worked tutorial would be better.

Video differed slightly from application.

Fairly instructive.

Very good but didn't cover every feature.

Mentions some unnecessary aspects.

Question 5. What is a flow?

A data flow graph.

A collection of blocks that handle data.

A set of linked flow elements, which can produce, process or display data.

Elements of a page that can dynamically fill in data from tables etc.

Provides, consumes, acts or modifies data in some way.

Two kinds: data and control. A flow is a thing that displays data.

SQL in graph form.

Data flow doing computation for display, embedded in a page.

Question 6. What is an action flow?

A flow graph that handles user control.

Blocks that handle user input and actions – side effects.

A flow in response to a user action.

One that does something such as post when the user clicks on it. More active; doesn't just display the data; user can interact with it, so buttons and textboxes.

Invokes a flow when something happens.

Action flow is control of the program – handling events.

Similar, but with form inputs and database actions instead of output blocks.

A control flow something like a petri-net.

Question 7. Are form controls flows?

Not sure.

Yes, to set default values.

Not really; can be access from flows, but not flows in themselves.

Placed inside a flow. Places where you can e.g. Add a button.

No, would have thought not.

No. Well, actually, come to think, yes they are.

Yes.

No, they are inputs and outputs to flows.

Question 8. Any other comments?

Parameterised links in reports.

Want to add a button to the report to delete a row.

Checkboxes, more control over styling.

Highlight connections when flow node selected, mini-map.

N/A

Ability to create multiple reports from one flow, ability to concatenate lists of rows together.

Conditional report formatting - e.g. "Nobody has signed up yet", checkboxes, heirarchical pages.

Buttons inside reports, select boxes.

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