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Dual: a web-based, Pac-Man-complete hybrid text and visual programming language

Praca magisterska
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Contents

Chapter 0

Introduction

0.1 Scope

This research spans a fairly broad area of knowledge, connecting – in order of importance – programming language design, web technologies, web application design and development as well as computer game development.

The main focus of this thesis is designing a programming language, which can have multiple deeply integrated editable representations.

I present a way to combine features of visual languages and text-based languages in an integrated development environment, which lets the programmer work with both representations in parallel or intertwine them in various ways.

A proof-of-concept interpreter and development environment for the language is implemented using web technologies.

Practical demonstration of the capabilities of the implementation is presented by writing a Pac-Man clone in the designed language[1]. This also provides a reference for assessing the performance of the implementation.

0.2 Choice of subject

The choice of this particular subject stems from my deep personal interest in programming language design. This research is an opportunity for me to create a project that demonstrates various ideas in this area that I developed over time and to explore and refine them further.

[1] The term "Pac-Man-complete" in the title of this thesis refers to a somewhat humorous description used by the Idris' programming language[48] author, Edwin Brady[79?], to describe the language. In the context of this dissertation it means that the designed programming language provides enough features to allow one to write a clone of the classic Pac-Man game in it.

0.3 Related work

With this research, I intend to explore certain aspects of programming language design as well as further the growth of visual programming languages, proposing a solution that improves over any existing comparable technology in terms of simplicity, expressive power of the language and usability.

The first and main part of this research is concerned with designing a programming language, which becomes the basis for the second part. This language, Dual, is mostly based on one of the oldest PL[2] families, the Lisp[82, 35] family. Lisp and its various dialects are consistently regarded as one of the most expressive PLs[64, 45], despite having a very simple syntactic and semantic core[78]. Dual is also influenced by many modern PLs, such as JavaScript (as defined by the ECMAScript[15]), which is the implementation language of its interpreter. Similarly to Lisp, Dual has a minimal syntax, although with some modifications and improvements (described in Chapter 2).

The second part of this research builds on top of theoretical[66] as well as practical[77] achievements in the field of Visual Programming Languages (VPLs), focusing on examining the latter. VPLs can be classified in various ways: [66, Section VPL-II.B], [68, Section Types of VPLs], [42, Section Definition]. I introduce my own classification by examining lanugages enumerated in [77]. Two major categories[3] that emerge from this classification are "line-connected block-based" and "snap-together block-based" VPLs. I design and implement a visual representation for Dual, which combines features characteristic to both of these categories. The development environment that is built for the language provides the ability to edit the text and the visual representation in parallel, with the changes made to one visible in the other immediately.

Visual languages are not especially popular compared to text-based languages. But recently they have been gaining more popularity, particularly in game development. Chief example and the main cause of this is Unreal Engine, the highly popular and mainstream[37, 88] game engine, which in the latest version introduced a visual programming language[69] as its primary scripting language. In fact this is the only scripting language that the engine supports, having dropped the UnrealScript language[85] included in the previous versions. This visual programming language will be compared to Dual to highlight its advantages.

The Dual language, both its representations and its environment – I will further use the terms "Dual system" or simply "system" to refer to these as a whole – are built entirely on top of the open web platform[30], which is ubiquitous. This gives the system great portability and makes the difficulty for the potential user to start working with it minimal. This is how the usability mentioned in the first paragraph of this section is defined.

[2]For the sake of terseness I will sometimes use the acronyms PL and VPL to abbreviate "programming language" and "visual programming language".

[3]By amount of languages that fall into each.

0.4 Goals

In line with the above, the purpose of this work is to introduce innovation as well as show a practical application of the developed solution. The concrete goals are:

- To explore and establish directions where innovation is possible in programming language design and implementation.
- To design and implement a programming language, which meets the criteria of expressiveness and usability outlined in the previous section.
- To design and implement a visual representation for the language, which will be directly and dynamically mappable to the text-based form. The same must be true in the other direction – text to visual.
- To create a prototype of the development environment for the language.
- To evaluate the practical usability and performance of the prototype by implementing a clone of Pac-Man and examining the process as well as the results.
- To contrast the features of the language with existing visual language systems and present possible ways of improving such systems.

0.5 Structure

This thesis is structured as follows:

Chapter 0 is this introduction.

Chapter 1 briefly describes technologies and tools used in developing any software described here as well as discusses the essential elements of the theoretical framework upon which the language was built.

Chapter 2 describes the design of the Dual programming language: its syntax, semantics, primitives, core functions and values. It also elaborates on programming language design in general.

Chapter 3 talks about the design of the language's visual representation and its development environment.

Chapter 4 describes the prototype implementation based on the designs. This includes the language and its intrepreter as well as the environment.

Chapter 5 contains a case study of a more-than-trivial application developed with Dual: a Pac-Man clone. Performance of the prototype implementation is assessed and possible adjustments and improvements are discussed.

Chapter 6 compares Dual to existing visual programming languages.

Chapter 7 summarizes and concludes.

Appendix A describes the contents of the DVD attached to this thesis and provides a short instruction on running the prototype.

Appendix B contains additional design ideas that may be implemented in the future.

Chapter 1

Background

This chapter briefly introduces the theoretical and practical components involved in design and implementation of the Dual programming language and its environment.

1.1 Web technologies

As stated in the introduction, one of the main design goals of the system is usability. This is accomplished in practice by building on top of the most accessible and ubiquitous platform – the web platform[89][1].

The language's interpreter and development environment are intended to work with and are built on web technologies: JavaScript, HTML5 and CSS. The prototype implementation makes use of Node.js, a server-side JavaScript runtime[51] and CodeMirror, a JavaScript library which provides basic facilities for the text-based code editor part of the system[55]. This part is modeled after modern web-oriented code editors with similar design philosophy[31], such as Visual Studio Code[61], Brackets[47], Atom[53] and many others.

1.1.1 JavaScript

The JavaScript programming language was created by Brendan Eich for Netscape[15, Introduction], the company which created the Netscape Navigator web browser. There is a line of evolution that leads from Netscape and its browser to Mozilla and Firefox[65, 74]. The language was developed in 10 days in April 1995[7].

Despite significant design flaws, JavaScript has became *one of* the most[97, 91], if not *the most*[95, Section Most Popular Technologies per Dev Type][94] popular programming languages in the world. In this section I will briefly look at some of the probable reasons for that from a programming language design perspective.

From a programming language design perspective, JavaScript has many great features, borrowed from excellent languages[15, Section 4 Overview], most notably:

[1] Also referred to as the *open* web platform[30]

- Scheme, one of two main dialects of Lisp[18]. It is a minimalist, but very extensible functional programming language. The features drawn from this language include first-class functions (treating functions as values), anonymous functions (also known as lambdas or function literals) and lexical closures.

- Self, a pioneering prototype-based Object-Oriented Programming language[10], which evolved from Smalltalk-80[4]. It introduced the concept of prototypes, which is an approach to OOP, where inheritance is implemented by reusing existing objects instead of defining classes. Prototype-based programming is the feature that JavaScript adopted from this language.

The two above languages are characterized by a very minimalist nature. Both languages as well as JavaScript[22] are dynamically typed – types can be checked only at runtime.

The final advantage of JavaScript is the fact that it is distributed with a ubiquitous environment of the web browser. This makes the language straightforward for developers to use. Easy to get started – attract novice developers Reach billions of users[93]

The above mixture turns out to create a very powerful and usable language.

In the recent years JavaScript's popularity has been steadily growing[92]. This translated to significant improvements in the language's standarization efforts. Since 2015, ECMA International's[58] Technical Commitee 39[57], the commitee which defines ECMAScript – the official standard for JavaScript – adopted a new process. Under this process, a new version of the standard is released annually[15, 14, 13]. The documents and proposals are publicly available at GitHub[59].

Static type checking for JavaScript is also possible with Flow[56] – a static type checker, which works either as a syntax extension or through comment annotations – or TypeScript[60] – which is a superset of JavaScript.

Concurrency model

In the context of the concurrency model, the JavaScript runtime conceptually consists of three parts: the call stack, the heap and the message queue. All these are bound together by the event loop[20], which is the crucial part of this model. An iteration of this loop involves the following steps:

1. Take the next message from the queue or wait for one to arrive. At this point the call stack is empty.

2. Start processing the message by calling a function associated with it. Every message has an associated function. This initializes the call stack.

3. Processing stops when the stack becomes empty again, thus completing the iteration.

This means, at least conceptually, that messages are processed one by one, in a single thread and an executing function cannot be preempted by any other function

before it completes. In practice this is more complicated and there are exceptions to these rules. But this explanation is sufficient for further discussion.

This model makes reasoning about the program execution very straightforward, but is problematic when a single message takes long to execute. The problem is observed e.g. when web applications cause browsers to hang or display a dialog asking the user if he wishes to terminate an unresponsive script.

For this reason it is best to write programs in JavaScript that block the event loop for as short as possible and divide the processing into multiple messages.

This concurrency model is called the *event* loop, because the messages are added to the queue any time an event occurs (an has an associated handler), such as a click or a scroll. In general input and output in JavaScript is performed asynchronously, through events, so it does not block program execution.

1.2 Programming language design and implementation

A very important family of programming languages and one which had the most influence on the design of Dual is the Lisp family. In this thesis I use the singular form "Lisp" to refer to the whole family rather that a concrete dialect or implementation – such as Common Lisp[17], Scheme[18], SBCL[63] or Racket[62] – unless otherwise noted.

Lisp is characterized by a very minimal syntax, which relies on Polish (prefix) notation for expressions and parentheses to indicate nesting. There are only expressions and no statements in the language. This means that every language construct represents a value. There is also no notion of operator precedence.

The two core components of a Lisp interpreter are the `apply` and `eval` functions[1, 44, Section 4.1]. The former takes as arguments another function and a list of arguments and applies this function to these arguments. The latter takes as arguments an `expression` and an `environment` and evaluates this expression in this environment. The typical implementation of `eval` distinguishes between a few types of expressions. The essential are:

- Symbols (also known as identifiers or names) – e.g. `velocity` – these are evaluated by looking up the value corresponding to the symbol in the environment, so `velocity` might evaluate to `10` if it is defined as such in the `environment`
- Numbers (or number literals) – e.g. `3.2` – these evaluate to a corresponding numerical value
- Booleans (boolean literals) – `true` or `false` – evaluate to a corresponding boolean value
- Strings (string literals) – e.g. `"Hello, world!"` – evaluate to a corresponding string value

- Quoted expressions – e.g. `'(+ 2 2)` – a quoted expression evaluates to itself; in other words a quote prevents an expression from being evaluated
- *Special forms* or *primitives*, which are expressions that have some special meaning in the language. These are the basic building blocks of programs. For example:
  - `if`, the basic conditional expression and other flow control expressions; the special meaning of these is that they evaluate their arguments depending on some condition
  - *lambda* expressions – essentially function literals, which consist of argument names and a body
  - *definition* and *assignment* expressions; these modify the environment; usually they treat their first argument as a name of the symbol in the environment, so it is not evaluated; the second argument is evaluated and its value is associated with the symbol

A Lisp expression can look like this:

```
(+ 2 (* 3 5))
```

Words are delimited by white space. Each sequence of words between parentheses can be viewed as a list[2]. Lists can be nested inside each other. Each list represents an expression, where the first element of the list is the expression's operator and the following elements are its arguments.

This parenthesized notation is called S-expressions[81, Section Recursive Functions of Symbolic Expressions; Section The LISP Programming System]. These are used to represent both code and data. For example the code from Listing 1.2 can be represented (in Common Lisp[3]) as data:

```
(list '+ 2 (list '* 3 5))

; or shorter equivalent:
'(+ 2 (* 3 5))
```

Where `list` is a function that produces a list that contains the values of its arguments.

`'` is a *quote* symbol. It prevents an expression from being evaluated.

`;` begins a comment that extends to the end of current line.

`+` and `*` are functions that perform their corresponding arithmetic operations: addition and multiplication respectively.

This data representation can now be manipulated. For example:

```
; set the ‘expression‘ variable to hold the same list value
; as in the above listing:
(setf expression '(+ 2 (* 3 5)))
```

[2] Originally the name Lisp was an acronym, which stood for "LISt Processing"[12, Section 1.2][6, Chapter 12]

[3] All the remaining listings in this section contain code in Common Lisp.

```
; the variable `expression` now represents
; the expression `(+ 2 (* 3 5))`

; replace `*` with `exp` in the `expression`
; since it is just an ordinary list,
; this is done with ordinary data manipulation functions:
(setf (first (third expression)) 'expt)

; the variable `expression` now represents
; the expression `(+ 2 (expt 3 5))`
```

Where `setf` evaluates its second argument and stores it in a variable represented by its first argument. The first argument can be – among other things[12, Section 11.15.1] – the name of the new variable or a place in an existing list.

`first` and `third` take a list as an argument and extract the first or the third element from that list accordingly.

`expt` is a function that performs exponentiation: it takes two numerical arguments and returns the value of the first raised to the power determined by the value of the second.

We can now evaluate the `expression`:

```
; returns 245, which is the result of
; evaluating (+ 2 (expt 3 5)):
(eval expression)
```

`eval` here is a function of one argument – an expression to be evaluated in the current environment. This is "a user interface to the evaluator"[17, Section 3.8, Function EVAL] (which can be understood as the internal function `eval` described at the beginning of this section).

The property of representing code and data in essentially the same form is known as homoiconicity[33, 43, 5]. In the case of Lisp an S-expression can be very straightforwardly mapped to a corresponding Abstract Syntax Tree (AST) node.

1.2.1 Abstract syntax tree and program representation

The term AST refers to a tree data structure that is built by parsers of programming languages to represent syntactic structure of source code in an abstract as well as easily traversable and manipulable way. In the simplest form, in expression-only languages such as Lisp each node of such tree represents a single expression. The tree is abstract in the sense that it does not necessarily contain all the syntax constructs that occur in the source code or encodes them in some *abstract* way. In case of Lisp, there's no need to store or represent bracketing characters `()` in the AST, as nesting is inherent in the data structure itself.

In theory, a programming language does not require a text representation and could be defined only in terms of a data structure such as a syntax tree. Practically, for a language to be useful, it needs to come with an editable representation that provides a convenient way for a programmer to construct programs. Currently the

most successful representation for that is the human-readable text-based representation, which evolved from more primitive and less convenient representations, such as punched cards[72, 32].

1.2.2 Text-based code editors

Constructing programs with text representation can be done with any text editor. This means that the representation is largely independent of a tool, which is an advantage. Any application capable of editing text can theoretically be used to edit any source code (ignoring details such as encoding, etc.). Such applications are universally available, so source code stored in text files can be edited freely on any platform with any tool.

But for complex programs a simple text editor quickly becomes inconvenient and a more specialized one is preferable. Such code editors introduce various features that greatly improve the convenience of working with a text-based representation of a programming language. For example:

- Automatic structuring of the text to emphasize blocks of code (autoindentation)
- Highlighting different syntactic constructs with different colors
- Context-based autocompletion
- Autoclosing of bracketing characters
- Automatic correction of errors
- The ability to fold distinct blocks of code
- Advanced navigation through the code: jumping to declarations, definitions, other modules or files
- Etc.

Most of these features require that the editor makes use of a parser to recognize the syntactic structure of a program.

Other advantages of a text representation, that stem from the multitude of ways that raw text can be manipulated and processed and are not related to any particular syntax:

- Find and replace with regular expressions
- Selecting/processing many lines or even blocks of text
- Editors often treat the source as a 2D grid of characters; each row and column of such grid can be numbered
- Debuggers, compilers and other elements of a programming language system can use row and column numbers in error messages

- Version control systems can easily compare (diff) and keep track of changes in text files

1.2.3 Visual programming languages

An alternative representation is the one employed by visual programming languages. By a visual programming language I mean a language that "lets users create programs by manipulating program elements graphically rather than by specifying them textually"[42, 68].

Such languages are usually tied to a particular editor, which allows the programmer to edit the source code with a mouse rather than the keyboard. That is instead of typing in streams of characters to be parsed and assembled into a structural form, the programmer inserts, arranges and connects together distinct visual elements to produce such a structure. Thus I contend that visual programming can be defined at the lowest level as manipulating a visual form of a language's syntax tree.

The design of the visual representation for my language involved a rough survey of visual programming languages. In this section I will describe the results obtained from this survey.

I classified each of nearly 160 languages listed in [77], according to type of their visual representation into several categories.

Additionally, I associated each language with a number $s \in [0, 3]$, which descirbes its "structure factor". This quantifies my subjective assessment of the readability of the representation compared to familiar text representation ($s = 3$). For example, if it appears that the representation consists of scattered blocks, connected by lines and the layout seems to be arranged by the user, with no editor-support for automatic structuring, s will be low. In other words, the greater the number, the better structured the representation.

This analysis is not strict and systematic, but rather heuristic-based. A language is classified based solely on the screen shots from its environment. Its purpose is to assess general trends and determine which solutions gained the greatest adoption in practice. This is to aid the further design process.

Below I present the results of this classification in the form of a list. The items are organized as follows:

- «Name of category» – «percentage of languages that fall into the category» – «the average "structure factor" s for the category»

  «short description»

Here are the compiled results:

- Line-connected block-based – 66% – 0.61

  Blocks or boxes connected with lines or arrows.

- Snap-together block-based – 11% – 2.4

  Resembles familiar text representation, except that the structure is produced by snapping together blocks, as in jigsaw puzzles.

- Other representations – 23% – 1.39, notably:

  - List-based – 2.5% – 2
    Nested lists, possibly with icons.
  - GUI-based – 2.5% – 1
    Buttons with icons that represent various components.
  - Nested – 2.5% – 2
    Nested windows, boxes, circles or other "scopes". A border of each scope is clearly distinguishable.
  - Enhanced text – 2.5% – 2.75
    Similar to text representation, but with differing font sizes, embedded widgets, or other enhancements.
  - Timeline-based – 2% – 1.17
    Specialized for animations or music. Elements are placed on a timeline.
  - Others – 11% – *varying*
    The remaining 11% are various other representations: experimental, in-game or game-based VPLs, hybrid, specialized, esoteric, etc. A few examples are presented at the end of this chapter, in Section 1.3

The section 1.3 at the end of this chapter contains screenshots from editors and environments for VPLs in each of the categories, in order in which they appear in the above list.

The above results help set possible design directions. We may conclude that in practice there are basically two main types of visual representations: "line-connected block-based" and "snap-together block-based".

I used two more heuristics to verify this conclusion:

- I analyzed the top hits when searching the phrase "visual programming language" with popular search engines, especially by images. Most results link to websites with information about VPLs based on these two main representations. I searched the phrase in Bing, Google, Yahoo and DuckDuckGo and out of the top 20 hits I counted 14-18 (depending on the search engine), which would qualify.

- I analyzed the Wikipedia article about VPLs[42]. The first paragraphs of the definition state:

  > [M]any VPLs (known as dataflow or diagrammatic programming)[?] are based on the idea of "boxes and arrows", where boxes or other screen objects are treated as entities, connected by arrows, lines or arcs which represent relations.

This is essentially a description of the "line-connected block-based" representation.

The example screenshot at the top of the article presents the MIT Scratch programming language, which falls into the "snap-together block-based" category. [66, Section VPL-II.B].

1.2.4 Line-connected block-based representation

The results presented in Section 1.2.3 suggest that the most popular VPL representation is the flowchart-like "line-connected block-based". Editors which use this representation usually leave the layout of the program source completely to the user, providing no automatic structuring. This may easily result in disorder and true "spaghetti-code", where free-floating blocks are scattered around, connected by many intersecting lines. This is especially true for complex programs.

This lack of support for automatic structuring, which is an essential feature of modern text-based code editors is clearly a regression.

1.2.5 Snap-together block-based representation

The second most popular VPL representation is the "snap-together block-based". There, the code is presented and manipulated in terms of visual blocks, which can be dragged and dropped by mouse and snapped together like jigsaw puzzle pieces. This representation is self-structuring and is designed to resemble the familiar text-based, indent-structured representations.

The prime example of a VPL that utilizes this representation is MIT Scratch. This is because of its popularity[39, Section Community of users] – it is even referred to as "the most popular VPL"[**?**]. One classification even refers to the VPLs that use the "snap-together block-based" representation as "Scratch & friends"[68, Section Types of VPLs].

However Scratch was not the first language to use this representation. It was preceded by logoBlocks and earlier similar projects[**?**].

In fact, if we go far back in history of VPLs, we eventually arrive at the Logo programming language, which was a dialect of Lisp[**?** **?**]. It was not a VPL by the definition quoted at the beginning of Section 1.2.3, as it did not have a way to manipulate *program elements* visually. Nonetheless, one author calls it "the first real mainstream VPL"[**?**]. This is because it pioneered many ideas related to visual programming and was inclined in that direction. As is reflected in its many derivatives, which were indeed VPLs[**?**], such as the visual programming environment of LEGO Mindstorms[**?** **?** **?**].

1.3 Screenshots

This section presents screenshots that show examples of visual programming languages that fall into each of the categories discussed in Section 1.2.3.

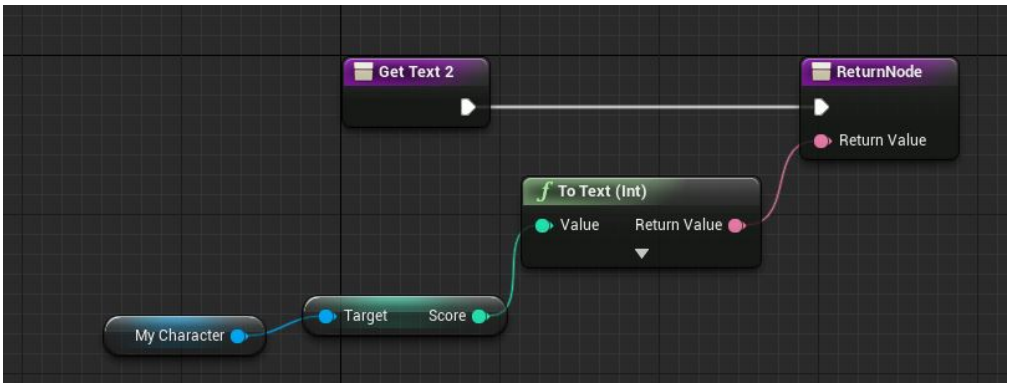

Figure 1.1: Blueprints Visual Scripting system; An example of a "line-connected block-based" VPL; screenshot from [100]

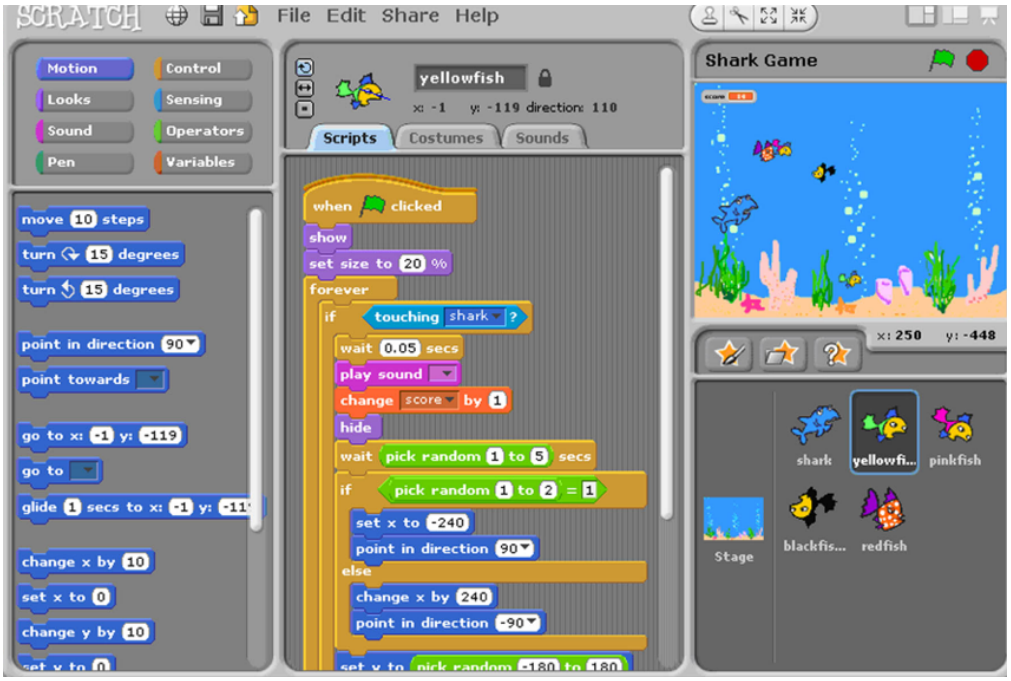

Figure 1.2: MIT Scratch programming language editor; An example of a "snap-together block-based" VPL; screenshot from [98]

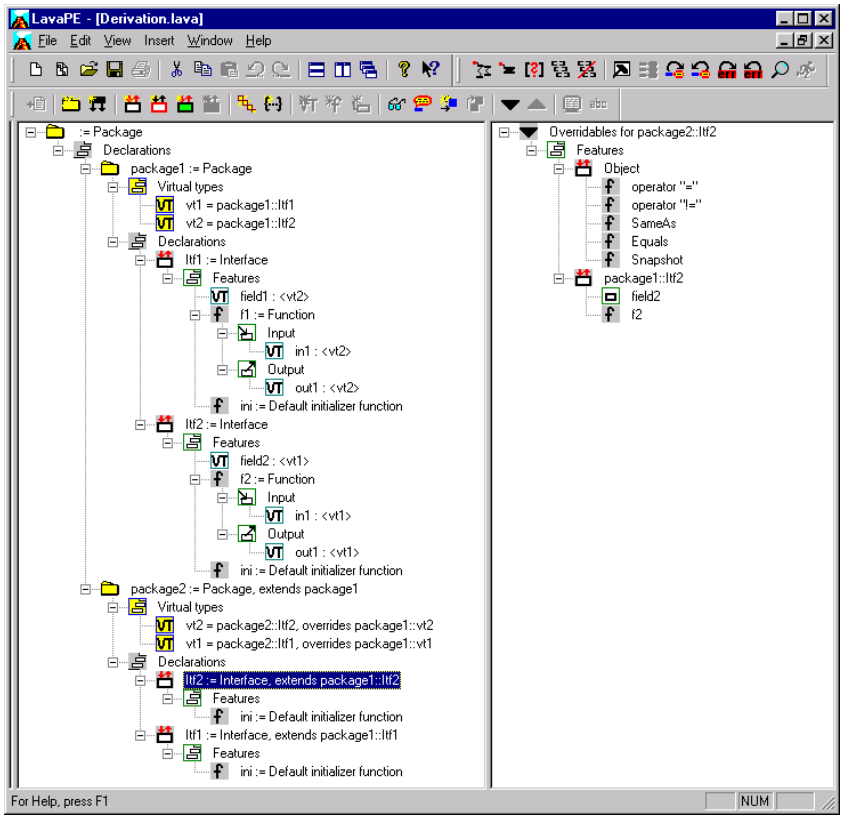

Figure 1.3: Lava programming language editor; An example of a "list-based" VPL; screenshot from [?]

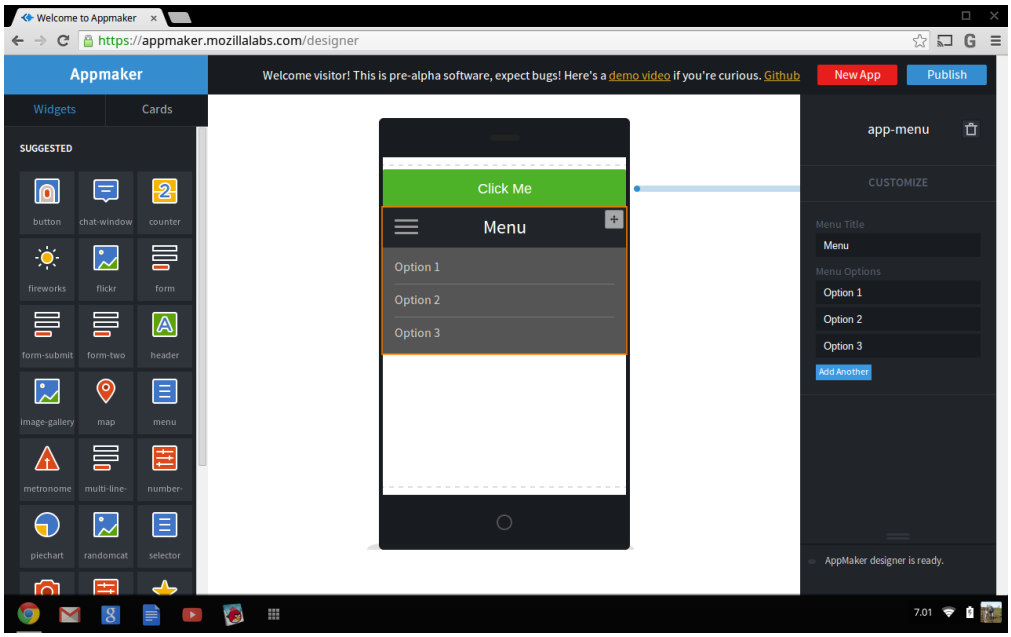

Figure 1.4: Mozilla Appmaker; An example of a "GUI-based" VPL; screenshot from [?]

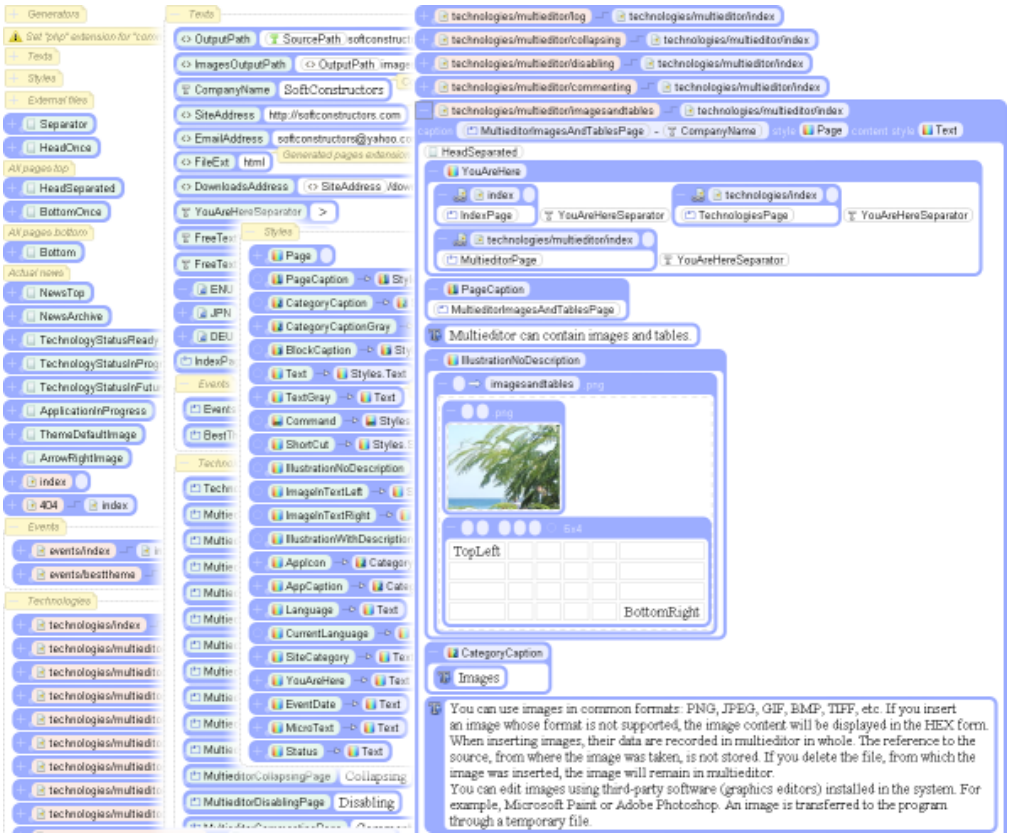

Figure 1.5: StroyCode editor; An example of a "nested" VPL; screenshot from [?]

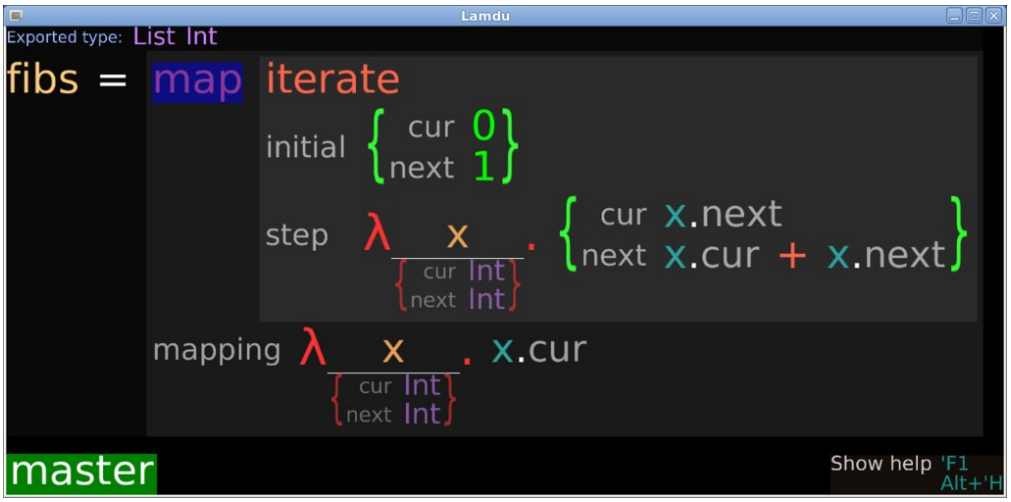

Figure 1.6: Lamdu visual environment; An example of an "enhanced text" VPL; screenshot from [?]

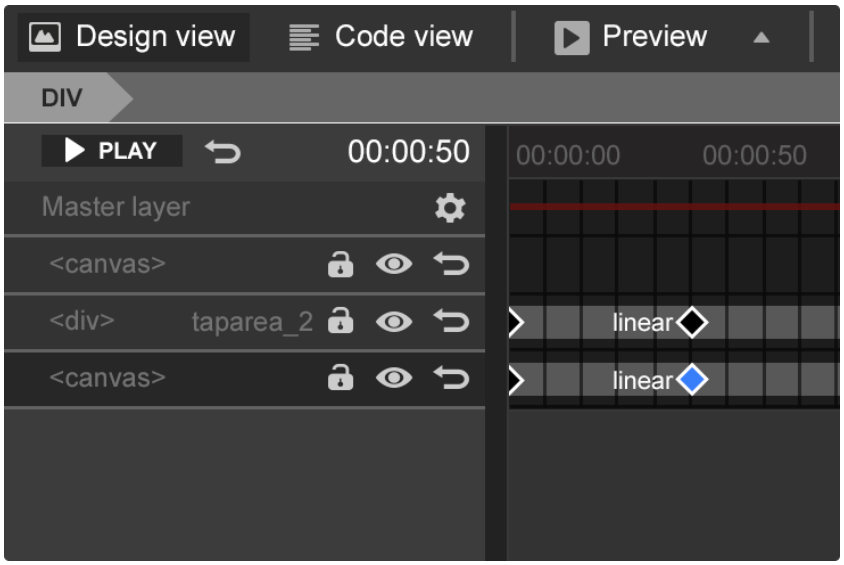

Figure 1.7: Google Web Designer; An example of a "timeline-based" VPL; screenshot from [?]

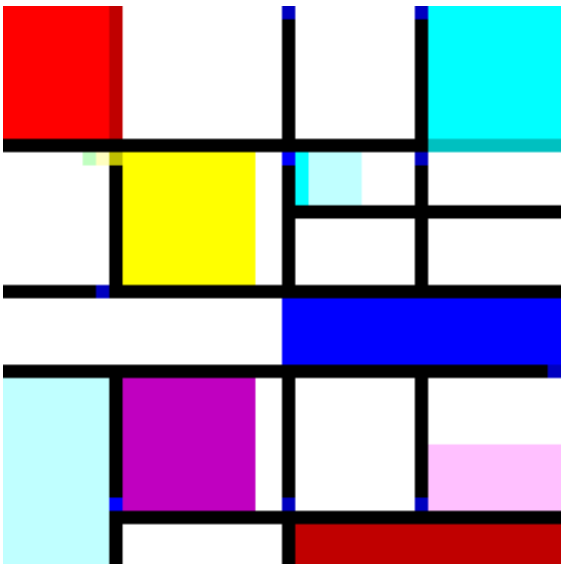

Figure 1.8: The esoteric programming language Piet; An example of an esoteric VPL; screenshot from [?]

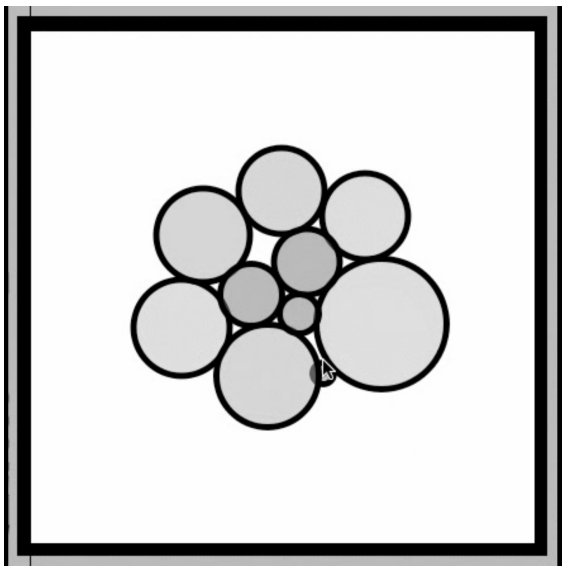

Figure 1.9: "Lily was a browser-based, visual programming environment written in JavaScript."[?]; An example of an experimental VPL; screenshot from [?]

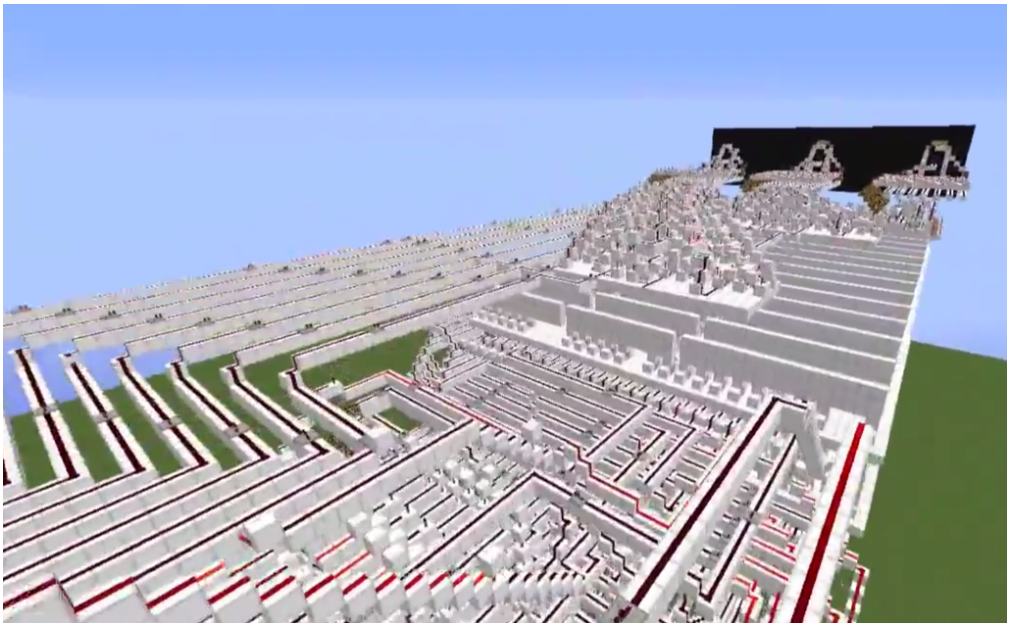

Figure 1.10: Minecraft[?] can be considered a visual programming lanugage. It's an example of a "game-based" VPL; "[S]omeone has created a fully programmable computer using Minecraft"[77]; screenshot from [?]

Chapter 2

Dual programming language design

This chapter describes the text representation of Dual, which is the basis for the executable representation for the interpreter (the syntax tree) and for the block-based visual representation discussed in the following chapters.

The evolution of programming languages is a gradual process. And so is the process of designing a single language. The approach that I found effective was iterative refinement, addition, testing, and sometimes subtraction of features. In practice this translates to intermediate designs and implementations being rearranged into new forms, with some discarded. I did not arrive at something that I could call the final form of the language, so a lot of the features described here are subject to change and improvement. I intend to work on this project further beyond the scope of this thesis.

The language was not originally intended to be a Lisp-like language or clone thereof, but throughout the research I ended up learning a lot about Lisp, sometimes by reinventing parts of this language. A somewhat philosophical interpretation of this would be that Lisp is built on fundamental principles that are (re)discoverable rather than invented.

In this and the following chapters I cover a lot of "design surface", only delving deep into some features that are relevant to core ideas that I wanted to convey in this thesis.

2.1 Syntax and grammar

Among the main design goals for the prototype of the language were simplicity and clarity. I wanted a language that is easy to parse and transform to a different representation. This restriction suggests that the syntax should be as minimal as possible.

I choose Lisp's syntax as the starting point. It is indeed almost as simple as one could imagine. But because of its almost complete uniformity it is often criticized. Some of the major criticisms are:

- In general it is hard to teach, because complex code gets easily confusing[9].

- The more nested the syntax tree, the harder it is to keep track of and balance parentheses; there tends to be a lot of closing parentheses next to each other in the source[46].

I made a few simple adjustments to the syntax in order to address these concerns, at least to some degree. These modifications do not significantly increase the complexity of a parser, but may considerably improve the syntax in terms of ease of use and readability for a human.

2.1.1 Basic syntax

Below I present the definition of Dual's grammar in left-recursion-free Backus–Naur Form. It is included here only for the sake of formality. I believe that for such a simple grammar BNF introduces more noise and is unnecessarily more complex than a textual description, possibly with the help of regular expressions or simply verbatim parser source code. For these reasons any extensions to this basic grammar will later on be introduced in these ways.

This is the BNF definition, a bit verbose for clarity:

```
<expression> ::= <word> | <call>
<call> ::= <operator> <argument-list>
<operator> ::= <word> <argument-lists>
<argument-list> ::= "[" <arguments> "]"
<word> ::= /[^\s\[\]]+/
<argument-lists> ::= <argument-list> <argument-lists> | ""
<arguments> ::= <expression> <arguments> | ""
```

BNF here is extended with the addition of a regular expression (between `/` delimiters) in the definition of `<word>`. The regular expression can be read as "any character which is not white space, `[` or `]`". This means that aside from white space, which acts as expression separator there are only two special characters that the parser has to worry about – the square brackets.

The above grammar definition is obviously very similar to Lisp's BNF description[80, 73].

The following expression in Lisp:

```
(+ 2 (expt 3 5))
```

has an equivalent expression in Dual:

```
+[2 expt[3 5]]
```

Comparing these, we may observe that in Dual:

- The primary bracketing characters are square brackets (`[]`) instead of parentheses. The reason for that design choice is that these are easier to type than parentheses or curly brackets (as they do not require holding the shift key), which matters considering the ubiquity of these characters in the source code.

- Expression's operator name is written *before* the opening bracket that precedes the list of arguments, as in `operator[argument-1 argument-2 ... argument-n]`.

Other than these two differences, Dual's notation is equivalent to S-expressions. Its advantages are:

- It is easier to parse by a human. Operators are clearer distinguished from operands. This is arguably because this notation is more familiar, bearing a similarity to the general mathematical notation (as in `f(x)`) and the most popular programming language syntax – the C-like syntax[1]
- If an expression has another expression as its operator, it is written as `op[args-1][args-2]`, which reduces the amount of nesting and thus the amount of identical bracketing characters appearing next to each other in the source code. Compare the equivalent S-expression: `((op args-1) args-2)`; and with multiple levels: `op[args-1][args-2][args-3][args-4]` vs `((((op args-1) args-2) args-3) args-4)`.

An interesting property of this syntax that, depending on the context, could be classified as an advantage, disadvantage or neither is that the sequence of characters `[[` is not legal, whereas in Lisp the analogous sequence `((` is.

Alas, this simple notation doesn't do away with a lot of other problems inherent in all minimal syntaxes, related to their homogenity. Later in this chapter I will introduce extensions and syntax sugar, which make the notation a little bit more diverse. Keep in mind that every special character that is introduced, is taken away from the set of possible `<word>`-characters, which implies that the regular expression for `<word>` is changed accordingly.

2.2 Comments

Comments are a basic and indispensable syntax feature of any programming language. I chose to include a comment syntax similar to the one found in Ada, Haskell or Lua:

```
-- a comment that extends until the end of the line

-- an expression that computes square root of 81:
sqrt[81]

--[
    this is a multiline comment
    --[
        multiline comments can be nested
```

[1] 11 out of the top 20 languages as of June 2016[97] have C-based syntax (by this classification: [36]). If we extend the syntax family to Algol-like, its virtually 20 out of 20 – [96]. There are no languages with Lisp-based syntax among the most popular ones.

```
        as long as [ and ] are balanced, anything can be nested
           within
        multiline comments

        for example:
        --[
            this is a comment that includes a piece of code:
            *[7 7]

            which would evaluate to 49
        ]
    ]
]
```

2.3 Numbers

Numbers in the language are represented as JavaScript numbers. This means that there's only one number type – 64-bit floating point[2]. They are implemented as follows:

- When a word is tokenized by the parser, it is converted to a JavaScript number with a Number type constructor, which returns either the corresponding value (if the word is parsable to a number) or the value `NaN`. In the former case, the numerical value is stored in the appropriate syntax tree node, as its `value` property.

- Upon evaluation, a syntax tree node is checked for the `value` property. If it has one it is given as the result of the evaluation.

- The fact that a number is stored as a syntax tree node, which contains the its string representation and its raw value, both obtained from the source code during parsing means that conversion from a number literal to string is zero-cost, which could be useful for optimization.

Thus all of the following JavaScript number literals are valid in Dual:

```
1
357
3.14
0x11 // hexadecimal
0b11 // binary
0o11 // octal
5e-2 // exponential notation
```

[2]Defined by the ISO/IEC/IEEE 60559:2011 (IEEE 754) standard: [16, 87]

2.4 Escape character

An escape character \ is introduced. It allows special characters to be included in variable names.

For example:

```
word\ with\ spaces\ and\ braces\[\]
```

would be a single valid word and could be used as an identifier for a variable.

2.5 Strings

String values are introduced in Dual as follows:

```
'[A quick brown fox jumps over the lazy dog]
```

' is a special operator that produces a string value. It takes any number of arguments, which must be valid expressions.

Strings support variable substitution (also known as string interpolation[?]). Assuming we have a variable `animal-0` with the string value `"bear"` and another variable `animal-1` with the string value `"duck"`, this string:

```
'[A quick brown {animal-0} jumps over the lazy {animal-1}]
```

would evaluate to:

```
"A quick brown bear jumps over the lazy duck"
```

Special characters inside string can be escaped with the escape character \. Note that balanced square brackets that are part of syntactically valid Dual expression do not have to be escaped.

The implementation of strings is explained in detail in Section 2.7. String interpolation is explained in Section ??.

2.6 Basic primitives and built-ins

This section enumerates and briefly describes Dual's basic primitives and built-in functions and values.

The items in Sections 2.6.1 and 2.6.2 are structured as follows:

- `«name» [«arguments»]`

  «description»

Where `«name»` is the name of the function/primitive and `«arguments»` are either the names that describe the arguments of the function/primitive or its arity. That is, the number of arguments that the function/primitive is defined for. This can be a fixed value (e.g `1`), a fixed range of values (e.g. `0..3`) or a range of values without an upper bound (e.g. `0..*`, which means 0 or more). An argument name

can optionally contain a colon character `:`, which is followed by the type that the argument is expected to have.

«description» is a brief description of the function/primitive.

2.6.1 Functions

The following basic functions are defined in the language:

- `list [0..*]`

  Returns a JavaScript `Array`[?], which contains the values of its arguments.

- `$ [0..*]`

  An alias for `list`.

- `apply [f args]`

  Works like Lisp's `apply`: it takes a function and a list of arguments and returns the result of applying the function to the arguments.

- `log [0..*]`

  Wraps JavaScript's `console.log` method[?]. It outputs the values of its arguments to JavaScript's standard output – web browser's console.

- `typeof [arg]`

  Wraps JavaScript's `typeof` operator. "[R]eturns a string indicating the type of the unevaluated operand."[?]

- `or [a b]` and `and [a b]`

  The basic logical operators – analogous to `||` and `&&` in JavaScript.

- `any [0..*]` and `all [0..*]`

  Like the above, but accept variable number of arguments. These return either `true` or `false`.

- `not [arg]`

  The logical negation operator (`!`).

- `mod [arg]`

  The modulus (`%`) operator.

- `-# [arg]`

  The unary minus operator. It negates its argument.

- `sum [0..*]` and `mul [0..*]`

  Perform summation and product operations on any number of arguments.

- `to-int [arg:number]`

  Converts its argument to an integer value, by truncating the decimal part.

- `strlen [str:string]`

  Returns the length of `str`.

- `str@ [str:string n:integer]`

  Returns the `n`th character of `str`.

Moreover, all basic binary inequality operators `<, >, <=, >=` as well as all basic binary arithmetic operators `+, -, *, /` are supported. Comparison operators: `=` and `<>` are equivalent to JavaScript's `===` and `!==`, which means they perform strict comparison, without implicit type conversion[`?` , Section Equality operators].

2.6.2 Language primitives

The Dual language supports the following primitives:

- `bind [name value]`

  Evaluates its second argument and binds this value to the name of the first argument. This name is bound within the current scope. This is a basic construct for defining variables, like `var` or `define` in other languages. Significant semantics here are that new scopes are introduced by function bodies, macro bodies and match expression bodies. The primitive also supports pattern matching to deconstruct the value and bind its components to possibly several variables. In that regard it works a lot like JavaScript's destructuring assignment[21] or similar features in other languages, such as Perl or Python. This primitive can be used only for binding names that don't exist in the scope at the point of its invocation. There are other constructs for mutating and modifying existing variables. There is no hoisting[25, Section var hoisting], as definitions are processed in order in which they appear in code.

  For example:

  ```
  bind [greeting '[Hello]]
  ```

- `if [condition consequent alternative]`

  This primitive serves as a basic conditional evaluation construct. Its semantics are like those of the analogous construct in Lisp. It accepts 3 arguments: first the `condition` expression, then the `consequent`, that is, the expression to be evaluated if the value of the condition is *not false* (note that this is a strict rule; any other value than `false` is interpreted as `true`; every conditional construct in the language follows this rule). The third argument, the `alternative` is the expression that is evaluated otherwise.

- `do [0..*]`

  Evaluates its arguments in order and returns the value of the last argument. Fulfils the role of a block of expressions.

  For example:

```
if [<[a 2] do [
    bind [b -[2 a]]
    log['[difference b:] b]
] do [
    bind [c -[a 2]]
    log ['[difference c:] c]
]]
```

- `while [condition body]`

  A basic loop construct. If `condition` is equivalent to *not false*, evaluates `body`. Repeats these steps until `condition` evaluates to `false`. Returns the value of the last evaluation of `body` or `false` if the body was not evaluated.

- `mutate [name value]`

  If a variable identified by `name` is defined within the current scope or any outer scope, changes (mutates) its value, so it now refers to the result of evaluating the `value` argument. The scopes are searched from the innermost to the outermost, in order. If the `name` argument doesn't identify any variable, an error is thrown. Returns the scope (environment), in which the primitive was evaluated.

- `dict [0..*]`

  Creates and returns a JavaScript object. It takes an even number of arguments. Arguments are considered in twos, as key-value pairs. These pairs determine properties for the new objects. Keys, which must be words, are property names and their corresponding values, which can be arbitrary expressions, are the values of these properties.

  For example:

```
-- creates an object with four properties and assigns it
-- to variable ‘car‘:
bind [car dict [
    id 0
    brand '[Ford]
    model '[Mustang]
    year 1969
]]
```

- `assign [2..*]`

  A wrapper for JavaScript's Object.assign()[**?**]. It copies the values of all properties from one or more source objects to a target object. Returns the

target object. The first argument is the target object, the following arguments are the source objects.

- `code' [arg]`

  Returns its argument without evaluating it. Used in macros, which return unevaluated code, which is substituted in the syntax tree and only then evaluated.

- `macro [1..*]`

  Returns a macro value. The last argument is the macro's body. The preceding arguments are the patterns for the macro's arguments. See Sections 2.9 and 2.11 for details.

- `of [1..*]`

  Returns a function value. The last argument is the function's body. The preceding arguments are the patterns for the macro's arguments. See Section 2.9 for details.

- `of  [2..*]`

  Returns a function value. Treats its penultimate argument as the function's body and all the preceding arguments as patterns for the function's arguments. See Section 2.9 for details.

  The last argument is used when the function is called and the values supplied as arguments do not match the patterns. If the argument is a function, it will be called with the same values as arguments and if it is a value it will be returned.

  This enables chaining functions together like so:

```
bind [f
    of~ [a b c log['[called with three arguments]]
        of~ [a b log['[called with two arguments]]
            of~ [a log['[called with one argument]]
                log['[called with zero or more than three
                   arguments]]
            ]
        ]
    ]
]

-- will log "called with two arguments":
f[3 2]
```

- `procedure [body]`

  Returns a function value. Its only argument is the function's body.

- `match [2..*]`

  Performs pattern matching. Its first argument is an expression to be matched. The following arguments are two-element lists, where the first element is the pattern to be matched and the second the expression to be evaluated if it matches. See Section 2.9.2 for details.

- `cond [1..*]`

  It works like a nested `if-else`s and similarly to Lisp's `cond`[17, Section 5.3, Macro COND]. Its arguments are two-element lists, where the first element is a condition that should evaluate to a boolean value and the second is the expression to be evaluated if it the condition is true. It evaluates at most one expression: the one that has a true condition. Conditions are checked in order.

- `. [2..*]`

  Property accessor. Essentially works like JavaScript's `.` operator[**?**]:

  For example:

  ```
  .[window Date now][]
  ```

  translates to JavaScript as:

  ```
  window.Date.now();
  ```

  If a property cannot be accessed, an error is thrown.

- `: [3..*]`

  Works symmetrically to `.` – it sets a property to a value specified by its last argument.

  For example:

  ```
  :[game-state hero ammo 5]
  ```

  translates to JavaScript as:

  ```
  gameState.hero.ammo = 5;
  ```

  If a property cannot be accessed, an error is thrown.

- `@ [arg]`

  Identity operator. Returns the value of its argument.

- `async [1..*]`

  Its first argument should be an asynchronous JavaScript function, such as `requestAnimationFrame`[28]. It applies this function to its remaining arguments.

2.6.3 Values

The following values are also defined:

- `true` and `false`

  Evaluate to their respective boolean values. `_` is an alias for `true` when used outside of pattern-matching. This enables a convenient compatibility between `match` and `cond`: if we're matching a single value and want to have a default case, then `_` is used to match any value. Similarly, if `_` is given as a condition in the last alternative of `cond`, it will evaluate to `true` and work as the default case.

- `undefined`

  Evaluates to JavaScript's `undefined` value. It is a primitive type that is used by the language to mark values that have not been assigned a value. Also, functions that do not explicitly return a value, return `undefined`[**?**].

- `window`

  Provides access to JavaScript's global `window` object[**?**].

2.7 Enhanced Syntax Tree

In order to enable full mapping between any number of program representations at the syntax-level, a modification of an AST was designed as a data structure representation of Dual's syntax. I call this structure the Enhanced Syntax Tree (EST). This crucial element in the language's design is described in this section.

The primary representation of a program in Dual is the EST. Although itself not directly editable, it can contain references to any number of editable representations, such as the text and visual ones.

These other representations contain back-references to the EST. Thanks to this, a change to any of the representations can be propagated to every other representation.

Every representation must come with:

- A way to translate it to an EST.
- A way to generate it for a given EST.
- A way or ways to manipulate it.

While translating, generating and manipulating, it must be ensured that each entity of the representation has a bidirectional association to a corresponding EST node.

For example, for text representation:

- Translation to EST is done with a parser.

- Generation from EST is done with an unparser[**?**].
- Manipulation is done with a text editor.

To ensure that the associations are kept, there must be objects that represent "text fragments". These objects then must contain references to corresponding EST nodes and vice versa.

White space characters and comments have no semantic significance, unless serving as separators could be considered one. After parsing, bracketing characters also serve no purpose and can be safely discarded, without influencing the meaning of the program. This is indeed done when constructing an AST from text in most programming languages.

In case of Dual though, no characters are discarded. Instead, white space, comments, brackets and any other characters are included in the EST, connected to appropriate nodes. Storing all characters in the EST means that the entirety of text representation, in structural form, is accessible straight from the syntax tree. This allows an unparser to recreate it *exactly*.

Such design greatly simplifies the implementation of and integrates with the language features such as:

- Automatic indentation. The EST contains all white space. If a new node is inserted into it, it can be initialized with white space of its siblings and/or ancestors, etc..
- Documentation comments. Comments can easily be associated with corresponding code blocks (EST nodes), which can be useful for automatically generating documentation in any format.
- Any expression can be unparsed to its original form straight from syntax tree, which can be used for debugging. For example, if a Dual program is built by manipulating visual representation entirely without the use of text and an error occurs while interpreting it, a single EST node – the one that contains the erroneous expression – can be unparsed and presented by the debugger in editable form. This may allow the user to fix the error quicker than manipulating blocks, without the need to unparse the entire program.
- Any expression can be stringified (serialized) on-the-fly and this string can be used as a value in the program or stored in a file.

2.7.1 Structural representation of strings

The last feature from the above list provides an interesting way of implementing strings in the language. Instead as streams of characters, they could be kept in structural form – as syntax trees. In combination with pattern matching this enables language-native structural manipulation of strings[3]. For example we could write:

[3]See: [90] and [38, Section Pattern matching and strings] for similar concepts.

```
bind [str '[A quick brown fox jumps over the lazy dog]]

bind [words [_ _ third-word {rest}] str]

bind [characters [_ _ third-letter {rest}] third-word]

-- logs "o" to the console:
log [third-letter]
```

Where `words` deconstructs a string into individual words and binds these words to identifiers provided as its arguments. `characters` performs an analogous operation on the character-level. The notation `{rest}` matches zero or more arguments (see Section 2.10 for details). `log` outputs the values of its arguments to the JavaScript console.

A downside here is that such representation of strings is not very efficient. A simple optimization would be to keep the raw form of the string (a stream of characters) as a value in the corresponding syntax tree node. So the raw representation is extended instead of replaced. Having these two forms alongside each other would enable the programmer to use the familiar string manipulation methods as well as structural manipulation without significant performance impact.

2.8 Syntax sugar for function invocations

In order to reduce the amount of *closing* brackets appearing next to each other in program's text, two additional simple notations were introduced. The first is addition of the pipe special character (`|`). It is used for single-argument functions.

If a function is invoked with only one argument, we can omit the closing bracket `]` and replace the opening bracket `[` with `|`. `|` can be viewed as a right-associative "invocation operator". For example:

```
foo | bar | baz
```

is equivalent to:

```
foo [bar [baz]]
```

The parser produces equivalent syntax trees for the above cases.

Below I present more examples to illustrate the utility of this syntax. Note that `<=>` symbol used in comments means "equivalent to":

```
-- compute factorial of 32:
-- <=> factorial[32]
factorial|32

-- find 9th Fibonacci number:
-- <=> fibonacci[9]
fibonacci|9

-- compute sine of pi:
-- <=> sin[pi]
```

```
sin|pi

-- compute cosine of the number that is
-- the result of multiplication of pi and 5!:
-- <=> cos[*[pi factorial[5]]]
cos|*[pi factorial|5]

-- convert 33.2 to an integer (truncate .2):
-- <=> to-int[33.2]
to-int|33.2

-- construct a list with one item,
-- which is a string "hello":
-- <=> list['[hello]]
list|'|hello
```

Another special character (`!`) was introduced for analogous use in zero-argument expressions (procedures):

```
-- invoke a procedure that changes
-- some state variables in its outer scope:
-- <=> set-initial-state[]
set-initial-state!

-- sum two random numbers:
-- <=> +[random[] random[]]
+[random! random!]

-- bind a value returned by an immediately
-- invoked procedure to an identifier:
-- <=> bind [forty-two procedure [42][]]
bind [forty-two procedure [42]!]

-- evaluates to 42:
forty-two
```

2.9 Pattern matching

A simple, yet powerful pattern-matching facilities were added to the language, which further extend its expressive power.

Pattern matching works with bindings, functions, `match` primitive and macros.

The pattern matching works in a way similar to most other languages that support this feature (e.g. ML family). The general rules are:

- A literal (strings or numbers are supported) value matches itself:

```
-- computes factorial of a number:
bind [factorial
    of~ [0 1
    of~ [n *[n factorial[-[n 1]]]]]
]
```

```
-- logs `120`:
log [factorial|5]
```

- An identifier (word) matches any value, which is then bound to the identifier:

```
bind [simple-print of [x log|x]]

-- logs `3`:
simple-print[3]
```

- A wildcard pattern (_) matches any value, but does not bind:

```
-- returns its third argument, discards the rest:
bind [get-third of [_ _ x x]]

-- logs `3`:
log [get-third[1 2 3]]
```

  As such it can be useful for discarding some values, depending on other values or extracting some values from a structure (see next point).

Also the following expression-patterns are supported:

- `list` or `$` is used to destructure lists:

```
bind [$[_ _ third-element] $[0 1 2]]

-- logs `3`:
log [third-element]

-- it works for arbitrarily nested lists as well:
bind [
    $[  _ $[  _  pick  _   _]   _]
    $['|a $['|b  '|c '|d '|e] '|f]
]

-- logs `c`:
log [pick]
```

- Comparison operators (= < <= >= <>) match if a value passes the comparison; it can be viewed as a shorthand notation for simple guards[8, Chapter Pattern Matching Basics, Section Using Guards within Patterns]:

```
-- returns the sign of a number
-- note: `-#` is the unary `-` operator:
bind [sign
    of [=|0 0
    of [<|0 -#|1
    of [>|0 1]]]
]

-- logs `-1`:
log [sign|-77]
```

Other pattern-expressions are not supported and using them will result in a mismatch.

2.9.1 Destructuring

Pattern matching works with bindings, the language allows destructuring assignments and definitions[21]. An example of a such definition would be:

```
bind [
    $[a b $[c d]]
    $[1 2 $[3 4]]
]

bind [
    $[  _   x   y  {   rest   }]
    $['|a '|b '|c  '|d '|e  '|f]
]

-- logs `1 2 3 4`:
log [a b c d]

-- logs `b c ["d", "e", "f"]`:
log [x y rest]
```

2.9.2 `match` primitive

The above examples show pattern matching used in function definitions and for destructuring values by binding their components to identifiers. There is also the `match` primitive, which can serve the role of a `switch` statement from C-like languages. It is however much more powerful, as any complex values supported by the pattern matching system can be matched, including lists. This allows switching on multiple values and in any combination.

The `match` primitive's first argument is a value to match and all subsequent arguments are two-element lists, where the first element is the pattern to match and the second is the expression to evaluate in case of a match. The primitive tries the matches in order and only evaluates the expression related to the first successful match. The subsequent matches are not evaluated.

Here are example uses for `match`:

```
bind [state '|game-on]

-- will execute the `play` procedure:
match [state
    $['|game-on play!]
    $['|game-paused display-pause-menu!]
    $['|game-screenshot capture-screenshot!]
]

-- ...
```

```
-- note: . is the access operator
-- .[a b c] is equivalent to a.b.c in other languages
bind [$[x y] .[player postion]]

-- we can easily replace complex conditions:
match [$[x x y y]
    $[
        $[>|0 <|screen-width >|0 <|screen-height]
        log|'[player visible]
    ]
    $[_ log|'[player not visible]]
]
```

2.10 Rest parameters and spread operator

Another syntax extension that I introduced involves two additional special bracketing characters: `{` and `}`, which serve several purposes:

- If used in function definitions, they indicate that a function or macro is variadic – it accepts a variable number of arguments[**?**].

  If a function is invoked with an equal or greater number of arguments than stated in its definition and the last argument's name in this definition is specified between `{` and `}` then any extraneous arguments are available in the function's body in a list with the name that was specified inside the curly braces. The order of arguments is preserved. For example:

  ```
  bind [variadic-function of [a b {args}
      log [a b args]
  ]]

  -- logs `1 2 [3, 4, 5, 6]`:
  variadic-function[1 2 3 4 5 6]
  ```

  This is essentially the same as the "rest parameters" mechanism known from Lisp[12, Section 12.2.3], recently also adopted in JavaScript (as of the ECMAScript 2015 standard[23]).

- The above extends beyond function definitions. It works in any place, where pattern matching works:

  ```
  bind [$[a b {rest}] $['|a '|b '|c '|d '|e]]

  -- logs `["c", "d", "e"]`:
  log [rest]
  ```

  This enables non-exact matching. If only the first few elements of a list are important and a list with variable number of elements is acceptable as a match, the extra elements can be dropped by using this syntax.

- If used outside pattern matching, curly braces act as an universal list splicing and flattening operator. If an argument is given to a function surrounded by curly braces and this argument is a list then it is treated as if every individual element of that list was provided in its place.

  If an argument in curly braces is not a list, then curly braces behave like the identity operator and return it unchanged.

  There can be multiple arguments inside one pair of curly braces or multiple curly-braced arguments given to a function. All of these arguments will be expanded in the way described.

  For example:

```
bind [f of [a b c d e f log [a b c d e f]]]
bind [args $[8 7 6]]

-- logs `9 8 7 6 5 4`:
f[9 {args} {$[5 4]}]

-- or alternatively,
-- surrounding all arguments with curly braces
-- logs `9 8 7 6 5 4`:
f[{9 args $[5 4]}]

-- curly braces can surround any argument
-- or any sequence of arguments,
-- regardless of position in the invocation list;
-- logs `9 8 7 6 [5, 4]`:
f[{9 args} $[5 4]]
```

  This works similarly to the spread operator from ECMAScript 2015[?] or the splicing syntax `,@` used in Lisp's backquotes[17, Section 2.4.6], [12, Section 9.4], but is much more flexible. It can be used in every function or macro invocation, not just in backquotes. Also, if there is more that one list-argument that should be spliced, they can be grouped together inside curly braces and do not have to be individually "tagged".

  Curly braces can also be used as a nicer syntax for the fundamental function `apply`:

```
bind [numbers $[1 2 3 4 5]]

-- evaluates to 15:
apply [sum numbers]

-- also evaluates to 15:
sum[{numbers}]
```

- They also serve as string interpolation notation. When a string is evaluated, all expressions surrounded by `{` and `}` that appear inside this string are evaluated and spliced into its value before the value is returned.

For example:

```
bind [name '|Bill]

-- logs `Hello, Bill.`:
log ['[Hello, {name}.]]
```

This gives us a very convenient notation for string interpolation, similar to e.g. template literals in JavaScript[24].

To escape curly braces inside a string we can double them or use the escape character \:

```
-- logs `Hello, {name}.`:
log ['[Hello, {{name}}.]]

-- also logs `Hello, {name}.`:
log ['[Hello, \{name\}.]]
```

There is also a special type of string – an HTML string, where interpolation notation is the reversed – double braces cause substitution, single braces do nothing:

```
bind [name '|Bill]

-- logs `<h1>Hello, Bill.</h1>`:
log [html'[<h1>Hello, {{name}}.</h1>]]

-- logs `<h1>Hello, {name}.</h1>`:
log [html'[<h1>Hello, {name}.</h1>]]
```

This is to enable embedding CSS and JavaScript code inside those strings, without having to constantly escape brace characters.

- Related to the above point, curly braces are used in `code'` strings that are returned by macros. They work similarly to curly braces in strings, except that the substituted values should be unevaluated expressions (syntax tree nodes). Also, code strings are never interpreted as streams of characters, and are always stored as syntax trees.

  This use of curly braces is very similar to Lisp's unquote syntax (`,`)[11, Section 1.3.8].

  The next section (2.11) provides examples and explanation of macros in Dual.

2.11 Just-in-time macros

The experimental approach to Dual's design gave rise to a very interesting feature, which could be described as first-class just-in-time expanded macros.

Macros in Lisp-like languages are different than the macros provided by the C preprocessor or similar macro systems. They are much more powerful[**?**].

Essentially, macros are a way to transform code from one (usually much terser) form to another. They can extend the language's syntax, create new syntactical constructs or Domain-Specific Languages (DSLs)[**?** , Chapter 3].

Lisp-like macros are integrated with the language and operate on its code or, more precisely, syntax trees[4]. Such a macro can be described as a function that takes code as arguments and returns code as a result. This code is then expanded into the syntax tree, replacing the macro. A macro can perform arbitrary computation while it is evaluated, just like a function. Macros are written in the same language as the code they transform.

2.11.1 First-class

Unlike traditional Lisp macros, in Dual macros are first-class, because they are treated like any other value.

In order to support first-class runtime macros, a Lisp interpreter can be modified as follows[84][5]:

- Primitives are moved into the top-level environment[6]. They thus are no longer treated as special case by the `eval` function.
- A new primitive, `macro` is added, which is essentially equivalent to `lambda`, except that it produces macro values instead of function values.
- The `apply` function is now responsible for checking the type of an expression's operator, which can be a `primitive`, a `macro` or a normal expression. This determines whether the arguments should be evaluated before application.

This results in a simpler, more uniform and at the same time more powerful interpreter. A major advantage is that:

> Because of their first-class nature, first-class macros make it easy to add or simulate any degree of laziness[84].

A macro in Dual is defined with the `macro` primitive and bound to a name with the `bind` primitive:

```
-- defines an ‘unless‘ macro,
-- which works like the ‘if‘ primitive,
-- except that the provided condition is negated
bind [unless macro [condition body alternative
    code'[if [not[{condition}] {body} {alternative}]]
]]

bind [a 100]
```

[4]For brevity I will sometimes use the term "code" when I mean a syntax tree.

[5]Recall a brief description of an implementation of a Lisp interpreter from Section 1.2.

[6]The top-level environment contains the basic functions and values that are available to every program.

```
-- will log "a greater than 3":
unless [>[a 3]
    log|'[a less than or equal to 3]
    log|'[a greater than 3]
]
```

Because a macro is a first-class value, there is no need for a special primitive for defining macros, such as `defmacro` in Lisp[17, Section 3.8, Macro DEFMACRO].

2.11.2 Just-in-time

Macros in Dual are just-in-time expanded, because the expansion happens at run-time, when a macro is encountered and evaluated by the interpreter. There is no separate macro-expansion time.

For simple macros the expansion works as follows:

- A macro invocation is encountered by the interpreter.
- It is expanded into code by evaluating it.
- The node in the EST containing the macro invocation is permanently replaced by the expanded expression.
- The expanded expression is evaluated and its value is returned as the value of the invocation.
- Next time when the interpreter arrives at the same point in the EST, the macro will already be replaced by the expanded expression. Thus, the cost of macro-expansion is one-time.

Macros in Dual can also return other macro values. If a macro returns a macro value instead of code, this value is evaluated. If, in turn, the result of this evaluation is another macro value, this one is evaluated as well, and so on, until a code value is returned. It then is expanded as described above.

This feature nicely composes with Dual's variation of Lisp's syntax in terms readability, particularly by reducing the amount of adjacent closing brackets in the source code and introducing blocks without the need for explicit use of the `do` primitive.

As an example. the below listing presents a macro named `if*`, which defines a slightly different syntax for the `if` primitive. This syntax wraps the condition, consequent and alternative parts of the `if` in separate blocks delimited by `[]`. The condition is required to be an infix expression in the form `a operator b`. The consequent and alternative blocks take care of wrapping all expressions within them in `do` blocks. This makes it more convenient and less error-prone to write complex `if` expressions:

```
-- defines the `if*` macro
-- it returns a macro, which returns a macro,
-- which returns another macro
```

```
-- arguments of each of these macros
-- are then spliced in the appropriate places
-- in the code that creates the resulting ‘if‘ expression:
bind [if* macro [a op b
    macro [{then}
        macro [{else}
            code'[if [apply[{op} {a} {b}] do[{then}] do[{else}]]]
        ]
    ]
]]

-- the macro is used as follows:
if* [a < b][
    log ['[a is less than b]]
    a
][
    log ['[b is less than or equal to a]]
    b
]

-- the above expands to:
if [<[a b] do [
    log ['[a is less than b]]
    a
] do [
    log ['[b is less than or equal to a]]
    b
]]
```

Note that the macro gets rid of the explicit `do` expressions. It essentially defines a new language construct, which has the following template:

```
if* [--[condition: ] <value-1> <comparison-operator> <value-2>][
    -- consequent block:
    <expression-1>
    <expression-2>
    -- ...
    <expression-n>
][
    -- alternative block:
    <expression-1>
    <expression-2>
    -- ...
    <expression-n>
]
```

2.11.3 In combination with | and !

The combination of the macro system and the syntax sugar for zero and single argument functions (`|` and `!`) helps reduce the amount of bracketing characters even further.

For example, if we define a `match*` and `of*` macros as follows:

```
bind [match* macro [{args}
        macro [op
                code'[apply [{op args}]]
]]

bind [of* macro [{args}
    macro [{body}
        macro [alternative
            code'[of~ [{args} do[{body}] {alternative}]]
        ]
    ]
]]
```

Then the following expression:

```
bind [x 99]

-- will log "x is greater than one":
match*  [x]
| of* [<|0] [log|'[x is negative]]
| of*   [0] [log|'[x is zero]]
| of*   [1] [log|'[x is one]]
| log|'[x is greater than one]
```

Would be translated into the following:

```
bind [x 99]

-- will log "x is greater than one":
apply [
    of~ [<|0 log|'[x is negative]
        of~ [0 log|'[x is zero]
            of~ [1 log|'[x is one]
                log|'[x is greater than one]
            ]
        ]
    ]
    x
]
```

Notice that the `match*` macro does not use or need the native `match` construct at all.

The resulting syntax is somewhat similar to ML-style[41, Section Algebraic datatypes and pattern matching] languages. And yet it there is no complex grammar that defines this syntax. It is handled with a very simple parser.

This shows that a few simple, but general syntax rules and a powerful macro system, can be a very flexible tool for extending syntax.

Chapter 3

Development environment design

This chapter describes the design of Dual's development environment.

3.1 Overview

The overall design tries to merge features of modern code editors, such as Brackets[47], Visual Studio Code[61] or Atom[53] with visual programming language editors, such as the Blueprint Editor from Unreal Engine 4[**?**].

The environment is intended to work online, similarly to Integrated Development Environments such as Codeanywhere[50] or Cloud9[49]. It should also work as offline, like Scratch's offline editor[**?**].

A folder is considered a project, similarly to modern code editors, such as Brackets or Visual Studio Code.

It should be easily usable with minimal effort from the user to install it or set it up.

It should have minimal external dependencies

The environment should have the following components:

- A project manager, which should be capable of managing local as well as remote projects.
- A text editor with syntax highlighting, autocompletion, autoindentation, etc. for Dual. The text editor should conform to the design outlined in Section 2.7.
- A visual editor able to manipulate a visual representation of the EST with autostructuring. It should also conform to the design outlined in Section 2.7.

The layout of the editor should conform to universaly accepted standards where possible. There should be a menu bar at the top.

There should be a flexible global search faciltiy that can search through all editor options and menus.

There should be a console output area at the bottom of the screen

The editor should support the text and visual representation and should provide an interface to add new representations.

The appearance of the visual representation should be customizable.

3.2 Text editor

The text editor should have

3.3 Visual editor

The visual representation should be mappable to the EST. There should be a distinguishable and manipulable visual element for every EST node. Such an element should contain a reference to the node (and vice versa).

There should be ways to perform the following actions with the visual editor:

- Insert new nodes into EST.
- Remove existing nodes from the EST.
- Modify existing nodes in the EST.
- Replace existing nodes and subtrees in the EST.
- Move nodes and subtrees to different locations in the EST.
- Select and manipulate multiple arbitrary nodes and subtrees in the EST.

In short, the visual editor should provide ways to perform the same abstract operations on the EST that are possible when editing text and possibly more.

Some operations on raw text should also be reflected in the visual representation. For example the Find option. Searching through text should highlight the visual elements that correspond to the EST nodes that are connected to the text that contains the searched phrase. Regular expression based searching should also be possible. Replacing text with the Replace option should be reflected in the visual representation.

There should be a possibility to temporarily disable a representation by disconnecting it from the EST. Any changes made to other representations will then not be propagated to this representation. A disabled representation should become read-only until it is enabled. When it is enabled it should be updated to reflect the current state of the EST. At least one representation must be enabled at all times.

There should be a context-sensitive autocompletion feature. There should be an easily accessible library of functions and primitives with documentation.

User-defined functions should be added to this library upon definition and removed from it when they are removed from the source code.

The list of possible nodes displayed along with the context menu is implemented in terms of a simple autocomplete functionality on top of CodeMirror. Every item

in the autocomplete list is associated with a fragment of code, which is basically a signature of the corresponding function. User-defined functions could be easily automatically added to this list by extracting their signatures from definitions.

The templates could also be selected by the user from a visual library of puzzle pieces, like the one in Scratch (Fig. 3.1).

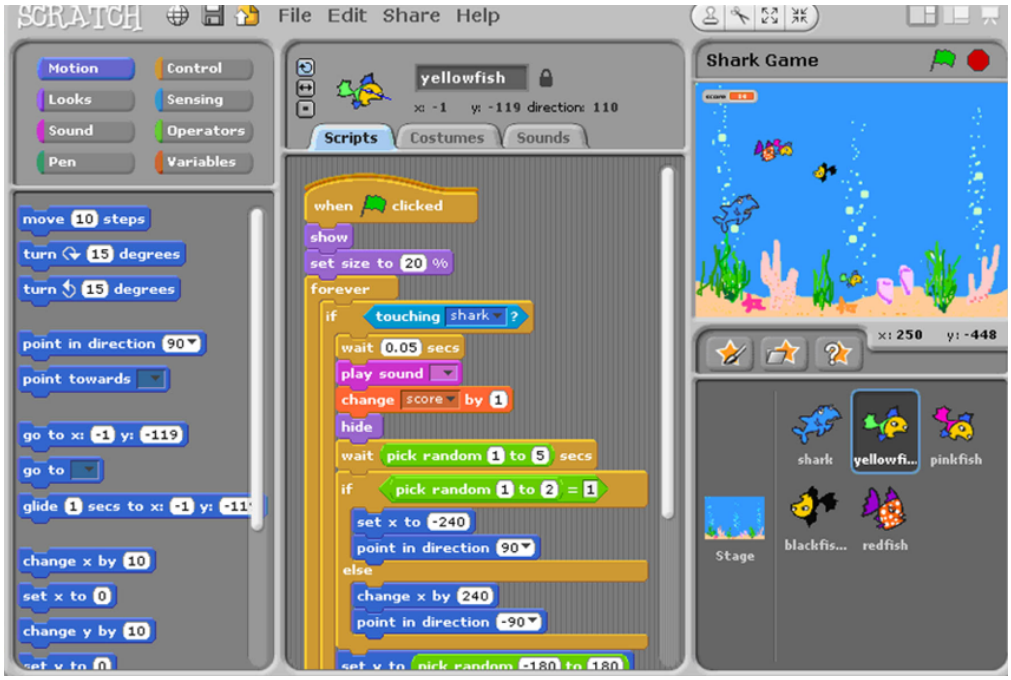

Figure 3.1: MIT Scratch programming language editor; screenshot from[98]

3.4 Visual editor

3.4.1 The visual representation

The design of Dual's visual representation draws from many visual programming languages. Analyzing these, we can observe several distinct approaches of which two particular designs are the most widespread and successful. These can be described as "line-connected block-based" and "snap-together block-based" visual languages. The former family is exemplified by the Blueprints Visual Scripting system of Unreal Engine 4[69] and the latter by MIT Scratch[29, 39].

Basic design principles: make it no harder to use than the textual representation ideally it should add useful capabilities, without taking away these provided by text editors

Existing visual languages are mostly criticized, because they fail to meet these basic criteria.

Flexibility

The fact that the visual representation is composed purely out of HTML and CSS
Fully customisable with CSS

Design

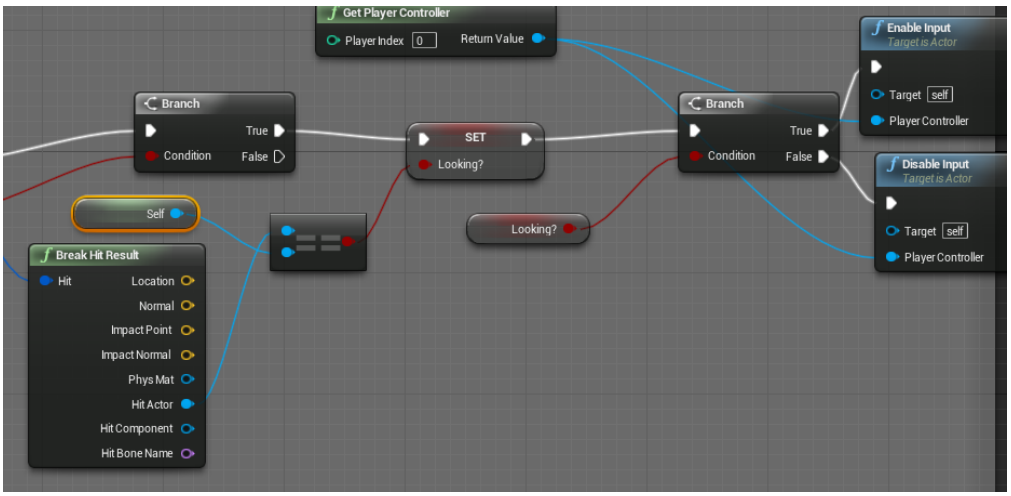

Figure 3.2:

Many iterations:

The visual form allows us to provide much more information about different elements of the program. Spatially relate this information with these elements through blocks and connections. Relate expressions with other expressions through connections, which can also carry additional information.

We can distinguish the following visual elements:

- Blocks, which represent expressions or individual nodes of the EST. Those in turn consist of:
  - A header, which contains an icon and the name of the expression's operator. Next to the header a documentation comment might be displayed.
  - Slots, which are the numbers or names of the arguments followed by an icon; below these documentation comments could be displayed.
  - Possibly additional buttons, which could be used to add more slots to variadic expressions.
- Connections between slots and blocks, which could also contain some useful annotations. The proposed design places type annotations there. These consist of the name of the type followed by an icon that represents this type. Connections actually have two parts: one extending from a slot, which in this case would contain the argument's type annotation, and one extending from a block header, which would contain expression return value's type annotation.

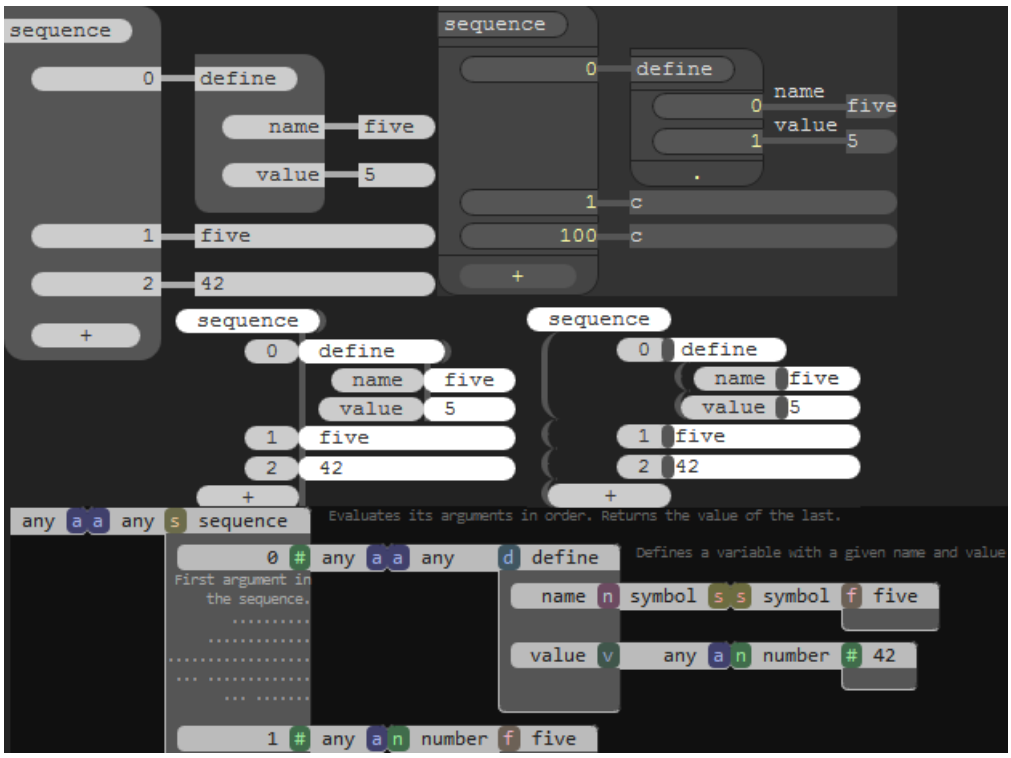

Figure 3.3:

Icons are a way to minimize the use of text to represent different entities

The text representation is very compact, which often is an advantage. This advantage can be maintained by the visual representation by making all the additional information optional. The user should have easy way of configuring whether or not and what informations should be displayed. By folding some textual elements into icons the visual representation could actually be made more compact than the text form.

Structure

The programmer could have the ability to alter the structure of the representation, but he should not be required to constantly shape it. A connected-block representations, such as the one in Unreal Engine 4 has no mechanism that automatically structures the visual code similar to autoindentation and other useful autostructuring features that evolved in code editors over time and experience with using text-based programming languages. This can be considered a regression on the visual editors' part.

The early designs show the following features that are not implemented in the final prototype:

- Names of the arguments are displayed instead of numbers if sensible.
- Names of types of variables

The colored squares with letters inside are actually placeholders for icons. I imagine a design, where the user is able to click on those icons and fold the blocks into a more compact form, hiding the names and excessive text. This could be done on the level of individual blocks, whole subtrees or the entire program – similar to code folding in text editors. This allows to have a big picture and general relationships between nodes always visible and at the same time gives an ability to focus on the details of the part at hand.

The text below the slots could be documentation comments associated with the given argument. Their visibility could be toggleable through clicking on them, on an individual or global basis, similarly to icons.

We can observe that there's a need to manipulate or set visual properties of individual objects, clusters of objects/subtrees as well as the entire program tree.

Figure 3.4: This design has the interesting property of visually illustrating the program flow with arrows.

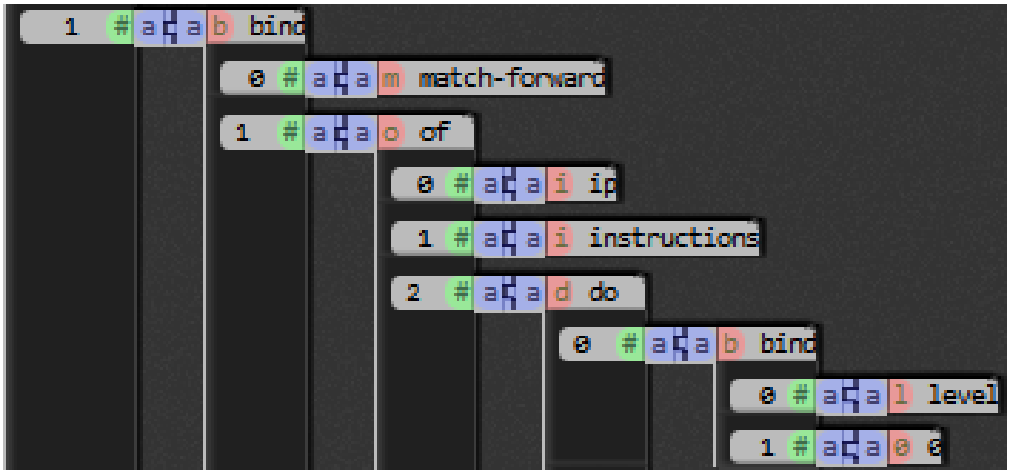
1 # a a b bind
0 # a a m match-forward
1 # a a o of
0 # a a i ip
1 # a a i instructions
2 # a a d do
0 # a a b bind
0 # a a l level
1 # a a 0 0

Figure 3.5:

Chapter 4

Prototype implementation

4.1 Programming discipline

The prototype was implemented largely in the spirit of exploratory programming: "the kind where you decide what to write by writing it."[54].

This approach in combination with a dynamic and flexible language like JavaScript enables one to quickly transform ideas to working prototypes and shape them as one goes along. But the usefulness of this method is limited, as it may quickly produce fairly low-quality code, as it is not focused on future maintainability.

Most of the features of the language and editor in the prototype are implemented as a proof-of-concept, although some are more refined than others in order to fulfil the major goals of this thesis, one of which was to implement a working non-trivial application in the language.

4.2 The language

The prototype implementation of the language contains all the features described in Chapter 2, with the following exceptions:

- Macros are not implemented.[1]
- There are two primitives, which produce function values: `of` and `of-p`. The second has the same meaning as `of` described in Chapter 2. The first has the same meaning, except that it does not use pattern matching when binding names to arguments. This primitive requires that all the names must be words.
- Destructuring is not implemented for assignments (it does not work in `mutate`), only for definitions (it works in `bind`). Pattern matching could easily be extended to mutation, although I have found it sufficient to be usable only in

[1] In fact, they partially *are* implemented, but are not usable. For example, there is a `macro` primitive available, which produces macro values. But it should not be used, as these macro values are not treated specially by the interpreter, so using them will not have the desired effect.

definitions and ended up not implementing it for assignments in the prototype.

- Comments are treated as a streams of characters, taking into account nesting and balancing of brackets in multi-line comments, but are not preserved on the EST as a tree-like structure.

- Strings are not recognized specially by the parser. They are stored and manipulated as syntax tree nodes, not as streams of characters. This means that the optimization described in Section 2.7.1 was not applied. The performance penalty is acceptable in the prototype implementation.

- The escape character
  has no special meaning. To substitute a special character in a string, the following built-in values are defined:

```
(left-bracket) -- escapes "["
(right-bracket) -- escapes "]"
(left-brace) -- escapes "{"
(right-brace) -- escapes "}"
(pipe) -- escapes "|"
(bang) -- escapes "!"
```

  So `'[(left-bracket)hello(right-bracket)]` would evaluate to: `"[hello]"`.

Lisp's syntax is as minimal as it gets[67], which makes
An interpreter for Lisp is also trivial to implement, so this is a good starting point.

There are many approaches to implementing interpreters for LISP in JavaScript[70], but the general principles are the same.

4.2.1 Macros

This macro system is not included in the final version of the prototype, although a proof-of-concept of it that I implemented in earlier prototypes

One feature that I experimented with while creating the prototype of Dual is support for first-class just-in-time expanded macros

4.3 The environment

The goal is to build an online Integrated Development Environment IDE, similar to Codeanywhere[50] or Cloud9[49], which works offline as well.

The current version of the development environment is intended to be used offline, on user's machine. Nevertheless it is implemented so that it could be easily transformed into an online system.

I decided to implement the system with minimal dependencies, so it can be easily installed and so I can achieve a greater level of integration by having more control over every part.

The only required dependencies for the basic functionalities of the prototype to work is a web browser and the CodeMirror library. An additional dependency is the Node.js environment – for running the stub of the project-manager.

The language's development environment is implemented as a web application. It consists of three parts:

- The server part, implemented in JavaScript on top of Node.js. This part's functions is mainly to enable access to user's file system, so any local folder can be opened as a project – modern web browsers restrict access to the local file system, because of security reasons. The server part also handles persisting changes to files and configuration.

- The project manager part, which communicates directly with the server part. The connection is maintained over a WebSocket[26]. This part provides access to user's file system via a custom folder selection interface. Basic configuration of server communication, such as changing the address and ports is also possible. Once a project is selected, the user may open it in the editor part.

- The editor part, which is the main component and can function as a standalone application. It can communicate with the server indirectly, through the `localStorage` mechanism[27].

The project manager and the editor, which can be considered the front-end parts of the system are designed to be a Single-Page Application[40]. The project manager exchanges JSON messages with the server through a WebSocket. This is used for updating the view with dynamic data. In order to facilitate the manipulation of the HTML structure of the page, which is the main application's view, I implemented a very simple web application framework, which binds the data from the server with the data on the client and the Document Object Model[3, Chapter 13].

Figure 4.1 shows an overview of the editor prototype's window. The basic layout is modeled after the aforementioned code editors. At the top of the window is the menu bar, below it a mockup of a global search input (not implemented). The left panel contains basic controls for selecting examples, invoking the parser and interpreter, toggling application view and adjusting the scale of the visual representation.

The browser's JavaScript console is used as the standard output. There is no built-in console.

The following options are implemented in the prototype:

- Available from the menu bar:

  - File->Save, which saves the current content of the text editor to a file named `save.dual` in editor's root directory. This only works if the server-side part of the environment is running. Otherwise the source will be saved only to browser's internal storage.

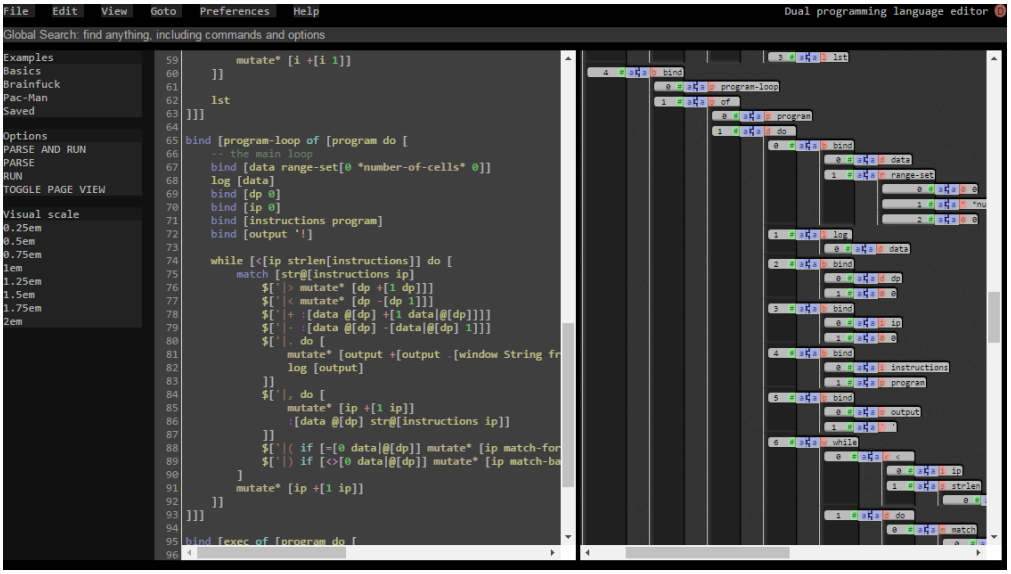

Figure 4.1: The editor

  - In the Edit menu: Undo, Redo, Cut, Copy, Paste and Select All options are supported. Note that by default web browsers restrict the access to the user's clipboard, so for Copy and Paste the standard key shortcuts should be used (Ctrl-C, Ctrl-V). All other conventional keyboard shortcuts are also supported, thanks to the CodeMirror library.

- Available from the left panel:

  - The options in the Examples submenu cause a corresponding source file to be loaded into the editor. This is for demonstration for the purposes of this thesis.

  - The Options submenu allows the user to invoke the parser and the interpreter separately or in combination as well as toggling between the "page" (also known as "application") and visual editor views. The application view contains an embedded web page (iframe), which can be manipulated by a Dual application. This is used to display the game view in the Pac-Man clone example.

  - The Visual scale submenu changes the size of the blocks in the visual editor. This demonstrates how manipulating one CSS property influences the rendering of the visual representation.

Some options have descriptive captions available that appear when the mouse cursor hovers over them.

4.4 Text editor

The text editor is built on top of the CodeMirror framework[55]. It was integrated with the editor in the following way:

- A custom syntax highlighting mode for Dual was defined.
- If a position of the text cursor in or the contents of the source change, a fragment of text corresponding to the appropriate EST node is highlighted. Also the corresponding subtree in the visual editor is highlighted. This works also in the other direction – when a node in the visual editor is selected, it is highlighted along with the corresponding text fragment. This demonstrates the core functionality of the system: it is "aware" at all times of currently focused meaningful part of the code, corresponding to an EST node. This is reflected in every representation that is associated with the EST.

Because every node in the EST is linked in both directions with a corresponding abstract element in a representation, any change to the element can be reflected in the node and, through the EST, in all other associated representations. This makes the system accurate and fast, as every change happens in an isolated context, which doesn't have to be reestablished every time a modification is made.

We can distinguish three representations used by the system:

1. The EST, which is the master representation of the program.
2. The fragments of text corresponding to EST nodes in the text representation are tracked by CodeMirror's TextMarker objects. These facilitate tracking and propagating any changes to and from this representation, as well as highlighting.
3. The visual representation, which is implemented in terms of pure HTML tables fully styled with CSS. This allows for easy and complete customization of the representation.

In case of the visual representation this is implemented in a rather straightforward way: every EST node has a corresponding set of DOM nodes. Thanks to this, we can track any actions performed on the DOM through the standard browser-implemented interface. This is solved in the prototype by attaching `click` event handlers to relevant nodes. Such an event triggers the following:

- A corresponding EST node is "focused" by the system.
- The visual node is highlighted.
- A context menu appears similar to that depicted in 4.2.

Figure 4.2 shows the context menu that has all the basic options for manipulating the visual representation. These perform their corresponding action on the

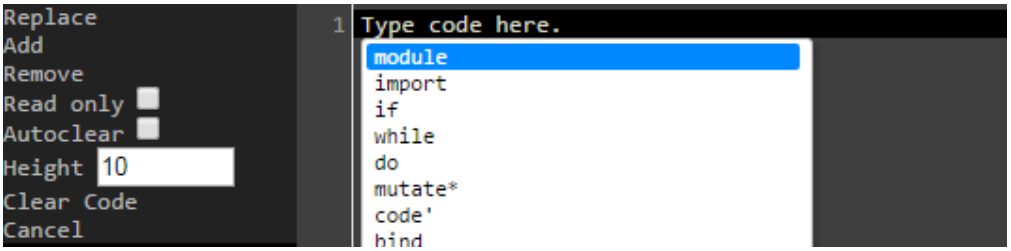

Figure 4.2: Visual editor's context menu

currently focused node and propagate it to the text representation. The options basic option are Replace, Add, and Remove.

The Remove option simply removes the selected node and its subtree from the DOM, the EST, as well as the associated text fragment.

The Add and Replace options make use of the small text-editor area next to the context menu. It contains a predefined list of names of some of the possible nodes that can be inserted. Selecting any of the names causes a template for the new node – in the form of an editable code snippet – to be inserted into the text-editor area. Such a template can be quickly adjusted by the user before inserting.

The user may also type in raw code into the text box, without selecting any templates. After entering the code and selecting the appropriate option, the text is parsed, transformed into TextMarker, EST, and DOM representations. Then all the versions of the fragment are inserted in appropriate places.

4.5 Performance

It could be optimized similarly to CodeMirror or other web-based text editors or applications. That is, only a visible portion (plus a margin, which allows for fast scrolling) of the code is rendered as DOM nodes at any time. The scrollbar is virtual and controlled by the editor rather than the browser.

Text editors like CodeMirror use similar amount of DOM nodes [[]], but thanks to these optimizations are able to handle megabyte-sized[75, Section General Approach] text files and are used in many real-world applications[76], which includes being a built-in editor in developer tools in major web browsers.

Another source of inefficiency is that parsing is done twice – once by Dual's parser and once by CodeMirror's system, which are incompatibile. A solution to that would be to implement a custom text editor or extend/modify CodeMirror to work with Dual's parser.

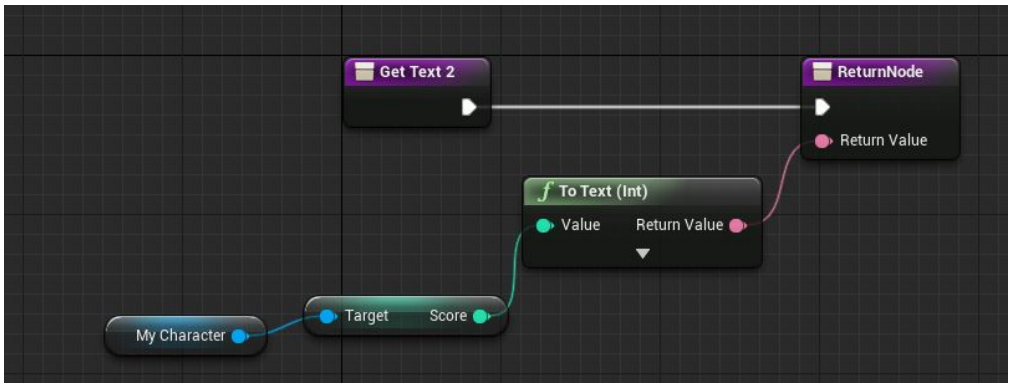

Figure 4.3: Blueprints Visual Scripting; screenshot from [99]

Chapter 5

Case study

Dynamic languages with a garbage collector have the advantage of letting the programmer use the exploratory style of programming, where he doesn't have to worry about memory management or other low level considerations. [][][] Doesn't have to design a complex type hierarchy or any similar scaffolding. He can just jump in and start implementing an idea. This is excellent for prototyping.

But when it comes to performance and robustness this approach shows its downsides very quickly. The safety of static types combined with a good development environment catches a lot of bugs and inconsistencies before runtime. Garbage collector mechanisms vary in implementation, each showing a different performance characteristic. In this chapter I will describe the implementation of a clone of Pac-Man in Dual and performance issues that I've encountered. These are very much related to the JavaScript environment, notably the event loop and the garbage collector, which has different implementations across browsers. The latter did shows a significant difference when comparing different web browsers.

Implementation of a non-trivial application allows to test the language design and quickly establish which features are the most useful in practice. I found that I could do away with a lot of the more complex ones net win

5.1 The game

It is actually a port of my earlier clone of the game, which was written in Links[52], a functional language.

5.1.1 Main loop

A typical game loop in a modern JavaScript game[19] relies on the `requestAnimationFrame` method[28]. This method takes a single argument, which is a function callback. This function is invoked by the browser before it repaints the contents of the window. Thus, it allows the game rendering to be synchronized with the browser.

The callback invoked by `requestAnimationFrame` receives a timestamp, specifying the time of the repaint event. Ideally and under the most common circum-

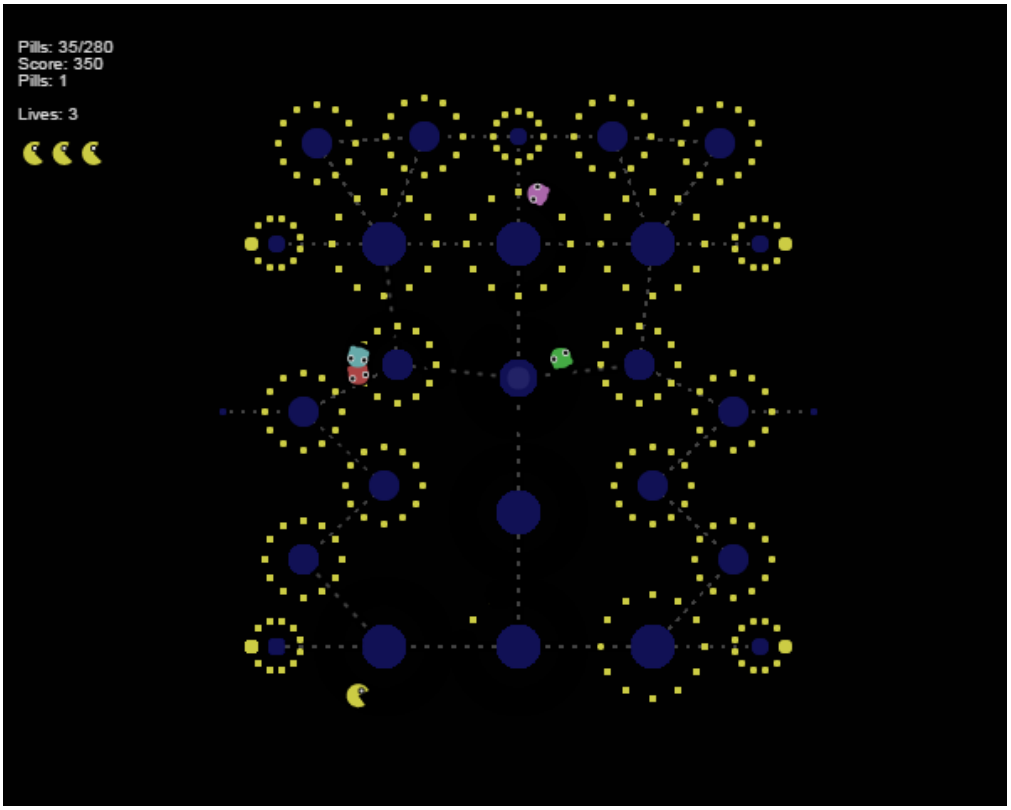

Figure 5.1: A screenshot from the game

stances this happens 60 times a second.

I implemented the game loop in Dual as follows:

```
-- [1] the amount of milliseconds between game state updates: bind
     [tick-length
--         50]

-- the main loop function: bind [main-loop -- arguments: -- game-
    state --
current game state -- last-tick -- time of the last -- game state
    update --
fps-info -- an object used for debugging, -- which contains
    information about
-- the frame rate -- current-time -- the time of the current --
    invocation of
the loop of [game-state last-tick fps-info current-time do [ --
    [2] schedule
the next iteration of the loop -- using requestAnimationFrame:
    async [
.[window requestAnimationFrame] of [next-time main-loop[ game-
    state
last-tick fps-info next-time ] ] ]

-- the timestamp of the tick after the last tick bind [next-tick
    +[last-tick
```

```
tick-length]]

-- counts how many state updates should be performed in this
   iteration: bind
--        [tick-count 0]

-- if the current time is past the timestamp of the next tick, the
    above
--        counter should be incremented; possibly more than by one
   , if the
--        difference is a multiply of tick-length if [>[current-
   time
--        next-tick] do [ bind [time-since-tick -[current-time
   last-tick]]
--        mutate [ tick-count .[math floor][ /[time-since-tick
   tick-length]
--        ] ] ] false]

-- perform the calculated amount of game state updates: bind [i 0]
    while
--        [<[i tick-count] do [ keep track of the time of the last
    tick:
--        mutate [last-tick +[last-tick tick-length]]

-- invoke the function that updates the game-state: mutate [ game-
   state
--        main-game-logic[game-state input-queue] ] mutate [i +[i
   1]] ]]

-- if there were game state updates, redraw game screen; else do
   nothing: if
--        [>[tick-count 0] mutate [fps-info draw[ game-state
   current-time
--        .[window performance now]!  fps-info ]] _ ] ]]]
```

5.2 Performance

Disparity between Firefox and Chrome, reflecting differences in garbage collector implementations.

Issue: interpreter is blocking the event loop. There's a lot of intermediate objects created that have to be garbage collected.

General pattern: Chrome more frequent garbage collections more regular more predictable

Details are a topic for another thesis

5.3 Possible improvements

Interruptable eval

Continuation-passing style State machine Anyway, explicit stack

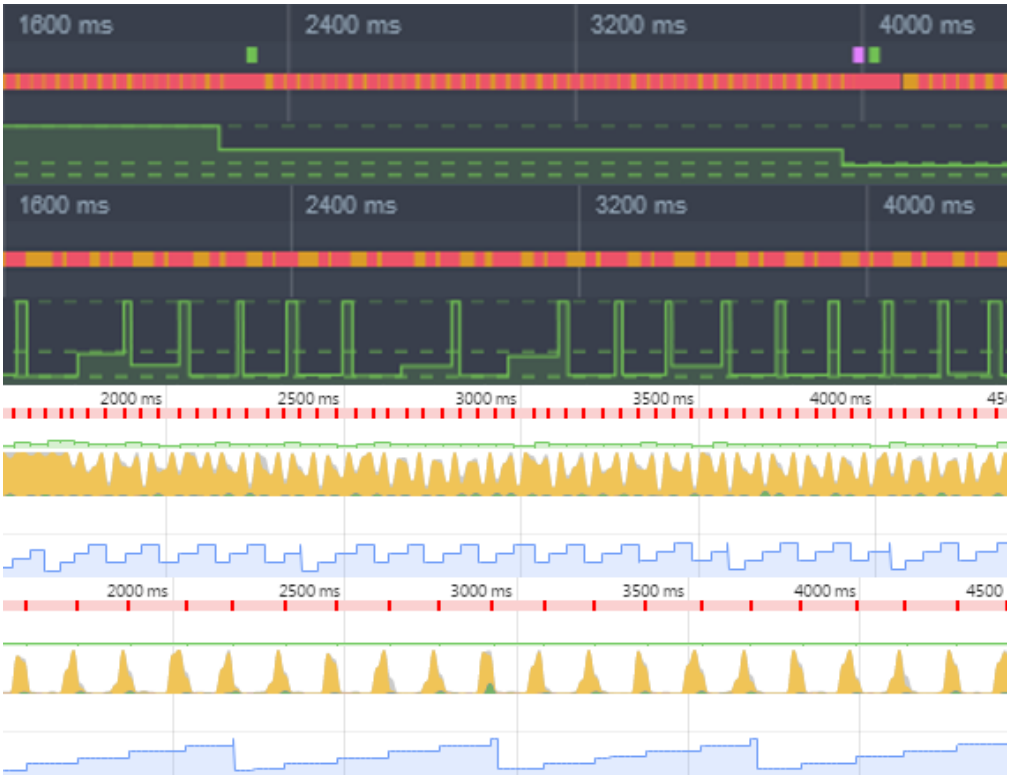

Figure 5.2: Comparison of Firefox' and Chrome's profiler outputs

Additional benefits: can pause and debug the application, step through can record the state and rewind

Chapter 6

Comparisons to other VPLs

This chapter compares Dual to the Blueprints Visual Scripting system of Unreal Engine 4 and to MIT Scratch.

General desirable characteristics of a scripting language:

- dynamic
- flexible
- suitable for rapid prototyping
- library of basic functions
- complementary to a non-scripting language

Blueprints:

- static, rigid, cumbersome
- no autostructuring
- no text representation
- no first-class functions
- no first-class macros?
- no sorting function available out of the box in 4.9.2

  and it's a commercial product basic functionality needs external libraries "The low-entry extended standard library has a sort array by comparator function, which is what you'd need here."
- difficult source control

  p4 was a nightmare

  diffing, etc. limited to the editor

- Blueprint does not really complement C++, which is also static and rigid

  rather: it intersects C++'s feature set; and it's poor at that: slow and incomplete

- not very good for rapid prototyping because of the above

BLUI, Coherent: web platform for UIs everywhere
Scratch:

- no first-class functions
- limited file I/O?
- educational
- in Flash/ActionScript
- only supports one-dimensional arrays, known as "lists"
- Floating point scalars and strings are supported as of version 1.4, but with limited string manipulation ability.

Snap! Scratch successor that fixes its shortcomings first class truly object oriented sprites with prototyping inheritance, and nestable sprites, which are not part of Scratch

Chapter 7

Summary and conclusions

I intend to continue my research with the goal of creating a modern real-world programming language useful for a specific range of tasks

I believe that there is room for a small and simple scripting language, which fuses Lisps, JavaScript's, Lua's best and most powerful features. Adding to that full support for visual programming designed to fix as much as possible of the obvious shortcomings of current visual languages as well as introducing innovation always providing direct mapping and fallback to text representation

If support for visual programming is good and innovative It has a chance to draw attention of designers and

The visual programming feature could draw the attention of non-programmers, designers and programmers, who work by means of prototyping and exploratory programming

Perhaps the above combination of features If well designed and executed Might be enough to outweigh [83]

JS: Ten akapit i kilka następnych brzmią jak z podsumowania. Sugeruję przenieść albo do rozdziału z podsumowaniem, ewentualnie na końcu rozdziału zrobić podrozdział z wnioskami. Na pewno nie powinno być tego we wstępie zanim cokolwiek zostanie zaprezentowane.

While implementing this project I learned that programming language design is a tremendous task, especially if the language being designed is intended to be of real-world use. Designing and implementing such a language absolutely from scratch, while introducing useful innovation cannot be done within the time limits of research for a thesis, unless perhaps by an experienced language designer. But such experience has to be gained somehow and this is an excellent opportunity.

The character of this research project is exploratory, although I intend to further develop ideas described here and continue my research, which will, as I hope, eventually result in creation of an innovative and useful language ready for real-world use.

That aside, I believe that at least some of the ideas described here are – in a varying degree – innovative and worth exploring further.

Even though the language presented in this thesis is complete in the sense of being able to implement any algorithm and non-trivial applications, as exemplified

by the Pac-Man clone, it is by no means a complete design. It should be viewed as a snapshot from a continuous design process that is intended to progress in the future.JS: Wydaje mi się, że ten akapit równiez pownien być w podsumowaniu

For these reasons the created environment is by no means complete and ready for use in developing complex applications. The degree of completeness of the project is reflected in:

- The core language, which is sufficiently expressive to implement any algorithm, i.e. Turing-complete[1]. A simple Brainfuck interpreter is included as an example program (see Appendix **??**) to demonstrate this[71].
- Implementation of several interesting additional features of the core language, which are described in this chapter JS: wymienić jakich
- The ablility of the language to implement also non-trivial applications. This is demonstrated by implementing a clone of Pac-Man, described in Chapter 5
- The direct correspondence of the visual and text representations, with the possibility of parallel dynamic editing; albeit the visual editing part of the editor includes only basic features and is not optimized in terms of performance; details are described in Chapter 3
- Implementation of the prototype of the language's development environment on top of the web platform, which includes a server-side and a client-side part. It runs locally on the user's machine, but is designed to be easily deployed as an online web application
- The editor has several useful features, such as basic support for text editing built on top of the CodeMirror JavaScript component with custom syntax highlighting and integration with the editor. The text editing component is integrated with the visual editing component, so that navigation or changes to each representation are tracked and visible to the user [[[]

[ ]

[1] In the same sense as JavaScript or C. No existing language is Turing-complete in the absolute sense, because of physical hardware limitations.

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Glossary

Document Object Model [[DOM description]]. 36

Enhanced Syntax Tree A syntax (parse) tree, which includes all of the "concrete" syntax, with its runtime-insignificant elements, such as white space and comments. It also contains references to other structures.. 20

Acronyms

AST Abstract Syntax Tree. 8

DOM Document Object Model. 36, 38, *Glossary:* Document Object Model

DSL Domain-Specific Language. 19

EST Enhanced Syntax Tree. 20, 37, *Glossary:* Enhanced Syntax Tree

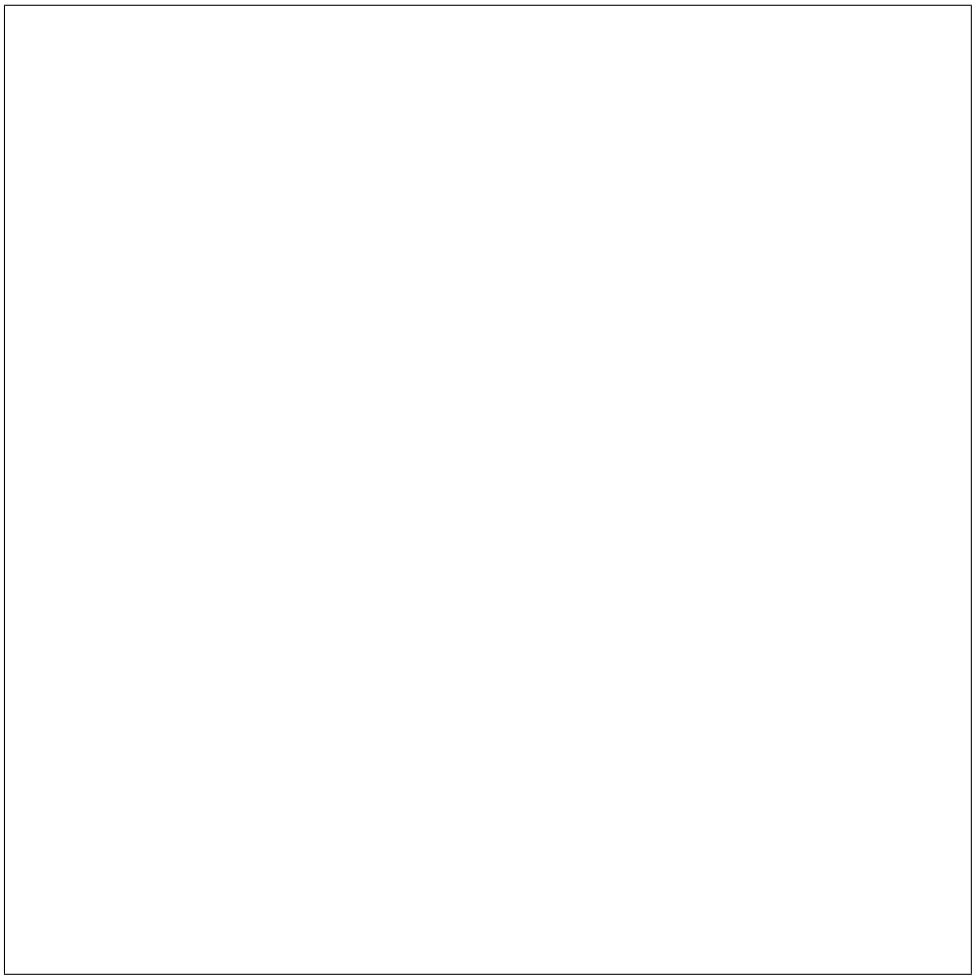
IDE Integrated Development Environment. 35

SPA Single-Page Application. 36

VPL Visual Programming Language. 10

Appendix A

DVD



The attached DVD contains the following directories:

dist – a runnable version of the prototype of the editor described in this thesis as well as all associated applications; also contains source files of all the applications

doc – electronic version of this thesis in PDF format and a presentation from diploma seminar.

ext – Node.js installer. Node.js is required to run the server-side of the application

src – only the source files of the applications developed in Dual

A.1 Running the prototype

It is assumed that you have a modern web browser compatibile with Firefox[1] 47 or Chrome[2] 51 – these were used in developing and testing the application. The source code is written using some ECMAScript2015 features, so it will not work on older browsers. In order to run the version distributed with this thesis, follow these steps:

1. If you want to run the server-side part of the application (it will work without it):
   (a) If you don't have Node.js already, install the latest "Current" version from the official distribution channel (`https://nodejs.org`), or use your operating system's package manager. If running 64-bit Windows, you may also use the installer from the DVD attatched to this thesis (`ext` folder). It was downloaded from `https://nodejs.org/dist/v6.2.2/`.
   (b) Open the `dist` folder in the command line.
   (c) By default, the server-side part of the application is configured to open `chrome` as the web browser that will handle the client-side. If you want to change that, edit the file `server-options.json` and change the `"browser"` property to a command that will open a different browser of your choice – e.g. `"firefox"`. Save the file.
   (d) Run the command `node server.js`. Before doing that you may optionally update all dependencies to the latest versions by running `npm install`.
   (e) By default the server-side part is configured to run on `127.0.0.1` and uses ports in the range 8079-8082, specified in the `server-options.json` file. Make sure these are available. If not, you may change the defaults again by editing the file.

[1] `https://www.mozilla.org/firefox`
[2] `https://www.google.com/chrome/browser/desktop/`

   (f) The project manager view should open in your web browser. You can change the same configuration options as in `server-options.json` here (under "Options").

   (g) Click the button "open current path as project" at the bottom.

   (h) See 3

2. Alternatively, if you want to just open the editor, open the `editor.html` file from the `dist` folder.

3. A new tab should open in the browser with the editor view. You can start using it as described in Chapter 3.

Appendix B

Design discussion

This appendix contains some ideas that are being designed for the future versions of the Dual programming language.

B.1 Comments

B.1.1 Built-in documentation comments

In principle multi-line comments could be implemented simply with the syntax analyzer checking the operator of the expression being parsed, and if it is -, treating such expression as a comment. The fact that this expression was already parsed and transformed into a structural tree-like form could be taken advantage of while generating documentation from comments. For example we could define a following Domain-Specific Language[1] for documentation:

```
--[
    the below is a documentation comment
    followed by the documented piece of code:

    --[[
        Calculates the circumference of the Circle.

        override!
        deprecated!

        this [circle]

        -- The circumference of the circle:
        return [number]
    --]]

    define [calculate-circumference procedure [
        mul[2 math.pi this.radius]
    ]]
]
```

[1] Inspired by [34])

B.1.2 One-word comments

If multiline comments were implemented as expressions on parser-level then, in combination with | special character we could have one-word comments, which could be useful for describing arguments to facilitate reading of expressions. For example we could implement list comprehensions, where:

```
$<-[^[x 2] x range[0 10]]
$<-[$[x y] x $[1 2 3] y $[3 1 4] <>[x y]]
```

would be equivalent to Python's[86, Section 5.1.3]:

```
[x**2 for x in range(10)]
[(x, y) for x in [1,2,3] for y in [3,1,4] if x != y]
```

As we see this notation is acceptable (if not cleaner) for simple comprehensions, but starts being less readable for complex ones. This could be alleviated by introducing one-word comments:

```
$<-[^[x 2] --|for x --|in range[0 10]]

$<-[$[x y] --|for x --|in $[1 2 3] --|for y --|in $[3 1 4] --|if
    <>[x y]]
```

which are easily inserted inline with code and have a benefit of clearly separating individual parts of an expression, because of being easily distinguished visually from the rest. This can simulate different syntactical constructs from other programming languages, like:

```
if [>[a b] --|then
    log['|greater]
--|else
    log['|lesser-or-equal]
]
```

Except that it is not validated by the parser. But we could imagine a separate or extend the existing syntax analyzer, so it could validate such "keyword" comments or even use them in some way. For example, we could add a static type checker to the language – in a similar manner that TypeScript or Flow[**?**] extends JavaScript. This would be completely transparent to the rest of the language, so any program that uses this feature would be valid without it and it could be turned on and off as needed.

To reduce the number of characters that have to be typed, we could decide to use a different comment "operator", such as **%**:

```
$<-[^[x 2] %|for x %|in range[0 10]]

$<-[$[x y] %|for x %|in $[1 2 3] %|for y %|in $[3 1 4] %|if <>[x y
    ]]

if [>[a b] %|then log['|greater] %|else log['|lesser-or-equal]]
```

Or even, at the cost of complicating the parser, introduce a separate syntax for one-word comments:

```
-- `%:type` could be a type annotation
bind [a 3 %:integer]
bind [b 5 %:integer]

-- will print "lesser-or-equal"
if [>[a b] %then
    log['|greater]
%else
    log['|lesser-or-equal]
]
```

In future versions of the language, comments will be stored separately from whitespace in the EST. This enables easy smart indentation – only a prefix of the relevant expression has to be looked at, no need to filter out comments. It also enables using comments structurally, as a metalanguage for annotations, documentation, etc.

B.2 C-like syntax

Throughout this thesis I introduced multiple ways in which the basic, Lisp-like syntax of Dual can be easily extended with simple enhancements, such as adding more general-purpose special characters, macros, single-word comments (as described in Section B.1), etc.

Going further along this path, keeping in mind that a real-world language should appeal to its users we find ourselves introducing more and more elements of C-like syntax. This section describes more possible ways in which the simple syntax could be morphed to resemble the most popular languages. Ultimately all this could be implemented with a conventional complex parser for a C-like language that translates to bare Dual syntax.

Below I present a snapshot from one of designs I have been working on in order to achieve some goals described in this section:

```
fit map" {f; lst} {
    let {i; ret} [0, []];

    while ((i < lst.length)) {
        ret.push f(lst i);
        set i" ((i + 1))
    };

    ret
};
```

This would be equivalent to:

```
bind ['|map of ['|f '|lst do [
    bind ['[i ret] $[0 $[]]]

    while [<[i lst|length] do [
        ret[push][f[lst|@[i]]]
```

```
        mutate ['|i +[i 1]]
    ]]

    ret
]]]
```

Using the notation presented in Chapter 2.
One may observe that:

- The syntax is much richer, somewhat C-like, but with critical differences, reflecting significantly different nature of the language. At a first glance, it has a familiar look defined by blocks of code delimited by curly-braces, inside which statements (actually expressions) are separated by semicolons; there are different kinds of bracketing characters (`{}()[]`) with different meanings (described below)

- Names of the primitives are *full* English words, although as short as possible. `let` introduces a variable definition – similarly to `bind`. `fit <name> <args> <body>` is a shorthand for `let <name> (of <args> <body>)`, where `of` produces a function value. This translates to `bind [<name> of [<args> <body>]]`.

- `{}` delimit a string; inside a string words are separated by `;`. Strings are stored in raw as well as structural (syntax tree) form. They are a way of quoting code. This provides an explicit laziness mechanism. One-word strings are denoted with `"` at the end of the word, which resembles the mathematical double prime notation.

- `[]` delimit list literals; inside list literals, elements are separated by `,`. Lists are a basic data structure. They are actually objects, somewhat like in JavaScript. If a list contains at least one `:` character (not shown in the example), it will be validated as key-value container; if it doesn't, it will be treated as array with integer-based indices

- `()` are used in function invocations; `f(a, b, c)` translates to `f[a b c]`; `,` separates function arguments; `f x` is a shorthand notation for `f(x)`. This, in combination with currying primitives into appropriate macros allows for elimination of excessive brackets and separators. Invocations of primitives resemble use of keywords from other lanugages.

- But at the same time primitives are defined as regular functions – they are no longer treated exceptionally by the interpreter. When they are invoked, all of their arguments are first evaluated. This works, because now it is required that the programmer quote any words that shouldn't be evaluated, such as identifier names when using `let`. So primitives are just regular functions operating on code, thanks to the explicit laziness provided by strings.

- `(())` introduce an infix expression, which respects basic operator precedence: (`((a + b * 2))` would translate to `+[a *[b 2]]`. This could be implemented with a separate parser based on the shunting-yard[2] or similar algorithm that is triggered by the `((` sequence. It would translate these infix expressions to prefix form and return them back to the original parser.