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A High-Level Pedagogical 3D Modeling Language and Framework

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I do not fear computers. I fear lack of them.
— *Isaac Asimov*

Resumo

As ferramentas de CAD são usadas por pessoas que realizam uma ampla gama de tarefas para a construção de edifícios ou outros projectos de desenho (*e.g.* arquitectos e engenheiros). Algumas destas tarefas são muito repetitivas e podem sofrer alterações ao longo do projecto, o que pode implicar recomeçar o desenho do início. Outras tarefas podem precisar de interpolação de funções matemáticas para modelar a visão do arquitecto, como pode ser visto na forma do museu Guggenheim em Bilbao ou na "Pála Siza Vieira", em Lisboa. Mas as linguagens de modelação tridimensionais disponíveis actualmente não são usáveis por pessoas que, como os arquitectos, não têm uma sólida formação em programação. Neste trabalho propomos uma linguagem de programação simples, adequada ao ensino, especificamente adaptada às necessidades de quem faz modelação tridimensional. Tendo em conta que a linguagem AutoLISP é usada por uma grande parte dos arquitectos (apesar de ser usada, principalmente, para automação de tarefas repetitivas), a nossa linguagem é baseada na linguagem Scheme (um dialecto de Lisp), de modo a atrair quem já trabalha com AutoLISP. Esta linguagem irá, eventualmente, ser usada numa cadeira de programação orientada a alunos de arquitectura, de modo a ensinar os fundamentos dos sistemas generativos aplicados a arquitectura, permitindo aos estudantes concentrarem-se no seu trabalho e não em detalhes arcaicos da linguagem. A linguagem suporta vários *back-ends*, extensões e optimizações. Tanto as extensões como as optimizações podem depender ou não do *back-end* utilizado, permitindo aos programadores de extensões adicionar funcionalidades à linguagem, bem como optimizações do modelo para certos *back-ends*.

Abstract

Computer Aided Design (CAD) tools are used by people which perform a wide range of tasks required in building construction and other design projects (*e.g.* architects and engineers). Some of these tasks are often repetitive and may suffer several changes throughout the project, which may imply a complete re-design. Other tasks may require interpolation of mathematical functions in order to model the architect's vision, as can be seen in the shape of the Guggenheim museum, in Bilbao or the "Pála Siza Vieira", in Lisbon. But current 3D modeling languages aren't usable by people (such as most architects) who don't have a solid background in programming. We propose a simple, easy to learn, programming language specifically tailored to the needs of 3D model designers. Since AutoLISP is widely used by architects around the world (although mainly confined to the automation of repetitive tasks), our language will be based on the Lisp dialect Scheme, in order to attract people who already work with AutoLISP. This language is expected to eventually be used in a programming course directed at architecture students, in order to teach the fundamentals of generative systems as applied to architecture and allow students to focus on their work instead of some outdated details in their programming environment. The language is able to support multiple *back-ends*, extensions and optimizations. These extensions and optimizations may be *back-end*-dependent or independent and allow extension writers to easily add functionality to the language and *back-end* developers to optimize models for their *back-end*.

Palavras Chave
Keywords

Keywords

Computer aided design
Programming languages
Teaching
Scheme
3D modeling
Parametrization of 3D models

Palavras Chave

Desenho assistido por computador
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Ensino
Scheme
Modelação tri-dimensional
Parameterização de modelos tri-dimensionais

Contents

1 Introduction **1**
1.1 Technical Contributions . . . 2
1.2 Outline . . . 2

2 Related Work **5**
2.1 AutoLISP and Visual LISP . . . 5
2.1.1 Primitives . . . 7
2.1.2 Conclusions . . . 8
2.2 Generative Modeling Language . . . 9
2.2.1 Primitives . . . 10
2.2.2 Conclusions . . . 11
2.3 Programming LAnguage for Solid Modeling . . . 11
2.3.1 Language Primitives . . . 11
2.3.2 Conclusions . . . 13
2.4 POV-Ray . . . 13
2.4.1 Ray-Tracing . . . 13
2.4.2 Scene Description Language . . . 13
2.4.3 Conclusions . . . 14
2.5 X3D . . . 14
2.5.1 The Format . . . 15
2.5.2 Primitives . . . 16
2.5.3 Conclusions . . . 17
2.6 Grasshopper 3D . . . 18
2.6.1 Conclusions . . . 19
2.7 Comparative Table . . . 19
2.7.1 Available 3D Primitives . . . 20

3 Development Stages **21**
3.1 Tool Survey . . . 21
3.2 Language Implementation . . . 21
3.3 Primitive Object Selection . . . 22
3.4 Evaluation . . . 22

4 VisualScheme **23**
4.1 A Domain Specific Language . . . 23
4.2 Why Scheme? . . . 24
4.3 Architecture . . . 25
4.3.1 Basic Architecture . . . 26

4.3.2 *Front-end* 26
4.3.3 *Back-end* 27
4.4 Optimizations 28
4.4.1 Translated Primitives 29
4.4.2 Caching 30
4.4.3 Measures and Conclusions 31
4.5 Extensions 31
4.5.1 Cylinder Between Two Points 32
4.5.2 *Back-end* dependent extensions 32
4.5.3 Conclusions 33

5 Evaluating the Work **35**
5.1 Modeling the Gare do Oriente 35
5.2 Grasshopper Test Case 39

6 Conclusions **43**
6.1 Future Work 45

A VisualScheme Manual **47**
A.1 Primitives 47
A.1.1 2D Primitives 47
A.1.2 3D Primitives 50
A.1.3 Operations 52

List of Figures

2.1 AutoCAD rendering a set of Doric order columns designed with AutoLISP 6
2.2 Grasshopper diagram for drawing Doric-order columns 19

4.1 Solution architecture 26

5.1 Gare do Oriente 36
5.2 Roof plate model 37
5.3 Arc beams 38
5.4 Different parameterizations of the prototype function 38
5.5 Gare do Oriente model 39
5.6 First Gare do Oriente sketch made in Grasshopper 41
5.7 Grasshopper code for the Gare do Oriente model 42

List of Tables

2.1 High-level comparative table between AutoLISP, GML, PLaSM and POV-Ray 20

4.1 Optimization testing times 31

List of Listings

2.1 AutoLISP code for drawing Doric-order columns 9
2.2 GML code for drawing Doric-order columns 10
2.3 PLaSM code for drawing Doric-order columns 12
2.4 POV-Ray code for drawing Doric-order columns 14
2.5 Part of the X3d code for drawing Doric-order columns 17
4.1 Optimized `apply-translation` 29
4.2 Optimized `draw` and `draw*` 30
4.3 Code for creating cylinders between two arbitrary points 32
4.4 Code for our current loft implementation 33
4.5 Code for our current loft extension 33
5.1 Code for the model's basic shapes 37
5.2 Function that generates a roof plate 37
5.3 Function that generates a support beam 38
5.4 Prototype "tree" function, which builds one of the basic tree-like structures which will be tiled to form the building 39
5.5 Function that generates the full Gare do Oriente 40

List of Abbreviations

API	Application Programming Interface
CAD	Computer Aided Design
CDF	CAD Distillation Format
COLLADA	Collaborative Design Activity
COM	Component Object Model
CSG	Constructive Solid Geometry
DSL	Domain-Specific Language
DXF	Drawing Interchange Format
ECMA	European Computer Manufacturers Association
GIS	Geographic Information System
GML	Generative Modeling Language
GPL	General Purpose Languages
HTML	Hyper Text Markup Language
IBM	International Business Machines
IDE	Integrated Development Environment
IPC	Inter-Process Communication
MPEG	Moving Pictures Experts Group
NURBS	Non Uniform Rational Basis Spline
PDF	Portable Document Format
SDL	Scene Descriptions Language
SQL	Structured Query Language
VRML	Virtual Reality Markup Language
XML	Extensible Markup Language

Chapter 1

Introduction

In the past, traditional architecture avoided complex geometric objects due to the lack of tools and excessive cost of materials and parts which had to be made specifically to build these objects. Nowadays, with computer aided design (CAD) and computer aided manufacturing (CAM) tools, it is possible to mass-produce unique parts for roughly the same cost of producing the same quantity of identical parts [HDG09], thus allowing a higher degree of freedom to the architect. As can be seen in the works of Santiago Calatrava, Siza Vieira, and others, architects want and will create more unusual shapes, if given the opportunity. Unfortunately, some of these shapes are impractical to create using the point-and-click interface of a current CAD system, because they are often based on mathematical functions that are difficult to model by hand and must be explicitly programmed. However, few architects use programming for the generation of these complex geometric objects, using it, at most, for automating tedious tasks, such as rigid sequences of commands.

We believe architects should be able to express themselves and realize their vision, whatever that may be. And, to model shapes based on mathematical functions, architects must use programming tools to aid them in building the desired model. It is known that most vanguardist buildings such as the "Pála Siza Vieira", from Portugal's Expo '98 pavilion or the Guggenheim museums' buildings in Bilbao and New York are usually based on well-defined mathematical functions that can be computed, meaning that those buildings can be generated programmatically. The "Pála Siza Vieira", for example, is based on a mathematical curve called catenary, which has a simple and precise definition that is directly implementable in a programming language. Santiago Calatrava's Gare do Oriente is another example where a programmatic approach is desirable, as it is a regular structure with intricate repeated details.

Experimentation is another important requirement that justifies the programmatic generation of forms: when idealizing the form of a complex geometric object, the designer may want to experiment with different parameters for its components. If one needs to repeatedly design the whole building just to change some parameter values, experimenting becomes an impractical task. However, with a programmatic approach, an architect may design a fully-parametrized object definition and then just change the parameters until the generated form satisfies the initial vision.

Although architects can imagine an out of ordinary shape for a building, nowadays, the programmatic realization of that shape cannot usually be achieved by an architect without the resources to hire a group of programmers to create the 3D model. This solution is costly and may cause a mismatch between what the architect envisioned and the end result. To solve this problem, architects must be taught how to program.

Unfortunately, we cannot realistically expect architects to learn a system's programming language, like C, C++ or Java, because they require the programmer to keep track of many details unrelated to the geometric model. In most cases these languages also make it difficult to have the short feedback loops that an architect needs when testing different parameters for a model.

There has been an increasing effort on providing architects with more programming background, by teaching them how to program and how to use these modeling tools. However, the programming focus has been mostly on automating simple tedious tasks, such as long sequences of commands. While this work is being developed, a course on programming is also being taught to architecture students, in Instituto Superior Técnico, with a stronger focus on generative programming techniques. The language used till now has been AutoLISP but, to overcome some of its disadvantages, efforts are being made to turn to VisualScheme, the language proposed here, as the course's programming language, due to Scheme being a language that is appropriate for both teaching [FFFK03] and building commercial applications [WG07]. This course has had a great success in attracting students to the programmatic modeling of buildings, and teaching them how to abstract details and create parametrized buildings which can easily be experimented with.

This thesis presents the VisualScheme programming language, which intends to be a 3D modeling language oriented to architects. This programming language is a domain specific language (DSL) for 3D modeling built on top of the Scheme programming language. VisualScheme provides mechanisms for a programmer to define a 3D model of an object and then export it to a visualization program (the *worker program*). This 3D model is not composed of the definition of all the object's vertexes or triangles, but as a tree of high-level primitives and operations which will then be passed to a *back-end* (a module of the VisualScheme language that is in charge of communicating with the *worker program*) which will convert the tree of primitives and operations to the commands to be sent to the *worker program*. The *worker program* may range from a simple viewer (a browser with a VRML plug-in or support for the `<canvas>` tag) to a fully fledged CAD or building information modeling (BIM) program (AutoCAD, Bentley Generative Components, *etc.*). A paper describing this work was submitted and accepted for the 2010 Education and research in Computer Aided Architectural Design in Europe (eCAADe) conference [LMFC10].

1.1 Technical Contributions

With this work we designed and implemented the VisualScheme programming language with facilities for modeling 3D objects, as well as a *back-end*for AutoCAD. The language allows an architect with average programming skills and a familiarity with CAD tools the ability to produce complex objects. This language will be able to export its objects to several formats, maximizing the rewards of learning it by allowing the programmer to export to whatever format the client desires. The language design took into account portability issues that arise out of the possibility of having multiple output formats and minimized the dependency on format-specific features.

We also took into account pedagogical aspects like the students' needs, as this language is aimed at classroom and industry usage. The language was tested by students throughout its development stages, which helped understand where inexperienced users have more difficulty.

1.2 Outline

This dissertation comprises 1 chapters:

Chapter 1 introduces the work and presents its goals.

Chapter 2 presents the related work on 3D modeling languages and programs (AutoLISP and Visual Lisp, GML, PLaSM, Pov-Ray, X3D and Grasshopper 3D). In the end, a comparative table is presented, summarizing the characteristics of the languages described.

Chapter 3	shows the four main stages of this project: tool survey; language implementation; primitive selection; and evaluation.
Chapter 4	presents the language proposed here, called VisualScheme. It describes the technical aspects related to the implementation of the language, and how a VisualScheme program is organized.
Chapter 5	presents a case study (the Gare do Oriente model) with VisualScheme, and compares it to a solution in Grasshopper.
Chapter 6	concludes the thesis with a summary of the work, and suggests some guidelines for future work.
Appendix A	presents the primitive objects and operations that were selected and are available in VisualScheme.

Chapter 2

Related Work

In the following sections, several existing 3D modeling programming languages will be analyzed from the programmer's point of view. Although some are already in widespread use, there is still much work to be done in order to modernize these languages equating them (in programmer productivity features) to a modern general-purpose programming language.

A program that draws a set of Greek columns was written in every analyzed language so as to compare the languages and their pragmatics. The program was ported taking into account the language's pragmatics. As such, not all programs describe the columns in the same way, but the end result is the same in all languages.

2.1 AutoLISP and Visual LISP

Autodesk™[1] is one of the leading vendors of architecture-related software in the world. Its AutoCAD®[2] line of products is one of the oldest and most widely used in the area of CAD. With its products' impressive lists of features, Autodesk is one of the biggest players when it comes to geometric modeling. AutoCAD is used around the world by many architects, civil engineers and other people whose profession may involve designing complex objects (be they buildings, tubing, outdoor spaces, or other environments or objects with a more or less involved geometry).

AutoLISP®[3] [Aut09] is a Lisp-based programming language with a small kernel and a large set of geometric primitives used in AutoCAD for script-based geometric modeling. AutoLISP was designed to be used in conjunction with CAD tools like AutoCAD to automate repetitive tasks or to be used when precision is of the utmost importance and the manual tools don't fit the job. Despite the large number of scripts written, which attest to its adoption among Autodesk's clients, AutoLISP lacks several modern features that many programmers are used to have in a computer language. Of those missing features, some glaring examples are lexical scoping, fine-grained control over namespaces,[4] more evolved data structures,[5] exceptions, *etc*. Adding to those missing features are several features that every Lisp programmer (but not every programmer in general) is used to, like support for creating closures over free variables, and unbound/uninitialized variables yielding an exception when accessed.[6] The existence of

[1]`http://autodesk.com`

[2]`http://autodesk.com/autocad`

[3]`http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=1911627`

[4]Two documents have different namespaces, but the programmer can't define namespaces inside a single document (*e.g.* to separate different libraries).

[5]Arrays, structures, hash-tables, *etc*.

[6]By default, in AutoLISP, unbound variables yield the value `NIL` when read, which is the source of many hard-to-find bugs in AutoLISP programs. [Ste03]

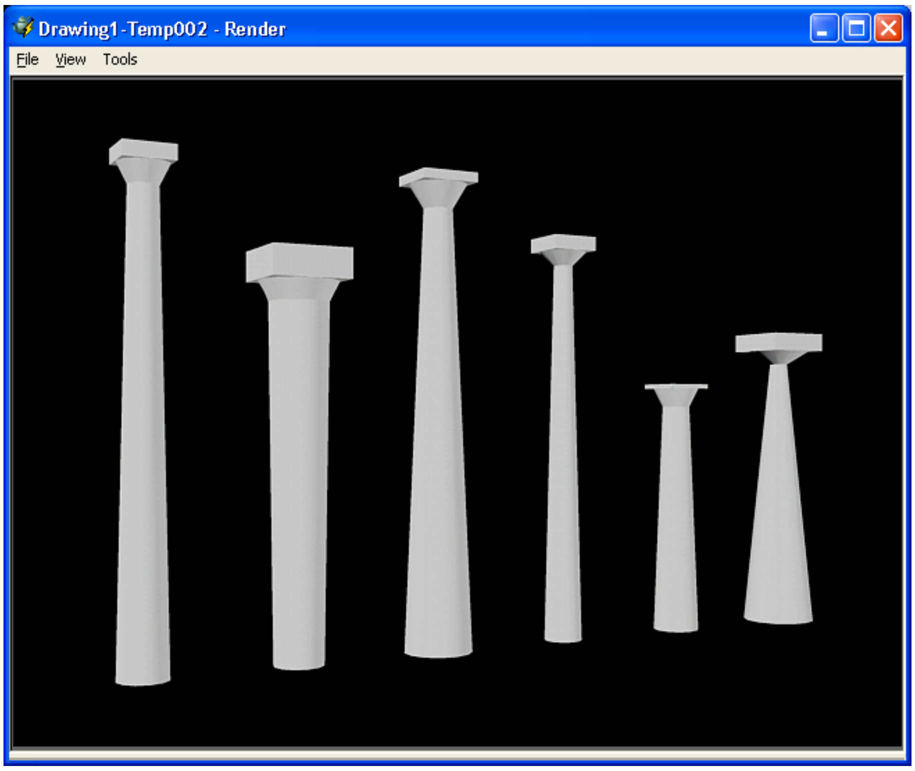


Figure 2.1: AutoCAD rendering a set of Doric order columns designed with AutoLISP

only one namespace for functions and variables allied to the lack of lexical scoping makes programming in AutoLISP a real challenge for anyone with previous experience in Lisp-like languages. Visual LISP® is a later, more evolved version of AutoLISP that can interface with AutoCAD's ActiveX® components, both internal and external (plug-ins) but still lacks most of the features that make up a modern programming language. From now on in this document, the term "AutoLISP" will be used to refer to AutoCAD's Lisp-like scripting language, always referring to the latest edition.

Most architects only use AutoCAD with its point-and-click interface or, for the few (comparatively) of those that use AutoLISP, have some small AutoLISP scripts to automate some simple repetitive tasks. These tasks are usually very easy to accomplish either by hand or by programming. But AutoLISP is very underutilised because most architects aren't well versed in the art of programming, nor do they understand all the implications of the features (or lack thereof) of AutoLISP, performance and expressiveness-wise. The argument that Lisp-like languages have a "strange syntax" isn't an issue, because the majority of AutoCAD users know very little about programming in general and most of those that know, only know AutoLISP.

With AutoLISP, programmers can write a script that uses AutoCAD's API to manipulate objects in a document. An AutoLISP script has access to a large number of AutoCAD's object creation functions, including functions to create primitive geometric objects like circles, lines, spheres, poly-lines and text. And operations on those objects, such as unions, intersections and subtractions. AutoCAD's objects are also available in AutoLISP, represented as entities. These entities represent the object and all its attributes as a property list with key$\rightarrow$value pairs. The class, material and position are examples of the attributes stored in an entity as AutoCAD's "group codes" [Aut08]. Lisp's property lists are used to ease its manipulation by AutoLISP programs due to AutoLISP's built-in utility functions that work with property lists. If needed, scripts can also interact with the environment and ask the user to perform certain actions (*e.g.* select points, entities, enter numbers) that provide input to the AutoLISP functions.

Although modern Lisps are often considered functional programming languages, the absence of lexical scope [Sco00] in AutoLISP introduces many obstacles when writing higher-order functions[7] due to the possible name collision between the free variables in the function passed as argument and any variable in the execution control flow until that function is called (including variables from the definition of the higher-order function), which can lead to very hard to find bugs. The "functions as arguments"[8] higher-order functions can be written in AutoLISP with some name-mangling in their parameters and local variables' identifiers. If there is no name-sharing between parameters of different functions, we can program this kind of higher-order functions in AutoLISP. This is a "quick hack," and not really a solution to avoid the problems mentioned, but can't be guaranteed to work (especially when using other people's libraries) and seriously degrades code readability. The same can be said for the "functions as return values"[9], with more obstacles: Due to AutoLISP's dynamic scope and lack of closures, it is impossible for a function to capture the bindings of its free variables, as it's usual in most functional programming languages. If this function is returned from another function then, when invoked, those free variables will either be unbound or be bound to a possibly completely unrelated variable than the one the programmer wanted.

Another feature that most Lisp programmers will miss in AutoLISP is the macro system. Neither hygienic [Cli91] nor non-hygienic [SG96] macros are available for creating language extensions. While, for programmers with background on Algol-descendant programming languages,[10] macros aren't essential, most Lisp programmers consider them[11] fundamental features, due to being able to implement completely new control structures and change the "shape" of the language with a simple mechanism.

2.1.1 Primitives

In this section we describe the AutoCAD primitive objects, which can be created using AutoCAD's command line, AutoLISP, ActiveX and .NET scripting facilities.

Lines There are various types of lines in AutoCAD. The simple `Line` is a line between two points, but there are more general line objects, including `Polylines`, `LightweightPolylines` and `MLines` (multiple lines following the same path), all of which create two-dimensional lines. The `LightweightPolyline` is an optimized version of the `Polyline` object which, given a set of coordinates of the vertexes, creates a line between each vertex and the next. These lines are often used for creating paths for extruding 2D shapes. Additionally, one type of three-dimensional line is available, the `3DPolyline`, which can be created with points that are not all in the same plane.

Curves In AutoCAD, we can create various kinds of curves. Open or closed. `Arcs`, `Circles`, `Ellipses` and `Splines` are available. An `Arc` is defined by a center, a radius and a start and end angles. An `Ellipse` is defined by a center, the length of the major axis and the ratio between the two axis, while the `Circle` is an ellipse with a ratio of 1.0. The `Spline`[12] is a particular type of curve which passes through N given points;

Meshes A mesh represents an object's surface using planar facets. In AutoCAD, two types of meshes are available: The `PolygonMesh` and the more general `Polyfacemesh`. The `PolygonMesh` is a matrix of $M \times N$ vertexes, which are the vertexes of the facets. The `Polyfacemesh` is more general, where an array of vertexes is given and then an array of facet definitions is also provided. Each facet is composed of four of the given vertexes;

[7]Higher-order functions are functions that take functions as arguments and/or return functions as results. These functions are fundamental in functional programming to abstract common behaviour.

[8]Also known as the *downward funarg* (functional argument) problem. [Mos70]

[9]The *upward funarg* problem.

[10]C, C++, Java, C#, *etc*.

[11]Lisp macros, not to be confused with macros in a language like C, where macros are simple text replacements.

[12]Splines in AutoCAD are quadratic or cubic NURBS curves.

Box A box is a parallelepiped which is defined by a central point (the center of the parallelepiped) and its three dimensions: length, width and height;

Cone A cone which is define by its center $\langle x, y, z\rangle$, its base radius (the base is centered at $\left\langle x, y, z - \frac{h}{2}\right\rangle$) and its height ($h$). Also available is an elliptical cone, which has an ellipse as a base and an extra argument: the minor radius;

Cylinder A cylinder is defined using the same parameters as a cone (center, radius and height), and has an elliptical counterpart as well;

Extrusion An extrusion of a `Region`[13] along a path. An optimized version is available when the path is a straight line, possibly having an angle different from $\frac{\pi}{2}$ radians with the region. Revolution of a region has also an optimized case, where a region is revolved around a user-defined axis for a given angle;

Sphere A sphere is centered around a given point and has a user-defined radius;

Torus A torus is an extrusion of a circle around a point, which yields a ring-like shape. The torus is defined by its center, the radius of the torus (the distance from the center of the torus to its outer edge) and the tube radius (the radius of the extruded circle);

Wedge A wedge is half a parallelepiped, with triangles as its side facets. It is defined by a center point, its length, width and height.

Along with the primitives to create several 3D objects, there are some transformations available. Objects can be rotated in space by providing an axis of rotation and an angle to rotate the objects. A `Move` method is available to move the objects in 3D space, as well as the `ScaleEntity` method which scales an entity equally in the X, Y and Z planes. For more controlled transformations, a `TransformBy` method is available, which receives a transformation matrix and applies the transformations described in it.

Also available are the 3D CSG operations, for union, intersection and difference of 3D solids. All these functions yield another 3D solid and the original solids can be deleted or kept for further uses, depending on the user's choice.

In Fig. 2.1, the output of the AutoCAD Doric-order columns script can be seen. The pragmatic of programming in AutoLISP (if any) is to just send the primitive commands to AutoCAD as can be seen in the definition of `cut-cone` which uses the `command` primitive.[14] In this script every column is given a starting point and some parameters to control its shape and size as can be seen in Fig. 2.1. The `box2` function was defined in a way analogous to it, but using AutoCAD's `BOX` primitive command.

2.1.2 Conclusions

Being the most used CAD program in the world, AutoCAD and its programmability features must be taken into account for this work. Despite showing its age, AutoLISP is still used by many groups of people with disparate programming skills, for automating all kinds of tasks in AutoCAD. Although widely used, its potential is very underutilised. Many architects either don't know it's available or only use it by emulating what they would do manually, thereby automating some simple repetitive tasks. Besides being a language without many features that most programmers take for granted, it is also shunned by many programmers due to being Lisp-like. On the other hand, most AutoCAD-using professionals will prefer a Lisp-like language due to already being familiar with the syntax.

[13] A `Region` is a closed two-dimensional loop.

[14] In Visual LISP there are wrapper functions for every AutoCAD ActiveX/COM method, but the primitive AutoCAD commands are still widely used.

(a) AutoLISP definitions

```
(defun shaft (p height base-r top-r)
  (cut-cone p base-r top-r height))

(defun capital (p height base-r top-r)
  (cut-cone p base-r top-r height))

(defun abacus (p height length)
  (box2 (+xyz p (/ length -2.0) (/ length -2.0) 0)
        (+xyz p (/ length  2.0) (/ length  2.0) height)))

(defun doric-column (p
                     shaft-h shaft-base-r
                     capital-h capital-base-r
                     abacus-h abacus-l)
  (shaft p shaft-h shaft-base-r capital-base-r)
  (capital (+z p shaft-h) capital-h capital-base-r (/ abacus-l 2.0))
  (abacus (+z p (+ shaft-h capital-h)) abacus-h abacus-l))
```

(b) AutoLISP main program

```
(erase-all)

(doric-column (xyz 0 0 0) 9 0.5 0.4 0.3 0.3 1.0)
(doric-column (xyz 3 0 0) 7 0.5 0.4 0.6 0.6 1.6)
(doric-column (xyz 6 0 0) 9 0.7 0.5 0.3 0.2 1.2)
(doric-column (xyz 9 0 0) 8 0.4 0.3 0.2 0.3 1.0)
(doric-column (xyz 12 0 0) 5 0.5 0.4 0.3 0.1 1.0)
(doric-column (xyz 15 0 0) 6 0.8 0.3 0.2 0.4 1.4)

(zoom-extents)
```

Listing 2.1: AutoLISP code for drawing Doric-order columns

2.2 Generative Modeling Language

The Generative Modeling Language (GML)[15] is a simple stack-based language for describing 3D objects. Traditionally, lists of geometric primitives are used to model 3D objects. Instead, with a generative approach [Ley01], geometric models are created by composing operations and the design becomes focused on rules for transforming primitive objects instead of focusing on combining these primitives. Keeping track of only the necessary operations to model an object typically consumes much less space than storing the results of that computation (for example, a mesh of triangles). As the processing power increases, it becomes easier to generate huge amounts of data *on the fly*, only when the data is needed.

Although initially based on Python,[16] its authors decided to use Adobe®'s[17] PostScript®[18] as the core language for GML because it's much simpler to manipulate programmatically [Hav05]. Doing without most typesetting and many of PostScript's 2D operations, the GML is much simpler and very familiar to anyone familiar with its ancestor. GML extends the PostScript set of operations with several others, from vector algebra to the handling of polygons, including several conversions [Hav03]. This language is not for the common architect, though. Being a postfix language, it's not very easy to learn to someone who is not familiarised with programming, in general, at least. Although very simple, postfix languages are even less familiar to most programmers than Lisp-like languages. The main goal of GML is not to be just a 3D modeling language *per se*, but to enable the building of higher-level tools for 3D modeling that use GML programs. These GML programs would be created by advanced users and used by all kinds

[15]http://www.generative-modeling.org/
[16]http://python.org
[17]http://adobe.com/
[18]http://adobe.com/products/postscript

of users, from beginning to advanced, to facilitate some operations.

With its twelve simple rules for evaluating programs, GML is very easily adopted by a programmer, but not so easily by an architect. Because of the abstract nature of programming, a person that is not well versed in abstract thinking may find it hard to read the program's source code and know what its output will be like. The forced abstract thinking allied to the need of maintaining state (in the programmer's mind) while reading the program definition, due to GML not being a functional language but an imperative one, are two of the reasons this language is not very well suited for architects or designers to design objects, although it could very well be used as a back-end for a tool that simplifies GML's use.

(a) cut-cone utility item for the shaft and capital

```
Columns.Config begin
usereg

!top-r
!base-r
!height

material setcurrentmaterial
(0,-1,0) :base-r divisions circle
3 poly2doubleface

:base-r :top-r sub
:height 3 vector3 extrude

end
```

(b) Item for drawing an abacus

```
Columns.Tools begin
usereg

!length
!height
!p

:length  2.0 div !l2
:length -2.0 div !l-2

:l-2 0 :l-2 vector3 :p add
:l2  0 :l2  vector3 :p add

3 quad
3 poly2doubleface

0 :height neg 3 vector3 extrude
end
```

(c) Item for drawing a Doric-order column

```
usereg
!a-l
!a-h
!c-b-r
!c-h
!s-b-r
!s-h
!p

:p :s-h :s-b-r :c-b-r shaft

0 :s-h neg 0 vector3
:p add :c-h :c-b-r :a-l 2.0 div capital
0 :s-h :c-h add neg 0 vector3
:p add :a-h :a-l abacus
```

(d) Item for drawing the row of columns

```
deleteallmacros newmacro clear
Columns begin

(0,0,0) 9 0.5 0.4 0.3 0.3 1.0 column
(3,0,0) 7 0.5 0.4 0.6 0.6 1.6 column
(6,0,0) 9 0.7 0.5 0.3 0.2 1.2 column
(9,0,0) 8 0.4 0.3 0.2 0.3 1.0 column
(12,0,0) 5 0.5 0.4 0.3 0.1 1.0 column
(15,0,0) 6 0.8 0.3 0.2 0.4 1.4 column

end
```

Listing 2.2: GML code for drawing Doric-order columns

In GML programs are divided in libraries and items. Libraries are simple dictionaries of items or (recursively) other libraries. Both the TestGML and GML Studio .NET IDE store libraries on disk as eXtensible Markup Language files. In both these IDE, the programmer is able to execute a GML item which can then use any dictionary available in the program (or creating new, temporary, dictionaries).

2.2.1 Primitives

GML has named registers and dictionaries that allow a programmer to avoid stack manipulations and writing slightly unreadable code due to the few operations allowed to invoke on the stack. A value is stored in a register using the command `!register`, which pops the topmost stack element and stores it in the register named register. A register can then be read using :register, which pushes the value stored in the register onto the stack. Not pictured are the shaft and capital items which simply invoke the cut-cone item.

2.2.2 Conclusions

Despite being an unusual programming language (due to being stack-based), GML can accomplish what it's designed to: Being a terse postfix programming language, which enables programmers t describe shapes with relative ease and without having to model every used mesh. By modeling the objects using a high-level language, GML doesn't need as much information as a mesh-based program to store the objects.[19] For example, while a mesh-based program would need to store every single vertex in order to model a cube, in GML one just needs to store the high-level code that does the necessary operations: Create a quad (or a circle with four segments), turn it into a half-edge and then extrude it in the third dimension. In spite of all these advantages, GML is still a hard to learn language for most programmers. Especially people with (relatively) few programming skills and who are used to just one language that has a completely different syntax and is programmed in a completely different paradigm.

2.3 Programming LAnguage for Solid Modeling

The Programming LAnguage for Solid Modeling (PLaSM) is a functional programming language based on IBM's®[20] FL [AWW91] programming language, which is a programming language that evolved from John Backus' FP programming language which introduced function-level programming to the programming world [Bac78]. It is a functional design language for geometric and solid parametric design developed at the Roma Tre and La Sapienza universities [PS92, PPV95].

PLaSM takes on a programming approach to generative modeling, where geometric objects are generated by composing functions using the language's operators. It has a dimension-independent approach to geometric representation. PLaSM has support for higher-order functions in the FL style so, one way to look at it, is to see PLaSM as a geometric domain-specific language (DSL) for FL. No free nesting of scopes or pattern matching is allowed in PLaSM although an identifier can name any language object. Being a FL language successor, PLaSM shares much syntax with its ancestor. PLaSM also allows operator overloading and partially applied (curried) functions.

2.3.1 Language Primitives

PLaSM supports many elementary shapes through language primitives. Simples objects such as simplices, cuboids, cylinders and general polyhedra are available through simple primitive functions that have the same properties as any user defined function. Along with primitive object creation, there are many affine geometric transformations available for the programmer, including the always present scale, translation and rotation operations. These operations on coordinates can be arbitrarily composed and applied to polyhedra. There is also a primitive operator that limits the scope of these operations to let the programmer focus on local (object) coordinates when designing an object, and only when it is instantiated will the object be placed on the appropriate global (world) coordinates. PLaSM includes an operator for creating 1-D polyhedra, as well as creating n-dimensional skeletons of objects. Another powerful PLaSM primitive (which is a special case of the PRODUCT operator [BFPP93] (also available in PLaSM)) is the *Intersection of extrusions* operator (&&). With this operator it becomes very easy to generate

[19]But there is always a trade-off between memory and processing power.

[20]http://ibm.com

a building from its plant and sections. The programmer simply defines the plant and section and then uses the `&&` operator, embedding the sections in the right coordinate subspaces. The `&&` operator receives a vector that describes how to embed each of the two objects in the coordinate subspace of the 3D result. The operator then returns a binary function that receives both objects and returns the intersection of their extrusions. Also available in PLaSM are generalized Boolean operations, making PLaSM the first dimension-independent implementation of Boolean operations [PVBP01]. PLaSM also has operators for relative positioning of objects (`ALIGN`, `TOP`, `BOTTOM`, `LEFT`, *etc.*). Of these, only the `ALIGN` operator is dimension-independent. The others are only suitable for relative positioning of 3D objects.

(a) PLaSM definitions

```
DEF DoricColumn
  (ShaftH, ShaftBR, CapitalH, CapitalBR,
   AbacusH, AbacusL::IsRealPos) =
    Shaft:<ShaftH, ShaftBR, CapitalBR>
    TOP
    Capital:<CapitalH, CapitalBR, AbacusL/2.0>
    TOP
    Abacus:<AbacusH, AbacusL>;

DEF Abacus(Height, Length::IsRealPos) =
    CUBOID:<Length,Length,Height>;

DEF Capital(Height, BaseR, TopR::IsRealPos) =
    CutConeZ:<Height, BaseR, TopR>;

DEF Shaft(Height, BaseR, TopR::IsRealPos) =
    CutConeZ:<Height, BaseR, TopR>;

DEF CutConeZ(Height, BaseR, TopR::IsRealPos) =
    TrunCone:<BaseR,TopR,Height>:coneFacets;
```

(b) PLaSM main program

```
DEF Left3 = T:1:3;
DEF Columns = STRUCT:<
    DoricColumn:<9, 0.5, 0.4, 0.3, 0.3, 1.0>,
    Left3,
    DoricColumn:<7, 0.5, 0.4, 0.6, 0.6, 1.6>,
    Left3,
    DoricColumn:<9, 0.7, 0.5, 0.3, 0.2, 1.2>,
    Left3,
    DoricColumn:<8, 0.4, 0.3, 0.2, 0.3, 1.0>,
    Left3,
    DoricColumn:<5, 0.5, 0.4, 0.3, 0.1, 1.0>,
    Left3,
    DoricColumn:<6, 0.8, 0.3, 0.2, 0.4, 1.4>>;

Columns;
```

Listing 2.3: PLaSM code for drawing Doric-order columns

PLaSM's Xplode IDE[21] is a simple IDE that syntax highlights PLaSM programs for easy reading and serves as the interface for a PLaSM listener program. There is a VRML viewer (Fig. **??**) included in the IDE package which allows the programmer to export the solids to a VRML file for later viewing. The columns in the PLaSM program in Fig. 2.3 are built using the 3D positional operators rather than using a reference point and translating it to create the capital and abacus of the column. As the definition of the `Columns` object just creates a function, the function must afterwards be invoked.

[21]`http://www.plasm.net/tools/xplode_ide`

2.3.2 Conclusions

Despite the long learning curve for anyone not familiar with the FP or FL languages, PLaSM is a very expressive 3D modeling language where one can design big, complex parametrized objects with relative ease and make any change to the parameters, having the result just a render away. The completely functional approach, although better for parallelism and closer to the mathematical foundations of geometry, is harder to grasp for most people that learned to program in an imperative language (*e.g.* C, Java, *etc.*). But, by not having any imperative constructs, PLaSM may lose some audience among those who already knew how to program imperatively.

2.4 POV-Ray

The Persistence of Vision Raytracer (POV-Ray)™[22] is an open source ray-tracing program that grew out of David Buck's hobby ray-tracer, DKBTrace [Per01]. With its large comprehensive library of objects, colors, textures, and many available special effects and rendering effects, POV-Ray is one of the most widely used ray-tracers around the world, and has a very large community [23] where users can find help. The IDE included in its distribution has many features and documentation that help anyone using POV-Ray's scripting facilities.

2.4.1 Ray-Tracing

Ray-tracing is a method for generating digital images by simulating the path of light as it passes through the output image's pixels, simulating the way photons travel in the real world. This technique is capable of generating images with a high degree of photo-realism, although it's computationally very intensive. With this characteristic in mind, ray-tracing is mostly used for rendering images when off-line rendering is available, such as in the T.V. or movie industries. Infamous for its rendering times, ray-tracing wasn't even considered for real-time rendering applications until recently [Muu95, PMS$^+$05, DS07].

2.4.2 Scene Description Language

POV-Ray's Scene Description Language (SDL) is a Turing-complete language that allows a programmer to describe the world in an efficient and readable way. The scene description language is a very basic language with support for abstraction mechanisms (*e.g.* macros and functions). It's mostly a declarative language, which means most of the objects are defined at one time in the program execution and aren't modified afterwards. Although declarative, POV-Ray's SDL has some facilities for iterating and mutating variables, *e.g.* for placing a building's columns in a row or circle programmatically, instead of manually defining every column needed (which would have to change if one was to, *e.g.* change the number of columns).

Every POV-Ray scene needs a camera and, at least, a light-source. After placing these two concepts on the scene, the programmer may use whatever primitives are available from POV-Ray or in any imported libraries. Several primitive finite and infinite objects are available "out-of-the-box," as are more complex primitives like iso-surfaces and ways of combining objects, through Constructive Solid Geometry. Despite the power conferred to the programmer by the SDL, most complex models (*e.g.* realistic characters or complex man-made objects) in a scene are usually modeled using higher-level tools like the open-source Blender 3D[24] program and then exported to a format POV-Ray can use.

[22] `http://povray.org`
[23] `http://www.povray.org/community`
[24] `http://blender.org`

(a) POV-Ray definitions

```
#macro shaft(p, height, baseR, topR)
  cone { p, baseR, p + height*z, topR
         texture { shaft_pigment } }
#end

#macro capital(p height baseR topR)
  cone { p, baseR, p + height*z, topR
         texture { capital_pigment} }
#end

#macro abacus(p, height, length)
  box { p - <length/2.0, length/2.0, 0>,
        p + <length/2.0, length/2.0, height>
        texture { abacus_pigment } }
#end

#macro doricColumn(p,
                   shaftH, shaftBaseR,
                   capitalH, capitalBaseR,
                   abacusH, abacusL)
  shaft(p, shaftH, shaftBaseR, capitalBaseR)
  capital(p + shaftH*z, capitalH, capitalBaseR, abacusL/2.0)
  abacus(p + (shaftH+capitalH)*z, abacusH, abacusL)
#end
```

(b) POV-Ray main program

```
doricColumn(       0, 9, 0.5, 0.4, 0.3, 0.3, 1.0)
doricColumn(< 3,0,0>, 7, 0.5, 0.4, 0.6, 0.6, 1.6)
doricColumn(< 6,0,0>, 9, 0.7, 0.5, 0.3, 0.2, 1.2)
doricColumn(< 9,0,0>, 8, 0.4, 0.3, 0.2, 0.3, 1.0)
doricColumn(<12,0,0>, 5, 0.5, 0.4, 0.3, 0.1, 1.0)
doricColumn(<15,0,0>, 6, 0.8, 0.3, 0.2, 0.4, 1.4)
```

Listing 2.4: POV-Ray code for drawing Doric-order columns

The POV-Ray version of the program (Fig. 2.4) consists of macros for the smaller components of the columns which will then be put in place by the `doricColumn` macro by creating the objects appropriately translated in the z coordinate. Not pictured is the code to place the camera and light sources in the scene nor the code defining the shaft, capital and abacus' pigment as a light gray as that code isn't directly involved in the objects' modeling.

2.4.3 Conclusions

POV-Ray is a very good ray-tracer with a very helpful community built around it. It is capable of generating very high-quality photo-realistic renderings with small scripts due to its big high-quality object and texture library. The language in itself is declarative, although some support for imperative programming is present, in the form of macros. It is relatively easy for someone with some programming experience to start scripting POV-Ray, and start modeling parametrized objects programmatically with ease. The higher-order functions and capabilities for abstraction may be missed by some programmers, though.

2.5 X3D

X3D is a run-time architecture and file format to represent 3D scenes. It is a royalty-free open standard ratified by the ISO committee [ISO04], with various standardized encodings (*e.g.* XML and Classic

VRML [ISO05]) and bindings [ISO06] for several languages (*e.g.* ECMAScript and Java). X3D provides a system for the storage, retrieval and playback of graphics content embedded in an application. As the successor of VRML [ISO96], X3D is mainly fueled by web development and the possibility of embedding 3D content in a webpage in straight HTML [BEJZ09], which was one drawback the old VRML standard had.

While its predecessor – VRML – was dismissed as being "a technology in search of a use" [Shi98], X3D has already been implemented as a distribution format in several 3D authoring programs, such as AutoCAD, Revit and 3dsMax, among others. Multi-platform support also exists and a centralized repository of information about X3D is available from the Web3D Consortium.[25]

X3D has a rich set of general parametrizable primitives that can be used for a variety of purposes in engineering, scientific visualization, CAD and architecture, and more. X3D was designed to be compatible with the legacy VRML standard and very extensible. Developed taking into account the COLLADA [AP07] standard for 3D representation, X3D is designed for real-time communication of 3D data while maximizing interoperability among different tools.

2.5.1 The Format

X3D is a file format with two simple encodings: legacy VRML and XML. The VRML encoding exists for backwards compatibility as many VRML 2 worlds can be used as X3D with only minor changes [Web05]. The XML encoding is available to ease interaction with many different tools and to be able to exploit the many existing tools and libraries to read, write and validate the documents.

There are several profiles available for X3D, which allows for several levels of support. These range from the simpler Interchange profile to Full X3D:

Core The absolute minimal definitions X3D requires;

Interchange The basic profile for the interchange of information between applications. It supports geometry, texturing, basic lighting and animation primitives;

Interactive A superset of the Interchange profile which adds basic interaction with a 3D environment through sensor nodes, enhanced timing support and additional lighting primitives;

Immersive Supports everything in the Interactive profile and adds audio support, collisions, fog and scripting;

Full Includes all defined nodes, including NURBS,[26] H-Anim[27] and GeoSpatial nodes.[28]

Two additional profiles exist: The MPEG-4 Interactive profile, which is a small footprint version of the Interactive profile designed for memory and processor-challenged devices, and the CDF (CAD Distillation Format) which is in development in order to enable the translation of CAD data to an open format for publishing.

A X3D world is defined as a sequence of statements. The first of these is the Header statement, followed by a `PROFILE` statement. These statements are encoding dependent and contain some necessary information, such as the standard being used, along with its version, the character encoding being used and some optional comments for the file. This Header statement will always store its information in a human-readable format. The `PROFILE` statement will declare which of the 7 available profiles [ISO08a]

[25] `http://web3d.org/`
[26] Non Uniform Rational Basis Spline — A mathematical model for representing curves and surfaces
[27] Humanoid animation (`http://www.h-anim.org/`)
[28] To associate real-world locations to elements in the X3D world

will be used. Additional components, which are not in the selected profile, can be used by declaring them with a `COMPONENT` statement. Metadata about the world being defined can also be provided with a `META` statement. The ability to define new node types is given by the `PROTO` and `EXTERNPROTO` statements. These statements assign a name to a new node type along with the declaration of its interface. The `PROTO` statement defines the new node type functionality inline while the implementation of the `EXTERNPROTO`'s node type is implemented externally. As it is designed to have an interactivity component, routes can be defined to specify connections between fields of different nodes, using the `ROUTE` statement.

The X3D Core profile has all the above nodes and includes features for the grouping of nodes, controlling the rendering and lighting of the world, constructing shapes and controlling their texture, using interpolated functions for parameters, navigation and some environmental effects. The Interactive profile adds interactivity to the worlds through key devices and pointing devices. The Immersive profile adds more interactivity, augmenting the control of the various input devices and also includes scripting support for X3D. From one profile to the next existing nodes may be enhanced by adding some fields which raise its *Support level*, which ranges from 1 to 5, although some components stop at a level less than 5.

2.5.2 Primitives

X3D provides several primitives for primitive 3D geometric shapes:

Box A parallelepiped box that is centered at $\langle 0,0,0\rangle$ and has a length, width and height;

Cone A cone which is centered at $\langle 0,0,0\rangle$ and is defined by a radius (at the bottom of the cylinder) and a height. The side of the cone and the bottom cap may be specified as inexistent for rendering and collision detection;

Cylinder A cylinder which is centered at $\langle 0,0,0\rangle$ defined by a radius and height. The top and bottom caps, as well as the side of the cylinder may be specified as inexistent;

ElevationGrid Specifies a uniform rectangular grid of points with varying height in the $Y = 0$ plane. The number of elements is configurable (in both dimensions), as well as the spacing between elements for each dimension. The normal for each of the grid's quadrilateral (or even each vertex) can be specified, if the default values are not what the user pretends;

Extrusion Extrudes a two dimensional cross-section along a three-dimensional spine. The cross-section can be scales and rotated at each spine point. The sides, the begin cap and the end cap can also be specified as inexistent;

IndexedFaceSet A 3D shaped formed by constructing faces with the vertexes given. A user supplies a list of vertexes and a list of vertex indexes (into the first list) that will form the solid's faces;

Sphere A sphere that is defined by a radius and centered at $\langle 0,0,0\rangle$.

Additionally, there are nodes to group sets of nodes together for use as arguments, or for optimizations and transformations. A translation, rotation or scale transformation is always executed to a set of nodes and in regard to a certain point. The translation is absolute, with a translation vector. The rotation may displace the center instead of rotating the objects with the point $\langle 0,0,0\rangle$ as center. The scale can also have the center changed and can be non-uniform in among the different dimensions. The three operations can be combined in a single node. In this case, the operations are always performed in the following order: scale $\rightarrow$ rotation $\rightarrow$ translation.

Like the PDF file format [ISO08b], X3D has no control structures *per se*. The interpolators can be used in some situations where one would use control structures, but not always. Normally the designer would model in a high-level program (*e.g.* a Java program that uses X3D's Java bindings or a *point-and-click* program like Autodesk's Maya or Blender Foundation's Blender 3D) and then export the model to X3D.

X3D is aimed at being written by automated tools, and lacks high-level primitives to be practical for a human to model objects in it. Most of X3D's usage comes from tools which export models to X3D for web-based viewing and portability among different tools. As such, the X3D code for the Doric-order columns' model is a rather large file which we decided not to include in this document. Due to the lack of primitives, the columns' model had to be created using `IndexedFaceSet` and sets of points to build the faces of the columns. However, X3D is a language which can be used as a *back-end* for VisualScheme, allowing the programmer to export models to a variety of programs which support X3D. As an example, Listing 2.5 contains a snippet of the program to model the Doric-order columns.

```
Shape { # triangle mesh
        appearance Appearance {
                material         Material {
                ambientIntensity 0
                diffuseColor     1 1 1
                specularColor    0 0 0
                emissiveColor    0 0 0
                shininess        1
                transparency     0
                }
        } # appearance
        geometry IndexedFaceSet { # triangle mesh
                ccw    TRUE
                convex TRUE
                solid  FALSE
                coordIndex [
                           26,    1,    0, -1, # triangle    0
                           26,    0,   25, -1,
                           27,    2,    1, -1,
                           27,    1,   26, -1,
                           # More indexed faces
                           74,   48,   73, -1
                ] # 96 triangles
                coord Coordinate { point [
                        12.5 0 0, # coord point    0
                        12.48416328430176 0.1248452961444855 0,
                        12.43434238433838 0.2476829886436462 0,
                        12.3553524017334 0.3517448604106903 0,
                        # More coordinates
                        12.30000019073486 0 5
                ] } # 74 coord points
        } # geometry
} # triangle mesh
```

Listing 2.5: Part of the X3d code for drawing Doric-order columns

2.5.3 Conclusions

X3D is a simple, web oriented 3D file format, designed for embedding 3D content in web-pages and publishing content for use in any program that implements this standard. The XML encoding facilitates integration in existing tools while the legacy VRML encoding helps people who write X3D directly. Despite some criticisms, The X3D standard is getting widely adopted, from 3D modeling programs to web browsers to GIS[29] programs. There is a lack of CSG functions, which makes it better suited for modeling some kinds of objects with the help of higher-level tools which will do any necessary calculations and convert the CSG constructs into lower-level primitives. There are very few primitives which can then be combined to create much more complex objects.

[29]Geographic Information System

2.6 Grasshopper 3D

Grasshopper 3D is a plug-in for visual programming built on top of the Rhinoceros 3D modeling tool (Rhino). Rhino is a 3D modeling program which widely used in many design fields, such as marine and jewelry design, CAD/CAM and rapid prototyping. It's primitives are based on NURBS and it has several rendering options. Rhino is also used to convert between modeling program's file formats, since it can import from and export to a wide variety of formats. [PI09]

Like many other current CAD/CAM programs, Rhino represents free-form shapes as NURBS, which are a mathematical model of a shape, instead of using meshes, which are a collection of points which form adjacent flat triangles. By using NURBS instead of meshes, Rhino is more precise and easily handles transformations, allowing the user to specify how much accuracy is needed for a given rendering (for a sketch, an architect doesn't need the same accuracy in the drawing as for a photo-realistic rendering).

Being built on top of Rhino, Grasshopper leverages on all its primitives and operations, including the ability to use other Rhino plug-ins and extensions.

Grasshopper's programs are designed using a "boxes and arrows" model. Boxes represent primitives or operations and the arrows connect a box's output to another box's input. The inputs may also be fixed, using several widgets (including sliders and textual input), instead of deriving from another operation's results.

Grasshopper's block library contains blocks for primitives and operations from Rhino, which are available as Grasshopper blocks. These blocks can then be linked with each other, with the possibility of using the same output in several inputs.

Being based on a "boxes and arrows" model, Grasshopper makes it easy for anyone who knows the operations to start building a parameterized 3D model of an object. Instead of working on a 3D model using irreversible commands and storing the output of these commands using meshes, Grasshopper stores the sequence of operations needed to model the object and, when needed, sends the needed commands to Rhino. This implies that, when a change is made to the 3D model (by changing a connection or adding/removing boxes), the 3D model can be easily regenerated by Grasshopper, by sending the necessary commands to Rhino.

Grasshopper lacks any mechanism for block abstraction in its programs. Programmers work around this by drawing delimiters over sets of boxes and inserting text in the model definition, but these have no semantic meaning for the program, which makes it easy to get these annotations out of sync with the program. Besides not being able to abstract, there is no equivalent, in Grasshopper, to higher-order functions. Because of this, a programmer cannot easily experiment with transformation blocks in cases where a block iterates through a list of points. For example, the existence of a "higher-order-block" (a block which could receive other blocks as arguments) would enable the creation of said block, easily changing the operation performed by altering the corresponding connection.

Due to this lack of block abstractions, Grasshopper is less than adequate for the design of extensive, complex 3D models. There are blocks which can be programmed using C# or VB.NET, which can leverage Microsoft's .NET framework and any available libraries. But these blocks are simply a way to escape the visual programming paradigm, which allows a programmer to overcome the adversities which arise from this paradigm. If a programmer wants to abstract a set of blocks, the only way to do it is to replicate the set of blocks' operations in a single C# or VB.NET block, which also increments the complexity and requires more low-level knowledge while, at the same time, diverging from the visual programming paradigm. At the same time, abstraction using .NET blocks is a black box which can make reading programs much more difficult, depending on what operations that block is performing.

Small Grasshopper programs are easily understood by virtue of the visual nature of the connections between boxes. But as complexity grows, programs get considerably confusing to the point that, even for a small program, the programmer may have difficulty in remembering the corresponding between parts of the program and parts of the model. Although this happens also in text-based programming languages, this difficulty is aggravated, in Grasshopper, due to the lack of abstraction, which forces the programmer to remember a big part of the program in order to make any changes in the established connections.

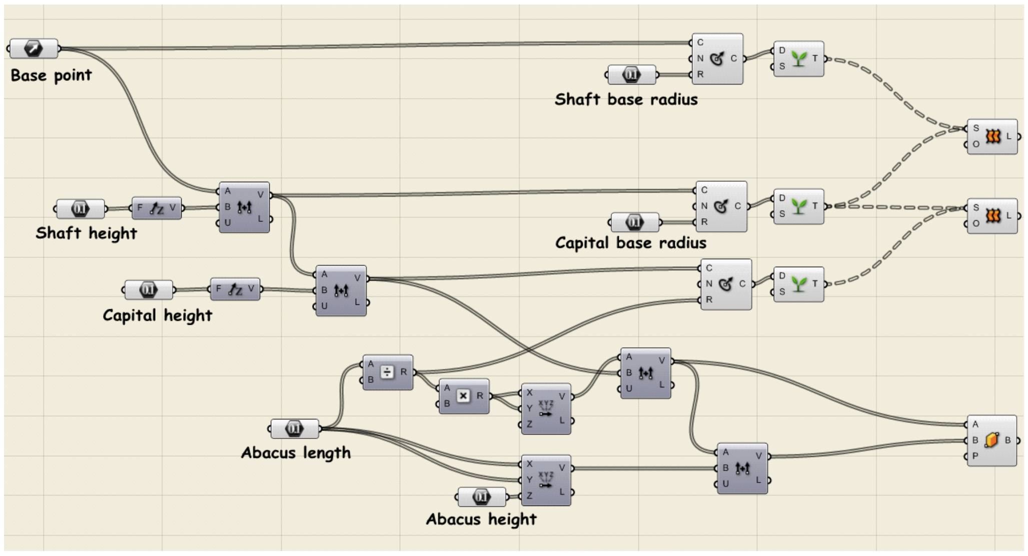


Figure 2.2: Grasshopper diagram for drawing Doric-order columns

In Fig. 2.2 is presented the grasshopper program to draw the set of Doric-order columns. The presented diagram can model one or several different columns, by changing the value of the annotated sources of data (the blocks above the labels). These blocks may have their values sourced from programmer defined constants or collections (specified in the block), parametrized sliders or other blocks.the flow of code is from the left of the block to its right.The rightmost blocks are the blocks which take as input circles and vectors and output the desired geometry (the columns). If the input of a block is a list, the block will be mapped over the list.

2.6.1 Conclusions

Grasshopper is a simple, visual programming language, which is designed with non-programmers in mind. Any person who can use 3D modeling programs with a point-and-click interface (and therefore knows the terms used and the modeling concepts involved) can create a simple parameterized 3D model with constraints between its properties (*e.g.* the model of a building where one of its sides is based on a mathematical equation and its height is a function of its width). Unfortunately, like other visual programming tools, when a model's complexity grows, the lack of user-defined abstractions makes it difficult for a programmer to build complex parameterized models (it is even impossible to use a function (implemented as blocks) to parameterize any part of the model). When a model gets complex, inevitably the programmer starts using the C# and VB.NET blocks (thereby defeating the visual programming paradigm).

2.7 Comparative Table

In this section we present a small comparative table (Table 2.1) of the high-level characteristics of each of the analyzed programming languages.

Feature	AutoLISP	GML	PLaSM	POV-Ray	X3D	Grasshopper
Paradigm	Multi-paradigm[a]	Stack-based	Function-level	Declarative	Declarative	Visual
Syntax	Parenthesized Prefix	Postfix	Prefix	Mixed	XML	N/A
Usage	Widespread	Limited	Limited	Widespread	Widespread	Limited
Learning curve	Short	Long	Long	Short	Short	Short
Expressiveness	High	High	High	Moderate	Moderate	Moderate[b]
Abstraction	HoF,[c] Function creation	HoF	HoF	Textual macros Functions	Node creation	C#, VB.NET Blocks, lines

[a]Functional and imperative paradigms, although some data structures are purely functional.
[b]Grasshopper may be more expressive if one takes into account C# and VB.NET blocks, which parts from the visual programming paradigm.
[c]Higher-order functions

Table 2.1: High-level comparative table between AutoLISP, GML, PLaSM and POV-Ray

These are very high-level characteristics of these languages, viewed by an architect's point of view. It is assumed the architect is marginally familiar with AutoLISP for the definition of each language's learning curve. POV-Ray's expressiveness suffers from not having functions, which are necessary when we want to design objects based on mathematical expressions and high-level functions.

2.7.1 Available 3D Primitives

The primitives available from the analyzed programming languages were separated in three different groups: 2D primitives, 3D primitives and operations on objects. The languages were then compared and a minimized set of primitives was constructed. While, for example, AutoCAD has several kinds of line objects (`line`, a simple 2-point line; `polyline`, a 2D line; `lightweight-polyline`, an optimized 2D line, and `3d-polyline`, a 3D line), we joined, in VisualScheme, these primitives into a single `line` object which can have multiple points of passage and exist in a 2D or 3D space. These primitives, in AutoCAD, are kept mostly for legacy reasons, as it evolved from 2D to 3D modeling and previous tools and plug-ins must be kept working. Other CAD tools have similar legacy constructs. This hinders architects in their daily work as they struggle to understand why a certain operation on a certain kind of line is not working as expected. The same can be said for several other primitives which may exist in related forms in different languages, but have a common parametrization which we use in VisualScheme. The minimized set of primitives can be found in appendix A, in the VisualScheme manual. This manual also contains references to some of the languages where the presented primitives can be found.

Even though not all the languages have the VisualScheme primitives available, they can be modeled (with more or less work) in any of the languages. For instance, in POV-Ray, there is no NURBS primitive available but a user can implement the formula for the curve (or download an already written library) and specify the level of approximation wanted. All the languages also have a very low-level triangle mesh object which enables the *back-end* writer to, if necessary, implement a primitive using this very primitive function, which is also available in low-level API such as OpenGL [AS04] and Direct3D [Bly06].

Chapter 3

Development Stages

In the first part of this work, several 3D modeling languages were studied and their features were compared to establish a starting point for our development.

This chapter presents the several development stages this project had. Its development was divided in four main stages: Tool survey, language implementation, primitive object selection, and evaluation. The first two were started in parallel. After surveying the existing tools, the primitive selection was started. The language will be continually developed, even after the work related to this thesis has ended. Throughout all the development stages, input was collected from architects and architecture students, in order to assess their difficulties and requirements when using the language. A case-study was also devised, using an iconic building from the city of Lisbon, which has a regular structure and was designed from scratch using CAD tools [Mol99]. This case-study also served as a comparative study with other technologies.

3.1 Tool Survey

Since the main goal of this project is to define a functional domain specific language for 3D modeling, one has to survey the available options (presented in chapter 2), analyzing their pros and cons. By surveying what is already available we have a point of reference so we can compare languages.

These tools were chosen to represent a wide variety of approaches to 3D modeling: imperative, declarative, functional and function-level programming languages, as well as visual programming languages. By analyzing several different approaches to the same problem, several ideas can be extracted from each of them to improve the final work. A basic set of primitives can also be derived from the intersection of these languages.

By knowing how 3D models are designed in existing languages, we can also create a batch of tests for our language.

3.2 Language Implementation

After surveying a set of languages and possible *back-ends*, the implementation of the language could start. Using what we learned from each of them, we chose the one that best suited our goals and which could be used for testing with end-users (as described in chapter 4).

After a first proof-of-concept language implementation, which included communication between the program used and our front-end but was too much low-level, a higher-level prototype was implemented and tested. The first implementation included a mechanism to emit low-level AutoCAD commands, which provide access to every AutoCAD function that is available from the command-line (and from AutoLISP). This mechanism was also ported to the new version as a *back-end*-specific feature, which is only available when using AutoCAD as a *back-end*.[1] The newer version controlled AutoCAD using more high-level communication protocols (ActiveX and COM), which improved its speed and allowed more control on the generated objects.

Optimizations are also possible at *back-end* level, by taking into account the whole object. A *back-end* can have an optimization pass where the tree defining the 3D model (which contains primitive objects and operations) is minimized and expensive operations (or sets thereof) are substituted with more efficient operations for that specific *back-end*, while yielding the same results.

3.3 Primitive Object Selection

To build the basis of the language, it is crucial to select and implement a set of primitive objects and operations.

This set of selected primitives (presented in appendix A)is comprised of basic solid primitives (*e.g.* spheres, boxes, cylinders), powerful lower-level objects (*e.g.* triangular meshes, height-fields), operations on objects (*e.g.* translations, rotations, scales) and operations on sets of solids (*e.g.* unions, intersections, subtractions).

The primitive objects and operations were carefully chosen in order to ensure that every object which is possible to model in one of the analyzed languages, is also possible to model in our language. References were made in the manual in order to track the equivalences between VisualScheme's primitives and operations to the ones present in other modeling systems.

The selected 3D primitives and operations are described in appendix A, along with references to other languages where that primitive or operation is available. These primitives were chosen by taking into account what is available in other modeling systems and compacting the set of primitives whenever two of them overlapped.

3.4 Evaluation

Feedback was collected from several students and the resulting knowledge was then incorporated in our design of the language and its primitives. This feedback was collected both directly, by providing the students with a test version of VisualScheme, or indirectly, by analyzing frequent mistakes students made in projects and exams (as can be seen in chapter 5).

Feedback is invaluable for the development of a programming language. It allowed us to detect wrong assumptions made initially and where the most common programming mistakes were being made, and helped us to better understand the students' way of thinking.

The case study of the Gare do Oriente 3D model also served as a valuable resource when comparing a textual programming based approach to a visual programming one (Grasshopper).

[1]The core language itself is *back-end* neutral but specific *back-ends* can supply additional features.

Chapter 4

VisualScheme

The objective of this work is to create a domain specific language (DSL) for 3D modeling to enable architects to design buildings in a programmatic way, thereby reducing the amount of work needed to experiment with different and elaborated shapes and allowing the programmatic modeling of 3D objects.

The language created is an internal domain specific language based on Scheme. It provides several 3D solid creating primitives, as well as operations on these objects.

VisualScheme programs are created by composing primitives and operations, creating a tree structure with primitives on its leaves and operations as the branches. Several library functions are available for the programmer to use, *e.g.* functions to iterate over sequences of points, generating them using interpolation, and coordinate transformation.

After building the model tree, it is passed to the *back-end*, which will convert it to the sequence of commands needed to generate the same model in the *worker program*, sending the commands afterwards. The model is, generally, *worker program*independent. The *back-end*may expose some *worker program*specific functions to the user which may break this independence but provide functions only available in that *worker program*.

In the following sections, we present the architecture of VisualScheme and its AutoCAD *back-end*, as well as some examples of possible extensions to VisualScheme which can be provided by library writers.

4.1 A Domain Specific Language

A domain specific language (DSL) is a language tailored for solving problems in a certain domain. While a general-purpose programming language (GPL) focuses on generality, allowing the programmer to solve any problem, a DSL is focused in a single domain, trading the generality for expressiveness in their domain. With this compromise, DSL programs are often shorter than their counterparts written in general-purpose programming languages.

Several DSL are currently in mainstream use like GraphViz[1] (for graph layout), SQL [ISO08c] (for interacting with databases) and the languages we analyzed in chapter 2, like POV-Ray and GML, which are oriented for 3D modeling.

DSL are advantageous due to a number of factors. For example [MHS05]:

- Appropriate domain-specific notations are, usually, more accessible in a DSL than they are in a GPL, due to significant investment in tailoring the language to that domain. These notations are directly related to the productivity improvement associated with DSL.;

[1] `http://graphviz.org`

- Domain-specific constructs are available in most DSL in order to abstract as much as possible. Being a DSL, several abstractions which may be impossible to do using a GPL and a library may be built;
- A DSL also offers the possibility of easier analysis, verification, optimization, parallelization and transformation of its programs. As it is, normally, much simpler than a GPL, where some analysis and optimizations are impossible to do;

VisualScheme is, in itself, a domain specific language for CAD built on top of the Scheme GPL, *i.e.* it retains Scheme's characteristics while adding the CAD functionality on top of it.

4.2 Why Scheme?

Our primary goals for the designed language were:

- It should be simple, familiar, with a short learning curve;
- It should not depend on the *worker program*;
- It should be "fast enough".

A Familiar Language

Because AutoLISP's users are already familiar with Lisp-like programming languages, another Lisp-like programming language such as Scheme can attract them, since it has the syntax, semantics and many of the features they already know how to use.[2] Additionally, programs can be built on top of a modern programming language with many new facilities and powerful constructs for writing readable, compact code and protecting against certain kinds of bugs which plague AutoLISP programs. A Lisp-like language's learning curve will be much shorter than another language with a much more evolved syntax, at least for AutoLISP programmers. Taking all this into account, Scheme was chosen as a modern Lisp-like language, as our language of choice for parametric geometric modeling in the XXI century.

A Simple and Functional Language

Since Visual LISP is already built into AutoCAD and used around the world, it was decided to use a Lisp-like language for the 3D modeling language that will be designed, so as to gather the largest audience possible. As a Lisp dialect, the Scheme language shares much of its simple syntax: The program is written in S-Expressions[3], which are then evaluated by the interpreter or compiled and executed. Scheme is also an actively developed programming language with a continually revised specification[4] [SDF$^+$07].

Scheme is also known for being a very simple language: the latest widely implemented standard (R^{5}RS [KCR98]) had only 50 pages. By emphasizing the evaluation of expressions (as opposed to the execution of commands), supporting recursion, having higher-order functions and performing tail-call optimization (among other things), Scheme can be considered one of the most widely used functional programming languages around the world.

Despite being a functional language, Scheme allows for side-effects, trading the "purely functional language" classification for the ability to use multiple paradigms, which makes Scheme a good teaching language (as can be seen by the success of books like [ASS96] and the TeachScheme! project [FFFK03]).

[2]An additional compatibility layer was implemented to make available a full AutoLISP interpreter, to run legacy scripts.

[3]An S-Expression is either an atom (*e.g.* a number, a symbol, a string) or a pair (`cons`) of S-Expressions

[4]The last Scheme standard was ratified in 2007

For our design language's first implementation, PLT Scheme[5] was chosen as the base Scheme implementation due to being one of the most actively developed Scheme compilers available, to its easy to reach and helpful community and its companion IDE, DrScheme[6], which is oriented for a pedagogical teaching of the language as well as its everyday use by an experienced programmer [FCF+02].

Worker Program Independent

The high-level language must be independent of the *worker program*. It should not be important for the programmer to know if the *worker program* is a CAD program, a 3D plotter, a simple visualizer, a flat file or a web-browser. Scheme does not depend on the *worker program*(unlike AutoLISP, which can only be used with AutoCAD). VisualScheme is divided in a *back-end* and a *front-end*, and the *back-end* is further divided in a *lower back-end* and a *upper back-end*. This *lower back-end* provides some Scheme functions to make the bridge between the Scheme process and the *worker program*, and the *upper back-end* maps the primitives of the language defined in this work into the *worker program*, using the functions defined in the *lower back-end*(being therefore, independent of the *worker program*). This is equivalent to using a machine-independent intermediate language when analysing and optimizing a program, before generating native code, as many modern compilers do [Lat02].

A Fast Language Implementation

Due to the sheer amount of data generated and operations executed when modeling a complex 3D object, the implemented language must not be a performance bottleneck. With a bottleneck in the interpreter or compiler, the resulting language would end up being unusable, because the ratio of the script execution time and the rendering would be high. If the language has a longer learning curve than simple tools like AutoCAD's basic drawing features, the programs would be used mostly for designing very complex objects, that would be (almost) impossible to design by using the non-automated AutoCAD drawing tools. This is especially significant because render times for drafts are practically instantaneous.[7]

By using an actively developed optimizing Scheme compiler (and just-in-time compiler and optimizer [FFS08]) with a very helpful community, the performance problem is easily addressed by taking it into account when implementing the *upper back-end* and the *front-end*.[8]

4.3 Architecture

The approach chosen to address the 3D modeling problem was to implement a compiler for a high-level 3D modeling language that is based on the Scheme programming language. This compiler will consist of two modules: The *front-end* and the *back-end*. The *back-end* will be dependent on the output the programmer wants to generate (exporting to AutoCAD, ArchiCAD, another (CAD) program or any file format for which a *back-end* has been written, like X3D or POV-Ray SDL). Several *back-ends* may be implemented so the programmer just has to write one program and then export it to the desired format, as long as no *back-end*-dependent features were used. The *front-end* will be built upon a small kernel language composed of Scheme and some *back-end* functions which won't depend on the output chosen.[9]

[5]`http://plt-scheme.org`

[6]`http://drscheme.org`

[7]As opposed to photo-realistic renderings which can take hours or even days, depending on the resolution of the output and the complexity of the objects.

[8]As the *lower back-end* is only a thin layer of abstraction over the base language's foreign function interface libraries, there isn't much need for performance considerations in the *lower back-end*.

[9]Although, in some special cases, there might be some features only available in some *back-ends*, most features will be *back-end* independent.

This component will provide the full-featured 3D modeling language which will include, first the basis, and then powerful constructs to the programmer in a language which can then be taught to architects.

VisualScheme is divided in two: a *back-end* and a *front-end*. The *lower back-end* will provide some Scheme functions, making the bridge between the Scheme process and the *worker program* that will be in charge of the calculations, and the *upper back-end* will map the primitives of the language defined in this work into the *worker program* (using the functions defined in the *lower back-end*). The *front-end* is comprised of the common primitives (which have to be implemented by every *back-end*) and other *back-end*-defined primitives for the *back-end* that is currently in use. The user programs will then use the primitives and operations made available by the *front-end* and *back-end*, with the syntax and semantics of Scheme. A diagram of this architecture is illustrated in figure 4.1.

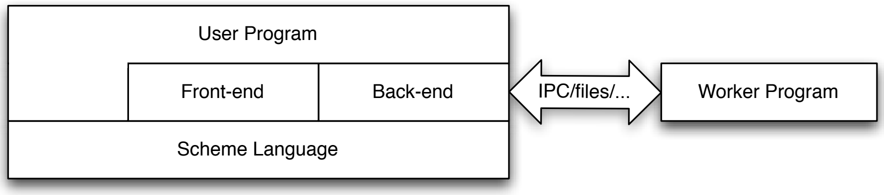


Figure 4.1: Solution architecture

4.3.1 Basic Architecture

The 3D programming language will be based on a Lisp-like language (the first implementation is based on PLT Scheme) and will communicate with AutoCAD (the first *back-end* to be implemented) via a foreign function bridge (the first *lower back-end* implementation uses Component Object Model (COM)[10] as the inter-process communication mechanism).

In the first implementation, the *lower back-end* establishes Scheme-side functions that map commands to the AutoCAD COM libraries. To do this, several missing COM features were added to MzScheme's[11] (PLT Scheme's virtual machine) COM implementation, MysterX[12] [Ste99].

In the planned architecture, the *front-end* of the modeling language is implemented as a set of macros that transform programs written in the designed language into regular Scheme programs (that use the *back-end* and a run-time library that was written to support the language). The language's programs are compiled and run by a Scheme interpreter/compiler/virtual machine, outputting the designed objects to the *back-end* (AutoCAD, in the current implementation). The means of communication from the *front-end*to the *back-end*is a tree composed of VisualScheme's objects and primitives. This tree contains all the necessary information to build the 3D model. The *back-end*will, upon receiving the tree, convert the tree into a sequence of *worker program*commands which will be sent to it, creating the model in its working space.

4.3.2 *Front-end*

The *front-end* is responsible for most of the operations available in our language. Only after the objects are modeled in the *front-end*, with high-level primitives, will they be marshaled to the *back-end* and used according to what the programmer wants.

[10]http://microsoft.com/COM
[11]http://plt-scheme.org/software/mzscheme
[12]http://plt-scheme.org/software/mysterx

The *front-end* is available to the programmer as a set of Scheme functions and macros that implement our DSL. Any Scheme program is also a VisualScheme program, which means programmers can use libraries written for Scheme and divide the program in more manageable parts.

Every model starts in the *front-end*, by combining several primitives with operations which act on them. The core language *front-end* provides several primitives for creating and operating on points and vectors, as well as the core primitive objects. Several transforms and constructive solid geometry (CSG) operations are available for transforming and combining the primitive (or compound) objects.

The full power of the Scheme language is available to the programmer, *e.g.* for the creation of extensions or additional modules. If needed, the core language can also be extended. For most changes the only thing needed is to add a library to ease the modeling of certain kinds of objects.

One possible extension would be to add more material, shading and reflection options. These options can be added to the tree by performing an additional pass after the modeling or by adding them while modeling the objects. After the modeling of the object is done in the *front-end*, the primitive and operation tree is passed to the *back-end* where it will be marshaled to the final model.

Our *Front-end*

The *front-end* is responsible for defining the language that will be available to the programmer and also the main structures that will be used by both the *front-end* and the *back-end*.

Our *front-end* defines several basic primitive objects and operations which work on them. As this is a general *front-end*, the primitives are generally both high-level and simple.

The primitive objects that are available are: circles, solid regions, boxes (parallelepipeds), cones, cylinders, spheres, tori, wedges and lofts. A primitive for text drawing is also available.

Transformations on objects, such as translations, rotations an scales are available, as well as operations on sets of objects, such as unions, intersections and differences. These operations accept any created object as argument and, just like the primitives, must be implemented in every *back-end*.

4.3.3 *Back-end*

The language is made *back-end*-independent by having a distinction between the language core (which provides the primitives and operations that use them) and the *back-end* (which effectively serializes or draws the primitives).

The language core is the same regardless of what *back-end* is in use. A user won't have to change anything in his program in order to change the *back-end* if he only uses the language core. Its functions and control and data structures are always the same and behave the same in the different *back-ends*.

The *back-end* may serialize the models to a file (*e.g.* a DXF, AutoLISP or POV-Ray SDL file) or use IPC to send commands to a program (*e.g.* using ActiveX to send commands to AutoCAD) which will then create the model's representations. The *back-end* is free to optimize the object and operations tree for itself (using more specialized *back-end* commands) and provide additional primitives for programs that don't need to be portable and require features that are only present in that *back-end*, as will be seen in section 4.4.

A simple *back-end* is written by defining a function called `draw`, which will receive a tree of primitives and operations and perform the necessary operations to model the tree in that target. A *back-end* may also define more primitives and operations on these for expanding the language (*e.g.* primitives for structural analysis on top of the 3D models), but must be able to model every core language feature.

The AutoCAD *Back-end*

The AutoCAD *back-end* was the first implemented *back-end*. As our immediate goal was to make available a modern language that could replace AutoLISP in an architect's workflow, we decided to create a Lisp-like language that was easy to learn and use for architects and only afterwards would we implement a fully-fledged AutoLISP emulation layer so we could run legacy AutoLISP scripts integrated with scripts in our language. COM communication was chosen as the communication mechanism due to being a well-established IPC mechanism in Microsoft's Windows operating system and the availability of libraries to facilitate the communication between our Scheme process and AutoCAD.

It is divided in 3 components: A tiny DSL to facilitate writing code which uses several functions for COM operations from the MysterX library, bridges for the primitive AutoCAD COM methods which model several primitive objects on AutoCAD's side and the upper part of the *back-end*, that acts as a compiler which transforms our trees that are composed of VisuaScheme's primitives and operations to commands to be sent to AutoCAD via COM.

COM DSL — The COM DSL is a library which helps developing applications that use COM in the Windows version of MzScheme. This DSL, which is implemented on top of MzScheme's MysterX COM library, has several utility functions and macros to facilitate communication through the COM protocol;

AutoCAD Bridge — The bridge between our language and AutoCAD's COM automation mechanisms are thin wrappers over the primitive COM methods, which marshal their arguments and invoke them on AutoCAD's side;

Compiler — The compiler component of the *back-end* takes a tree of primitives and operations (in our language's constructs), optimizes the tree and then interprets it, sending the commands to AutoCAD and saving the results on the program's side, if needed.

The compiler's optimization pass is very basic, but additional passes and transformations may easily be added. Possible optimizations range from very basic ones (*e.g.* the scale of a circle (two COM calls) may get transformed to the creation an ellipse (one COM call) and the translation of a box (two COM calls) may be transformed to the creation of an already translated box (one COM call)) to more complex optimizations, *e.g.* the creation of N objects by instantiating each of their M components and performing P operations ($N \times (M + P)$ operations) may be transformed to the creation of one prototype object and its subsequent copy and placement on the final position for the other $N - 1$ objects ($M + P + (N - 1) \times 2$ COM calls[13]).

Adding support for additional features (that may be implemented in a further revision of the core language or core-dependent primitives) is simple: The new primitive must be added to the compiler driver so it can be recognized and modeled on the other side. The compiler driver will then call a specialized function to model that object whenever it is encountered. If this is a *back-end*-specific feature or operation, its definition must be added (and exported) to the *back-end* to make it visible to any program which uses this *back-end*.

4.4 Optimizations

In VisualScheme we have mechanisms in place to allow *back-end* developers to optimize the object and operation trees and allow the objects to be modeled in a more efficient way.

[13] $M + P$ operations to create the first object in its desired final location. The other $(N - 1) \times 2$ COM calls copy the object and move the copy to its final location.

In this section we will be addressing possible optimizations on the AutoCAD *back-end* as an example of a major optimization which may easily be ported to several other *back-ends*.

Two optimizations will be described: A simple optimization that will convert a translated object into an object that is created at its final destination and a more complex optimization which collapses the creation of several objects into the creation of one master copy and its subsequent copy and transformations on these copy.

With both these optimizations we can substantially reduce the working time of our scripts on the AutoCAD *back-end*. The optimizations focus on reducing the total number of COM calls, which are the IPC mechanism in which the AutoCAD *back-end* is based. By reducing the number of IPC calls, we can have a big speedup in our scripts as the COM calls are where most of the time is spent, in the AutoCAD *back-end*.

4.4.1 Translated Primitives

Every available primitive in VisualScheme has a center point which is given by the user as an object created by the function `xyz`, or an equivalent point-creation function.

When creating several objects of the same type, a possible way of modeling them in VisualScheme is to create a base object and then copying it and performing the operations we need to place it in its final destination. As VisualScheme is a functional programming language, we can use the base object instead of doing a deep copy, thereby sharing it among all the objects.

Using this method, we end up with several translated primitives (and possibly rotated and scaled too) which entail to (at least) two COM calls to be modeled (one for creating the primitive and another one to move it to its final destination).

As every primitive has an anchor point (*e.g.* the `center` argument of a `box` or `cylinder`), we can simply translate this point when the *back-end* is instructed to create the translation of a primitive: *e.g.* when the *back-end* receives the translation of a cylinder centered at the origin by the vector $(1, 2, 3)$, it can just create a cylinder centered at $\langle 1, 2, 3\rangle$ instead of creating it at the origin and then translating it.

Three options are available to implement this optimization: a tree transformation, a peephole optimization [ALSU06] or a *front-end* optimization. For the purpose of this document, we chose to implement it as a peephole optimization as it can then be localized to the *back-end* function that deals with translations on objects and enables us to avoid performing optimizations which some *back-ends* could not support: some 3D modeling programs and languages only allow objects to be created centered on the origin of the 3D space (*e.g.* the primitives in X3D)..

To implement this peephole optimization, the function that marshals a translation to AutoCAD was altered. The non-optimized version of this function would marshal the translated object, getting a handle for the marshaled version, and then use the `Move` method from AutoCAD to translate it to its final location. The optimized version checks the translation object and, if it is a primitive object, simply draws a translated primitive where the origin was moved by the translation vector.

The optimized version of the function that deals with translations behaves as the following pseudocode:

```
(define (apply-translation translation)
  (if (primitive? (translation-object translation))
      (draw (translate-primitive (translation-object translation)
                                 (translation-vector translation)))
  (let ([obj (draw (translation-object translation))])
    (prim:move obj
               origin
               (translation-vector translation))
    obj)))
```

Listing 4.1: Optimized `apply-translation`

If the translated object is a primitive, then translate that primitive using a primitive VisualScheme function and then ask the *back-end* to model the resulting object, returning it afterwards.

A similar optimization may also easily be applied to the scale of a primitive and some cases of rotations.

4.4.2 Caching

The caching optimization is a major *back-end*-dependent optimization which has been implemented as an optimization test-case in the AutoCAD *back-end*. This optimization was implemented in order to reduce COM calls to a minimum.

As VisualScheme is a functional language, we can expect a significant amount of sharing in data structures, especially when we have repeating patterns in the modeled objects. With caching we can memoize [Nor91, CLRS01] some object's models and, instead of re-creating them whenever we need to model that object again, we would just copy the template and apply the necessary transformations to give it its final position and shape. Safeguards may also be put in place to ensure that the cache doesn't use too much memory space.

Our cache implementation is limited to caching only parts of an object the user asked to model (using the `draw` method that is exported by each *back-end*), with the cache being zeroed before the start of the `draw` routine. Support may easily be added to have a "world cache" which would memoize parts from every object, even if they're shared between objects in different calls to `draw`, even by having a two-level caching approach (a cache for global objects and a cache for local objects), similar to modern CPU [Dre07].

To implement this optimization, the `draw` function that is exported by the *back-end* becomes a trampoline function which sets up the local cache and then dispatches to the effective modeling function of the *back-end* (in this case, the `draw*` function), behaving in accordance to the pseudo-code in Listing 4.2.

```
(define (draw-top-level object)
  (set! cache (make-hash))
  (let ([result (draw object)])
    (clean-cache)  ;; Erases all the template objects in the cache
    result))

(define (memoized-draw object)
  (let ([obj (hash-ref cache object #f)])
    (if obj
        (copy-entity obj)
        (let ([obj (draw* object)])
          (hash-set! cache
                     object
                     (copy-entity obj))
          obj))))

(define (draw object)
  (case* object
    ;; [predicate? => function-to-apply]
    [primitive? => draw-primitive]
    [csg? => apply-csg]
    [operation? => apply-operation]

    [else (error …)]))
```

Listing 4.2: Optimized `draw` and `draw*`

The optimized version of the `draw` function will have an entry point (`draw-top-level`) where the cache for the current (top-level) object is created (if there is a whole-program cache, it is just maintained through calls to `draw-top-level`), the object is then passed to the function which verifies if we have a cache hit or a cache miss (the `memoized-draw` function). If we have a cache hit, we copy our template and return the copy. If it is a cache miss, we will draw the object (using the same `draw` function as before the optimization) and register a copy of it in the cache for further use. The `draw-top-level` function was exported from the *back-end* with the name `draw`, in order to comply with the *back-end-front-end* interface. We chose to keep the previous `draw` function in order to change the minimum amount of code. I we only want a global cache and not a per-object cache, we can simply delete the `draw-top-level` function and export the `memoized-draw` function as `draw`.

This optimization may also be made more selective so as to minimize the size of the cache. We could only cache finished objects (*e.g.* the result of any constructive solid geometry (CSG) operation) and not cache any transformations on them (*e.g.* translations or rotations), thereby minimizing the number of objects in cache and improving its access time.

4.4.3 Measures and Conclusions

The impact of each of the optimizations is at opposite ends of the spectrum, with the "Translation of Primitives" yielding a minor (but positive) speedup and the caching optimization yielding a speedup of at least a factor of two, in our test.

Our test consisted of a stress test for both of these operations: A grid of 50×50 cylinders was created by creating a matrix of cylinder objects. At first, a cylinder object is created, in the lower-left corner of the grid. The structure that describes that object is then copied several times and wrapped in translation structures which move the contained object to another point in space. After creating a whole row of 50 cylinders, that row is then acted upon in the same way, copying and translating it 50 times to finalize the grid.

The results are summarized in Table 4.1, with the average run time of three runs, for each combination of the described optimizations. All the tests were performed on the same machine[14], with a freshly started instance of AutoCAD (2008) and DrScheme (4.1.4).

Active optimizations	COM calls	COM calls (%)	Translation optimizations	Average Run Time (s)[a]	Speedup w.r.t. None
None	7853	100.0%	N/A	25604	1.0×
Translation of Primitives	5252	66.9%	2601	18187	1.5×
Caching	609	7.8%	N/A	1994	12.9×
Both	558	7.1%	153	1917	14.0×

Table 4.1: Optimization testing times

[a]Measured as "real time".

As we expected, the caching optimization is the most significant. The translation of primitives was not very efficient in optimizing the code but it could be extended for translations of unions or other CSG operations (*e.g.* by mapping the translation in the operation's objects and by composing several translations in one), which could improve that optimization. Many more optimizations can be implemented in the AutoCAD *back-end* that may yield a speedup in most or only a small part of programs.

4.5 Extensions

Extensions are a key feature of VisualScheme. The language is designed in order to facilitate the development and integration of extensions, which can range from simple additional object definitions to fully fledged model analysis and verification systems. In this section we will show how to extend the VisualScheme language with additional objects. All the relevant data structures are available to enable a developer to write sophisticated systems on top of our object model and extend it with additional objects and operations.

[14]An Intel®Pentium®IV 3.0 GHz, with 1GB of RAM and an integrated Intel 910GL graphics card

Extensions may be made to the common framework or only to a specific *back-end*. An extension made to a specific *back-end* may use any function that is not on the common framework but is available in that *back-end* to the end user. To create an additional object definition, we just need to create a function with the object's parameters as arguments and make the function return a description of that object obtained by combining language primitives and operations on them. Any additional object model available in an extension will be made available by a Scheme library, which must be enabled at run-time.

4.5.1 Cylinder Between Two Points

Our primitive `cylinder` object is created with its center in a given point and its caps perpendicular to the Z axis. To create a cylinder between two points we must create the cylinder and then perform some operations on it, namely rotations and translations. As this extension only uses functions and data structures from the common framework, we will create the new object model as a simple library that does not require a specific *back-end*.

To create a cylinder between two points, we will place it in the center, rotate it to give it the desired orientation, and then translate it to its final position. In order to create the cylinder between two points, p and q, we:

1. Calculate the vector $\overrightarrow{pq}$;

2. Create a cylinder with height $|\overrightarrow{pq}|$, centered at $\langle 0, 0, 0\rangle$;

3. Rotate the cylinder to give it the desired direction;

4. Translate the cylinder to its final location.

These operations will create and place a cylinder between the two points and will work on any compliant *back-end*. An example implementation is given in Listing 4.3. To perform the rotation operations, we use spherical coordinates to calculate how much of a rotation we need, with ϕ referring to the azimuth and ψ referring to the zenith angle.

```
(define (cylinder-from-to from to radius)
  (let* ([v-cyl (p->q from to)]          ; vector inside the cylinder
         [height (vlength v-cyl)]        ; height of the cylinder
         [m (p+v from (v*r v-cyl 1/2))]  ; middle of the cylinder
         [v-phi (esf-phi v-cyl)]         ; azimuth
         [v-psi (esf-psi v-cyl)]         ; zenith angle

         [cyl (make-cylinder origin height radius)] ; create the cylinder
         [r1 (rotate cyl 'z v-phi)] ; rotate for azimuth
         [r2 (rotate r1 'x v-psi)])
    (translate r2 (p->q origin m))))
```

Listing 4.3: Code for creating cylinders between two arbitrary points

4.5.2 *Back-end* dependent extensions

When designing a *back-end*-neutral language, we have to deal with the lowest-common-denominator problem: will the language be fully *back-end*-neutral and stick to what can be achieved by every *back-end*? To address this problem, we allow *back-ends* to extend the language's functionality with additional primitives or operations that may not be available in every other *back-end*. If a program uses these features, it may not be portable to some or all other *back-ends*. But on the other hand, it may make available several features that the user may want for that project. Also, the needed feature may be implemented from the most basic primitives (*e.g.* sets of triangles) of the other *back-ends*, if the need arises.

In this section we will describe how we added a feature for AutoCAD's lofted surfaces [Ste03] in our AutoCAD *back-end*. With the AutoCAD *back-end*'s architecture, we only need to create the new primitive constructor, the primitive handler and treat that case in the *back-end*'s dispatcher.

```
(define-primitive loft
  f start step stop?)

(define (draw-loft loft)
  (let* ([f (loft-f loft)]
         [start (loft-start loft)]
         [step (loft-step loft)]
         [stop? (loft-stop? loft)]
         [surfs (unfold stop? f step start)]
         [drawn-surfs (map draw surfs)])
    (apply prim:command* "._loft"
           (append drawn-surfs
                   (list "" "")))
    (entlast)))

(register-drawing-function loft? draw-loft)
```

Listing 4.4: Code for our current loft implementation

First we implement the primitive structure to represent lofted surfaces. This structure will contain a `start` argument, a function (`f`) which, given an argument, will produce a two-dimensional shape, a `step` function to step the argument and a `stop` function, which tests if we have arrived at the last shape of the loft. The dispatcher (the `draw` function) also has to support the loft primitive but that code was omitted for brevity (the dispatcher tests if the structure passed as an argument describes a lofted surface and, if it does, calls the `draw-loft` function, with that structure as its argument).

In the *back-end*, we unfold a list using the given high-level functions and create the corresponding shapes in AutoCAD. After creating the shapes that will guide the loft, a loft command is then issued to AutoCAD with the references to those shapes as arguments, in the order they were unfolded. The result is the creation of a lofted surface from a high-level function which receives a parametrization of the shapes and functions to generate the argument for the next function and a stop condition.

With this primitive, we can also create a utility function for lofting a set of already defined shapes. We can use the mechanisms described in section 4.5.1 to create an additional, simpler, interface for creating lofts when the lofted shapes are already created. The following code defined a loft object and implements the rest of the extension, being another one of the already implemented extensions in our growing library:

```
(define-primitive loft
  f start step stop?)

(define (loft-objects . objects)
  (make-loft first
             objects
             rest
             null?))
```

Listing 4.5: Code for our current loft extension

4.5.3 Conclusions

Our VisualScheme language is designed with extensibility in mind to allow for many future extensions such as adding objects, operations, and primitive hooks. The structure of the object and operations' tree is exposed to facilitate the development of analysis libraries on top of it, using the same model that will be marshaled to the *back-end*. We saw two examples of simple extensions, one to show how it is straightforward to add composite objects which can be used by any programmer and we saw how a *back-end* can add *back-end*-specific primitives with little additional effort.

Possible future extensions include support for "livecoding" [CMRW03], which comprises live performances involving music and visualizations, bi-directional coding, where the *back-end* would have hooks to recreate objects that were inserted in its workspace by means other than the VisualScheme language, or even computing deltas between the iterations of a program and only sending to the *worker program* the necessary commands to transform the objects in its workspace to those described in the new iteration of the program. Other very important extensions include analyzing the forces involved in the model and warning the architect if the object is not structurally sound or has a low thermal efficiency, which would cut on turnaround time between architects and civil engineers.

Chapter 5

Evaluating the Work

The goal of this work is to design a 3D modeling language. Care was taken to create a usable language, since most people who use CAD programs want to model more complex structures, but do not have a vast experience in programming and in programming environments. Therefore, usability, a short learning curve and the capability of generating an output that fulfills the designer's view are important. The primitives referenced here are documented on VisualScheme's manual, in appendix A.

In order to evaluate VisualScheme and its suitability for 3D modeling and teaching, several approaches were taken:

- Several architecture students were asked to opine on the designed language and help steer the direction in which it is progressing. Early feedback from the part of a group of architects was positive and further developments are expected in order for VisualScheme to be usable in the architecture course mentioned before;
- Programs from that 3D modeling course for architecture students were converted into our language. We also created several simple test programs and a more complex one, a model of Lisbon's Gare do Oriente (Fig. 5.1) in VisualScheme to illustrate how we could easily create a model with high-level parameters which could be tweaked by the designer to create several different objects.
- Designers with experience in other modeling languages and programs were also asked to implement the same model and provide feedback on the obstacles encountered.

In subsection 5.1 we describe in detail the model of Gare do Oriente, created in VisualScheme. We also analyze in detail in subsection 5.2 the modeling process that was undertaken by a student with a background on the Grasshopper visual programming plug-in for Rhino. Grasshopper is an environment for 3D modeling using visual programming which uses the Rhino modeler as *back-end*.

5.1 Modeling the Gare do Oriente

Gare do Oriente (Fig. 5.1) is an array of tree-like structures composed of metal parts, with translucent glass plates on top. The tree is composed of a main branch, with four smaller branches (beams) connected to it, which support the "leaves" Fig. 5.4a. The "leaves" are supported by smaller metallic rods which support the ceiling frame and glass plates (the "leaves" themselves).

A model was created in the VisualScheme programming language, by programming in an incremental fashion. That way, the designer can easily experiment with several parameters and correct the model, if needed. Throughout the development of this model, several test functions were written which were

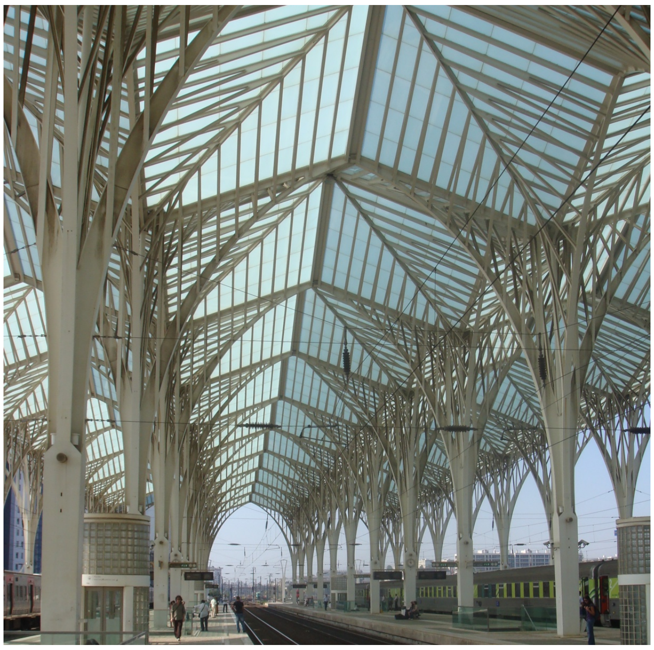


Figure 5.1: Gare do Oriente

referred to whenever any change was made to a relevant part of the program. With VisualScheme's interactive environment, the designer can write a function, evaluate it, and immediately inspect the result to see if it is the expected one. If corrections are needed, the function can be amended, re-evaluated an re-tested without re-evaluating the whole program. With these mechanisms, designers can test various models and individually test procedures that create parts of the model, building the model incrementally.

Several parameters are used throughout many functions in this model. For consistency, the same names have been given to variables which represent the same concepts. The main concepts in this model are:

`p`	A point which will serve as the anchor for the object;
`pr`	The center point of the roof;
`p0`, `p1`, `p2`, `p3`	Roof corners which will serve as anchor points for various lines;
`rho`	The radius of the beam's arches, which will influence the size of the roof;
`phi`	The starting angle (in the horizontal plane) of the object. This will allow the designer to rotate the various model parts;
`psi0`, `psi1`	The angles the beams will cover;
`n-bars`	Number of bars to use in the roof plates.

The model was divided in several basic shapes which were implemented using VisualScheme primitives (Listing 5.1). These shapes serve as abstractions over the VisualScheme primitives, to facilitate future changes, if needed. This simplified model of the Gare do Oriente has a few basic shapes: Supporting rods of various widths, the triangular glass plates on the ceiling, and the arched beams which support the structure and connect to the ceiling.

For this model, we also use several auxiliary functions to generate point sequences. The `line-sequence` function generates `n` equally spaced points between two points given as the first and second arguments. `arc-sequence` generates equally spaced (in angle) points along an arc. Its arguments are, in order, the center point (`p`), the arc's radius (`rho`), the horizontal angle (`phi`), and the start and end vertical angles (`psi0`, `psi1`). For the support beams, we needed to interpolate points through an arc, keeping them equally spaced, but only in the horizontal direction. For that, the `linear-h-arc-sequence` library function was used, which has, as arguments, the center point (`p`), the arc's radius (`rho`), the horizontal angle (`phi`), the start and end vertical angles (`psi0`, `psi1`) and the number of points to interpolate (`n`).

```
(define (support-rod-medium p0 p1)
   (make-cylinder p0 p1 0.4))

 (define (support-rod-small p0 p1)
   (make-cylinder p0 p1 0.2))

 (define (triangle p0 p1 p2)
   (do-thicken (make-region (make-line (list p0 p1 p2 p0))) 0.0001))
```

Listing 5.1: Code for the model's basic shapes

The model was started by assembling the roof plates (the glass plates and some of the supporting rods, Fig. 5.2). The roof plate is assembled by a function which abstracts some of the details. This function receives three points delimiting a triangle (the glass plates are triangles), as well as the number of rods to embed in the glass (Listing 5.2). The `rods` function takes two lists of points and creates a rod (a metal cylinder) between each corresponding pair of points in the lists. The `triangle` function calls the `make-3dface` primitive, abstracting it to account for possible changes.

```
(define (roof-plate p0 p1 p2 n)
   (unite
    (rods (line-sequence p0 p1 n)
          (line-sequence p0 p2 n))
    (triangle p0 p1 p2)))
```

Listing 5.2: Function that generates a roof plate

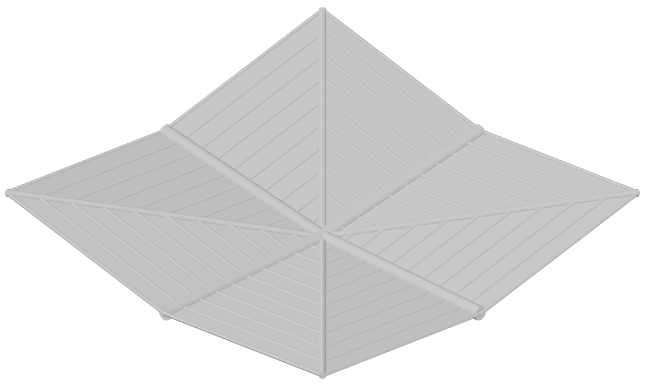


Figure 5.2: Roof plate model

After completing the ceiling plates, the next point of attack was the support beams (Listing 5.3, Fig. 5.3). The support beams' bases were abstracted by the `beam-base` function which creates a shape to be used as the profile of the beam (a 2D surface) and then sweep that shape along a spline to create the beam itself. The shape of the base is abstracted to enable an easy change of profile. For initial testing, a circle was used as the profile, but later on, the base was changed to be closer to the actual shape. The base shape is also scaled along the spline.

After completing the ceiling and the beams, we must unite them using the support rods. These support rods are completely vertical, which forces the designer to model them using an interpolation along an arc with an equal horizontal spacing between the points (instead of an equal spacing between points). The `roof-support` (Listing 5.4a) function draws these rods by iterating through sequences of points calculated by interpolation. After generating the lists, rods are created from the beam's arc points to each of the extremities' line sequences.

In the last step of the basic prototype (Listing 5.4b), we create a function which will call the previously mentioned functions, placing the sub-objects in their adequate places, forming the most basic part of

```
(define (arc-beam p rho phi psi0 psi1 n)
   (do-sweep
    (beam-base p rho phi)
    (make-spline
     (arc-sequence (+pol p rho phi) rho phi psi0 psi1 n))
    0      ;; Taper angle
    0.5)) ;; Scale
```

Listing 5.3: Function that generates a support beam

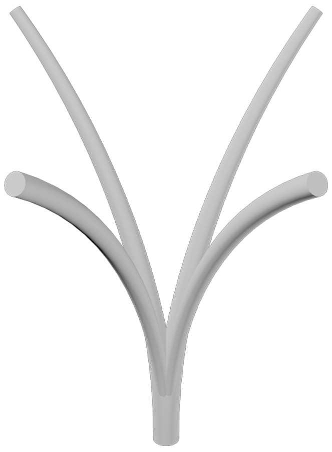
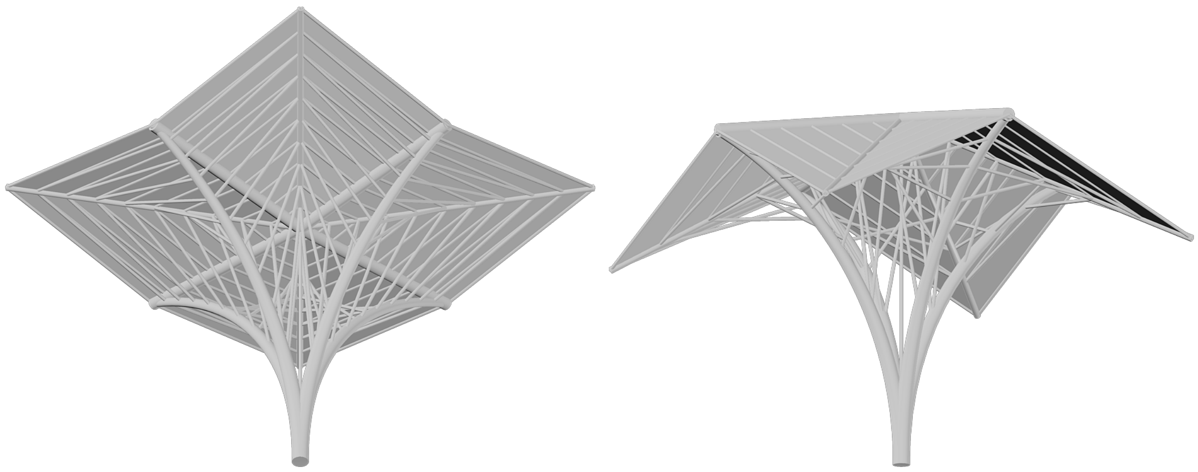


Figure 5.3: Arc beams

the station's structure, which will be tiled to create the final model. Several intermediate points are calculated: `pc` is the point of contact among the beams, *i.e.* the point where all the beams meet; `pr` is the center point of the roof (above `pc`). Each of the above described functions creates one fourth of the basic prototype. In the `beams-and-roof` function we iterate those functions through several angles, from 0 to 2π, in order to generate the whole prototype. To do this, we enumerate from 0 to 2π in four steps and call a helper function which determines where the key points of the current part will be located (the key points are the four corners of the roof) and calls all the necessary functions with adequate arguments.



(a) Prototype "tree" – Gare do Oriente (b) Another parametrization for the prototype "tree"

Figure 5.4: Different parameterizations of the prototype function

By changing the parameters of this prototype (the `beams-and-roof` function), we can build objects with very different features. The programmer can change any of the parameters and, interactively, experiment with the model's shape. As can be seen in Fig. 5.4b, where the programmer increased the angles covered by the beams. As the abstractions are built on top of each other and the parameters are channeled along the functions, the calculated points in each function will match and the model will still maintain the

```
(define (roof-support p pr rho phi psi0 psi1 p0 p1 n-bars)
   (unite
    (map (lambda (p0 p1 p2)
           (unite
            (rod p0 p1)
            (rod p0 p2)))
         (reverse (linear-h-arc-sequence p rho (+ phi pi)
                                        psi0 psi1 n-bars))
         (line-sequence pr p0 n-bars)
         (line-sequence pr p1 n-bars))))
```

(a) Roof support rods

```
(define (beams-and-roof p rho psi0 psi1 n h0 h1 n-bars)
   (let* ([pc (+z p (arc-height rho pi/2 psi1))] ;; Point of contact among beams
          [pr (+z pc (- (arc-height rho psi0 pi/2) h0))] ;; Center of ceiling
          [r (arc-width rho psi0 pi/2)])
     (define helper (phi)
       (let ([p0 (+cil pr r phi h0)]
             [p1 (+cil pr (* (sqrt 2) r) (+ phi pi/4) h1)]
             [p2 (+cil pr r (+ phi pi/2) h0)]
             [p3 (+cil pr (* (sqrt 2) r) (- phi pi/4) h1)])
         (unite (support-rod-medium pr p0)
                (support-rod-small pr p1)
                (roof-plate pr p0 p1 n-bars)
                (roof-plate pr p1 p2 n-bars)
                (arc-beam pc rho phi psi0 psi1 n)
                (roof-support pc pr rho phi psi0 psi1 p1 p3 n-bars))))
     (unite
      (map helper
           (enumerate 0 2*pi 4)))))
```

(b) Completed prototype

Listing 5.4: Prototype "tree" function, which builds one of the basic tree-like structures which will be tiled to form the building

desired properties.

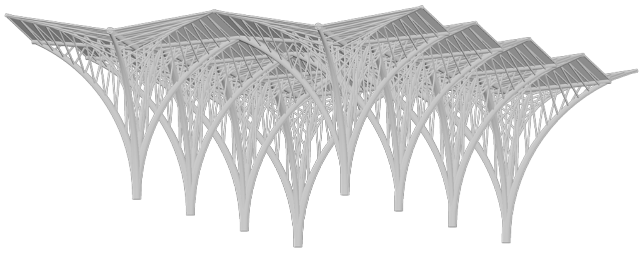


Figure 5.5: Gare do Oriente model

Finally, we distribute the prototype along the space we want to occupy with the Gare do Oriente (Listing 5.5). For this, we use the library function `distribute-in-space`. This function receives, as argument, a function that creates an object, two points which delimit the space where the first object will be placed, and the number of objects to place in the x, y, and z dimensions. The functional argument will receive a point and create an object around that point. In this example, we calculate the width of an object, so we can place the objects side by side, controlling overlap among them. The final result can be seen in Fig. 5.5.

5.2 Grasshopper Test Case

After completing the Gare do Oriente model, the same test case was given to architecture students, with a background on Grasshopper. The students were supplied with some reference pictures, not the VisualScheme model. In this section we will analyze the process of modeling a student undertook. Along the development of the Grasshopper model, feedback was gathered from its iterations.

The first attempt was made by creating the whole station as a single object, generating the roof and

```
(define (gare x y)
   (let ((rho 20)
         (psi0 (/ pi 8))
         (psi1 (/ pi 2)))
     (let ((width (* 2 (arc-width rho psi0 psi1))))
       (distribute-in-space
        (▯ (p)
           (beams-and-roof p rho psi0 psi1 30 1 3 10))
        (xyz 0 0 0)            ; origin of the box
        (xyz width width 0)    ; box boundary
        x                      ; X dimension
        y                      ; Y dimension
        1))))                  ; Z dimension
```

Listing 5.5: Function that generates the full Gare do Oriente

the pillars separately. Because of the lack of abstraction in Grasshopper, the student struggled with lists of points which, due to Grasshopper's programs' structure, can't be separated and abstracted, passing them as arguments to functions. These lists of points had to be generated in different places and, due to matching failures occurred when generating the object, as can be seen in (Fig. 5.6). These matching failures occur more frequently in Grasshopper, due to the lack of named parameters which can communicate information reliably across function calls.

The block structure is rigid and there are many connections which are difficult to track when the model's complexity grows. Even when the student tried to abstract parts of the model (by drawing a box around a set of blocks and labeling it (annotation)), the abstraction still forces the user to fully understand how it works (Fig. 5.7).[1]

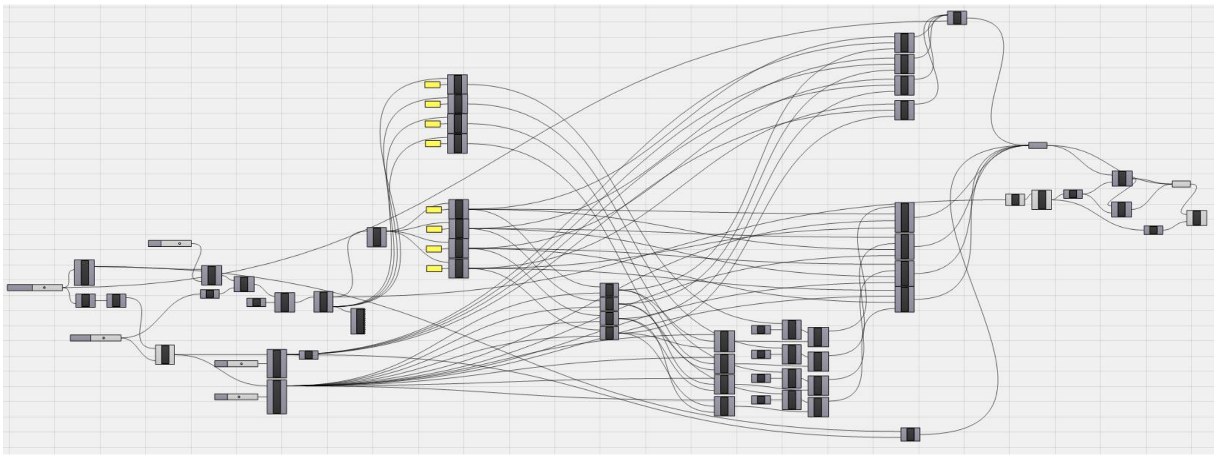
The second attempt used the same approach as the VisualScheme version described in section 5.1, *i.e.* a basic building block was designed and then an array of copies was created. The ceiling plates were defined as squares and then split in two, to create the bars. While, in the VisualScheme version, the user only needed to change one function in order to change the way these plates were built, in the Grasshopper version, the user has to alter several connections and blocks, possibly losing track of some of them.

The student also struggled with the precise control of the object's features (*e.g.* height), due to not having blocks available in Grasshopper for those purposes. The alternative would be to deviate from Grasshopper's proposed paradigm and use a block explicitly programmed in VB.NET or C# to create the arbitrary blocks needed, with appropriate inputs and outputs.

Eventually, even though steps were taken to avoid it, the complexity forced the user to create some VB.NET blocks with custom functions for sweep-related problems which were encountered during the modeling. The final model also had some parameters which could be controlled by editing VB.NET blocks, which would behave as feature selectors. This approach was chosen because, in a complex model, altering the way the model is built may involve changing many connections which, in a complex model, easily becomes unwieldy. What, in VisualScheme, can be accomplished by passing a function as a parameter, cannot be done in Grasshopper and the user must fall-back to a less flexible approach if this parametrization is desired.

If, during model building, the designer wants to add details to the model, the Grasshopper program must always be redesigned (except for very basic changes, such as changing the number of divisions of a line segment or controlling the size of basic shapes) and more connections must be added. Also with a well-abstracted model (abstracted using lines), many connections must be changed, even for a minimal change, as the abstractions do not eliminate (nor mask) these connections. Some connections may be hidden from the user (*e.g.* to aggregate all the model's parameters in the same place), but these hidden connections may, in fact, difficult the reading of the program when, later, a designer wants to understand

[1]The user can't simply use these "abstractions", *e.g.* if we abstract a beam using an annotation, the user will still have to know that a beam is an extrude along a path, find that set of blocks, and feed it with the desired parameters.


(a) Model

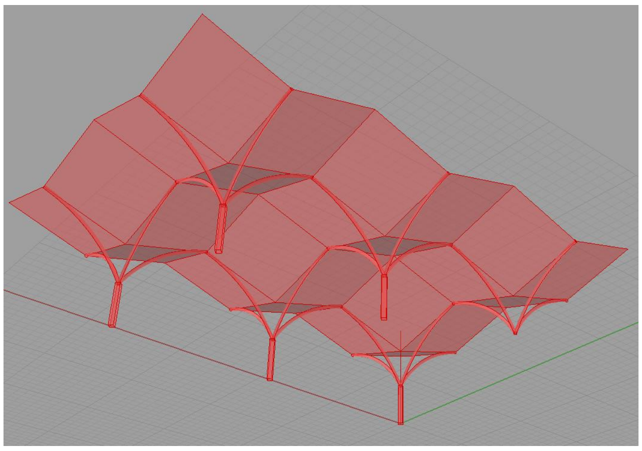
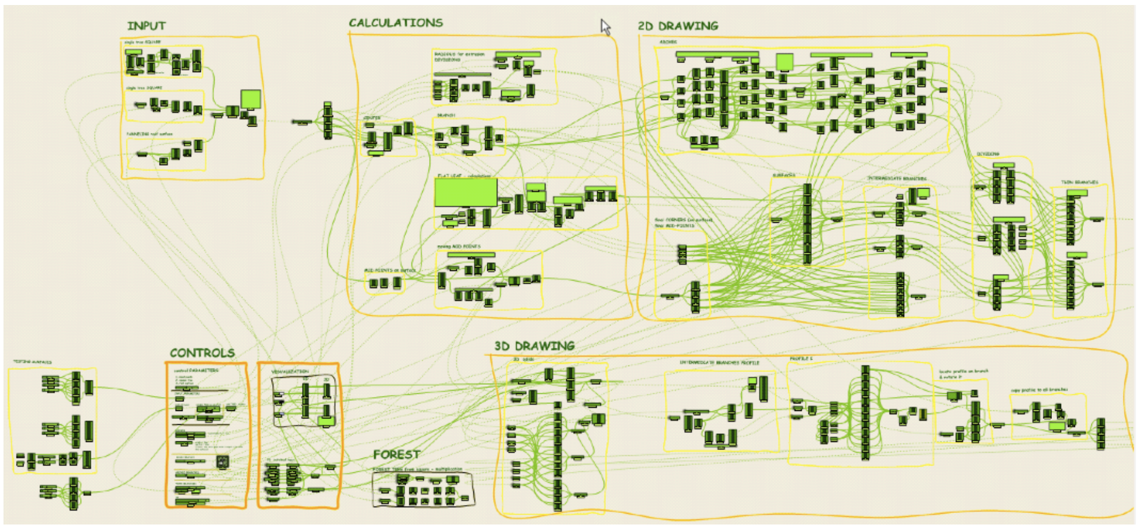
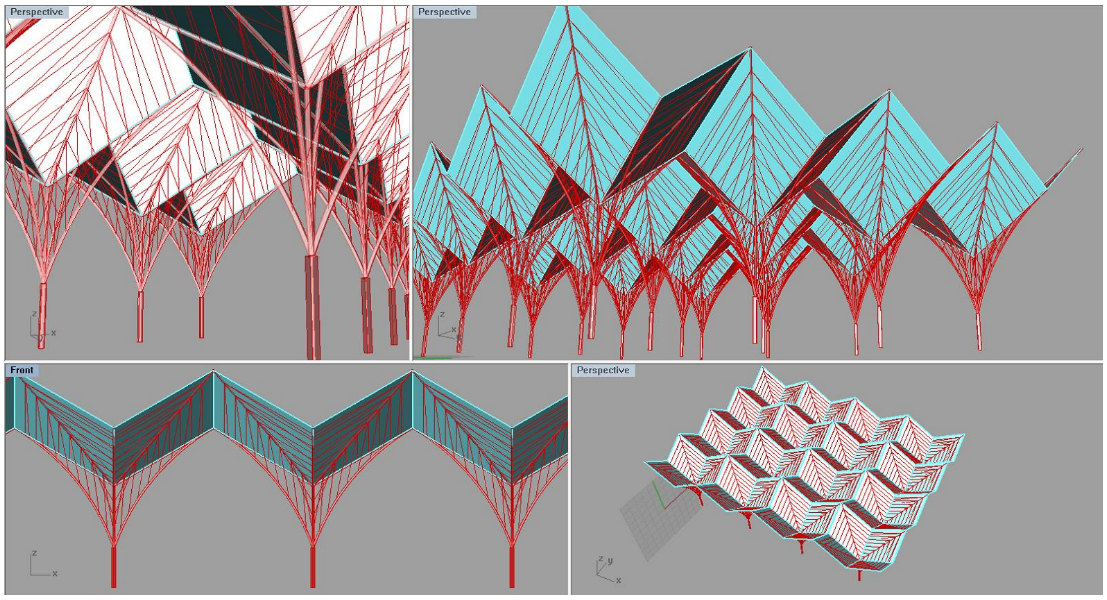

(b) Rendering

Figure 5.6: First Gare do Oriente sketch made in Grasshopper

how the program works and does not take into account some hidden connections. When deleting a set of blocks, a designer also has to take into account possibly hidden connections which may not be apparent at first. In contrast, the VisualScheme version, if abstracted properly, separates the implementation of several of the object's components. That way, one can change a part of the object without interfering in the other parts (for example, one can change the way the support beams are built without changing the implementation of the roof plates, if desired).



(a) Model



(b) Rendering

Figure 5.7: Grasshopper code for the Gare do Oriente model

Chapter 6

Conclusions

Most complex buildings are practically impossible to design manually, even with CAD tools.[1] Some means must be available in CAD programs to allow designers to express themselves without that limitation. One way to remove that limitation is to provide designers with a programming language with which they can programatically define and combine objects to form complex figures. With a programming language, designers have full control to define mathematical expressions which establish size and proportion relations among object's components and easily model objects according to those functions.

Being a project with a goal that depends not only on users' (architects) tastes, but also on the expressive power and ease of use of the language by experienced programmers, the balance of features and complexity of the language must be balanced with extreme care. The language should be easy to learn to someone experienced with CAD tools. AutoCAD is an unavoidable player in the CAD business so the language should, at the very least, be marginally familiar to someone who already uses AutoCAD's automation features.

With this work we've produced a high-level, teaching oriented (which is also adequate for a production environment) language for 3D modeling, called VisualScheme. The language is a DSL built on top of the Lisp-like language Scheme, inheriting its simple syntax and semantics. Besides retaining Scheme's characteristics, VisualScheme adds the CAD functionality on top of it, by defining the basic primitive objects and operations. This language has a common *front-end* and multiple *back-ends* available for the model output. From one programmatic definition of a 3D model we can create several ones for use in a 3D modeling program, ranging from CAD systems to simple visualizers or generating the OpenGL code to use the model in a video game. This language is extensible and the end-user (or a library developer) can extend it as needed, adding primitives for new objects, operations or other features, such as the ability to test building evacuations or optimizations on the programmed model. A *back-end* implementer may also define *back-end*-specific extensions or optimizations which will only be available in that *back-end*.

With VisualScheme's interactive environment, the designer can build models incrementally and test each part individually. Testing, amending and re-evaluating various models becomes a simpler task with immediate results, which allows the designer to experiment with different parameters until the model acquires its final form.

With this language, we open the doors to a generative architecture. Although not a complete novelty, this field of architecture was previously closed to people who did not know low-level languages like C/C++, Java or Visual Basic. With VisualScheme, we open this field to many architects who are already familiar with AutoLISP, and we provide a simple, high-level, easy to learn language to architects,

[1]Some kinds of buildings, that employ complex mathematical functions in their design can even be impossible to design manually.

whom we can teach how to use these tools to their advantage for rapid prototyping and the creation of parametrizable objects which can be used to explore a whole range of possibilities for a given architecture project, facilitating and fostering experimentation and exploration.

6.1 Future Work

Several projects may derive from this work, enhancing VisualScheme's potential as a multi-purpose language for 3D object modeling. These enhancements would make VisualScheme suitable for many more fields where modeling 3-dimensional objects is a requirement or a desired feature. From those possible enhancements, we highlight the following:

- Adding more primitives for 3D object modeling, including utility functions for other coordinate systems, support for textures or more parametrized objects and high-level operators. The creation of generic versions of some *back-end*-dependent features (such as AutoCAD's `loft`) will also be taken into account to increase the portability of 3D models;
- Incorporating VisualScheme in programming courses targeted at architecture students and teaching them how to model parametrizable 3D objects programmatically;
- Implementing more VisualScheme *back-ends*, such as a POV-Ray, Maya[2], Renderman[3];
- Translators may be created to convert POV-Ray worlds (or other 3D models from other software) into VisualScheme for use in other modeling programs for which a VisualScheme *back-end* is implemented. An AutoLISP emulation layer may also be implemented on top of VisualScheme, in order to ease the transition for AutoLISP users who already have sizable AutoLISP libraries and programs;
- Extending DrScheme or creating a new IDE for VisualScheme, to aid students and professionals in their 3D modeling by offering visual cues and low detail previews of the objects currently being modeled in the IDE, *on-the-fly*;
- Implementing the ability to round-trip between a VisualScheme program and the *back-end*, in order to ease the translation of any changes made to the project outside VisualScheme to the original source program (for example, when sharing the project with a civil engineer which can annotate our project);
- Using the ability to model 3D objects and using the same model to test for structural integrity, evacuation strategies in case of fire or other hazards, among other applications;

[2] `http://autodesk.com/maya`
[3] `https://renderman.pixar.com/`

Appendix A

VisualScheme Manual

In this chapter, we define the VisualScheme language's primitive objects and operations. VisualScheme's syntax is the same as PLT Scheme's [FFS08], except where otherwise noted. Manual entries are presented as follows:

Object

```
(obj argument-1)
(obj [argument-1 positive?] argument-2 . [rest (list-of number?)])
```

Also seen in: AutoCAD, GML

This entry describes the constructors of an hypothetical object. This object may be constructed using a procedure of one or two or more arguments. The first version (which has exactly one argument) can be called with arguments of any type. The second version may be called with two or more arguments. The first argument must be a positive number, the second argument has no type restrictions, while the arguments after it, if provided, must be numbers. This is accomplished using typing predicates.

A typing predicate is a procedure which must return true (`#t`) when called with an object of that type as argument. Any VisualScheme procedure may be used as a typing predicate. Typing predicates may also be created using the built-in helpers: `list-of`, `and` and `or`. The `list-of` helper provides a way to apply a typing predicate to every member of a list. The `and` and `or` helpers allow the typing of conjunctions and disjunctions of properties (for example, a natural number will obey a predicate of `(and integer? positive?)`). The `object?` typing predicate identifies one of VisualScheme's 3D objects by returning `#t` if its argument is the result of a VisualScheme primitive or operation. Data types are available for points (`point`), vectors (`gvector`), axis (`axis`) and planes (`plane`).

In the following sections a description of VisualScheme's available primitives and operations are presented, along with their constructor's arguments. A reference is also made to some other languages or CAD products where a similar primitive/operation can be found.

A.1 Primitives

A.1.1 2D Primitives

3DFace

```
(make-3dface [p1 point-3d?] [p2 point-3d?] [p3 point-3d?] [p4 point-3d?])
```

Also seen in: AutoCAD and stuff

Creates a solid-filled area (2D) between the specified four points. The points must be non-collinear.

Arc

```
(make-arc [c point?] [r positive?] [angle real?])
(make-arc [c point?] [r positive?] [start-angle real?] [end-angle real?])
```
Also seen in: AutoCAD, GML, and others

Creates an arc perpendicular to the Z axis, with the center at `c`, radius of `radius` units, from zero to `angle` radians. The four argument version is equivalent, but starts at `start-angle` radians and creates an arc with (`end-angle` − `start-angle`) radians.

Circle

```
(make-circle [c point?] [r point?])
```
Also seen in: AutoCAD, POV-Ray, GML

Creates a circle with center in `c` and a radius of `r` units. Similar to the `ellipse` with `r1` = `r2`.

Donut

```
(make-donut [c point?] [r1 positive?] [r2 positive?])
```
Also seen in: AutoCAD, PLaSM

Creates a circle of radius `r1` with a hole in the middle, of radius `r2`. Both the circle and the hole are centered at point `c`.

Ellipse

```
(make-ellipse [c point?] [r1 positive?] [r2 positive?])
```
Also seen in: AutoCAD, GML, and others

Creates an ellipse with center at `c`, and radii `r1` and `r2`.The radius defined by `r1` will be parallel to the X axis, while the one defined by `r2` will be parallel to the Y axis.

Filled region

```
(make-region [l primitive?])
```
Also seen in: AutoCAD, at least

Creates a solid-filled region with `l` as its delimiter line, which has to be closed.

Infinite line

```
(make-xline [p1 point?] [p2 point?])
```
Also seen in: AutoCAD, at least

Creates an infinite line which passes through both `p1` and `p2`.

Line

```
(make-line [p1 point?] [p2 point?])
(make-line [pts (list-of point?)])
```

Also seen in: AutoCAD, X3D, GML, and others

Creates a line between `p1` and `p2`. The second version creates a line which passes by all the points given as arguments, in order.

Parametric surface

```
(make-surface [f procedure?] [u-min real?] [u-max real?] [v-min real?] [v-max real?])
(make-surface [f procedure?])
(make-surface [fx procedure?] [fy procedure?] [fz procedure?])
(make-surface [fx procedure?] [fy procedure?] [fz procedure?]
              [u-min real?] [u-max real?] [v-min real?] [v-max real?])
```

Also seen in: AutoCAD (surface from a set of points), PLaSM

Creates a parametric surface using the procedure passed as argument as generator. Two possibilities exist for the procedures: Either a single procedure (`f`) will yield a 3-dimensional point, given the u and v coordinates in the surface, or 3 procedures (`fx`, `fy` and `fz`) will yield each of the point's coordinates (x, y and z, respectively). The points that result from applying the procedure(s) to every point with coordinates between (`u-min`, `v-min`) and (`u-max`, `v-max`) will be part of the surface.

Ray

```
(make-ray [p point?] [dir gvector?])
```

Also seen in: AutoCAD, POV-Ray

Creates a ray, which is a line finite in one direction and infinite in the other. The ray will start at `p1` and follow the direction of the `dir` vector.

Spline

```
(make-spline [pts (list-of point?)] [start-tg number?] [end-tg number?])
(make-spline [pts (list-of point?)])
(make-spline [pt1 point?] [pt2 point?] . [pts (list-of point?)])
```

Also seen in: AutoCAD, GML, and others

Creates a spline passing through all the points in `pts` (and `pt1`, `pt2`, if applicable), with parameterizable start and end tangents (using `start-tg` and `end-tg`).

Text

```
(make-text [origin point?] [size (and integer? positive?)] [str string?])
```

Also seen in: AutoCAD, GML, POV-Ray

Creates a text, with `origin` as its lower-left point, of size `size`, with `string` as its content.

A.1.2 3D Primitives

Box

```
(make-box [p1 point?] [p2 point?])
(make-box [c point-3d?] [w positive?] [l positive?] [h positive?])
```
Also seen in: AutoCAD, GML, X3D

The first version creates a box between `p1` and `p2`, while the second version creates a box with center at `c`, with width `w`, length `l` and height `h`.

Cone

```
(make-cone [c1 point?] [c2 point?] [r positive?])
```
Also seen in: AutoCAD, POV-Ray, X3D

Creates a cone with its base at `c1`, with radius `r` and endpoint at `c2`.

Cut cone

```
(make-cut-cone [c1 point?] [r1 positive?] [c2 point?] [r2 positive?])
```
Also seen in: AutoCAD, POV-Ray, PLaSM

Creates a cone with its top truncated. The bottom base will be centered at `c1` with a radius of `r1`, while the top base will be centered at `c2` with `r2` as its radius.

Cylinder

```
(make-cylinder [c1 point-3d?] [h positive?] [r positive?])
(make-cylinder [c1 point-3d?] [c2 point-3d?] [r positive?])
```
Also seen in: AutoCAD, POV-Ray, X3D

Creates a cylinder with a base in `c1`, a radius `r` and a height `h` (parallel to the Z axis). The alternative version creates a cylinder with its bases at `c1` and `c2`, with a radius `r`.

Elliptical cone

```
(make-e-cone [c1 point-3d?] [r1 positive?] [r1* positive?] [c2 point-3d?] [r2 positive?])
```
Also seen in: AutoCAD, PLaSM, GML

Creates an elliptical cone (a cone with an ellipse as its base). The lower base will be centered at `c1` while the upper base will be centered at `c2`. The major and minor radii of the lower base are given by `r1` and `r1*`, while the major radius of the upper base is given by `r2` (both bases share the same ratio between radii).

Mesh

```
(make-mesh [pts-array (list-of (list-of point-3d?))])
```
Also seen in: AutoCAD (3DMESH), POV-Ray, GML

Creates a mesh object with the points specified in the array. The array must be rectangular (with $M \times N$ points).

Polyface Mesh

```
(make-polyface-mesh [verts point-3d?] [faces (list-of (list-of (and positive? integer?)))])
```
Also seen in: AutoCAD (PFACE), POV-Ray, PLaSM

Creates a 3-dimensional mesh object with the faces defined in the `faces` array. the `faces` array will contain sets of numbers which index the `verts` list, creating faces with the referenced vertices.

Pyramid

```
(make-pyramid [c1 point?] [r positive?] [s (and integer? positive?)] [c2 point?])
(make-pyramid [c1 point?] [r positive?] [s (and integer? positive?)] [c2 point?]
              [r2 positive?])
```
Also seen in: AutoCAD, GML

Creates a pyramid of `s` sides, between `c1` and `c2`. Its lower base (centered at `c1`) will have radius `r`. Its upper base will either be an endpoint (first version) or have `r2` radius.

Sphere

```
(make-sphere [c point-3d?] [r positive?])
```
Also seen in: AutoCAD, GML, PLaSM

Creates a sphere with center `c` and radius `r`.

Superellipsoid

```
(make-supperellipsoid [e positive?] [n positive?] [s positive?])
```
Also seen in: POV-Ray

Creates a superquadric ellipsoid, which can be used to create boxes and cylinders with round edges, among other interesting shapes. The superquadric ellipsoid is described by the following equation, occupying roughly the same space as the result of `(make-box (xyz (- s) (- s) (- s)) (xyz s s s))`:

$$f(x,y,z) \quad = \quad \left(|x|^{\left(\frac{2}{e}\right)} + |y|^{\left(\frac{2}{e}\right)}\right)^{\left(\frac{e}{n}\right)} + |z|^{\left(\frac{2}{n}\right)} \quad = \quad s$$

Torus

```
(make-torus [c point-3d?] [r positive?] [t-r positive?])
```
Also seen in: AutoCAD, GML, X3D

Creates a torus centered in `c`, with a radius `r` and a tube radius of `t-r`.

Wedge

```
(make-wedge [p1 point?] [p2 point?])
(make-wedge [c point-3d?] [l positive?] [w positive?] [h positive?])
```
Also seen in: AutoCAD, GML

Creates a wedge between `p1` and `p2`. The second version creates a wedge with a center in `c`, width `w`, height `h` and length `l`.

A.1.3 Operations

Edges

```
(do-edges [object object?])
```
Also seen in: AutoCAD, PLaSM

Yields the wireframe of a 3D object.

Extrusion

```
(do-extrude [surf object?] [p (or positive? vector-3d? primitive?)])
(do-extrude [surf object?] [p (or positive? vector-3d? primitive?)] [taper real?])
```
Also seen in: GML, POV-Ray

Extrudes a surface `surf` along a line `p`, tapering `taper-angle` radians. If `p` is a number, extrudes `p` units in the Z direction. If it is a vector or a line (straight or curved), extrusion is performed in its direction.

Guided loft

```
(do-guided-loft [objects (list-of object?)] [guides (list-of primitive?)])
(do-guided-loft [objects (list-of object?)] [path primitive?])
```
Also seen in: AutoCAD, PLaSM

Lofts the objects passed in `objects` either using guides of a path. If using guides, the objects will be lofted using the objects in the second argument as guide curves, tracing the path of matching points along the guides. If a path is used, the objects are traced along that path.

Intersection

```
(intersect [args (list-of object?)])
```
Also seen in: AutoCAD, POV-Ray, GML

Yields the intersection of all the objects passed as arguments.

Loft

```
(do-loft [objects (list-of object?)])
(do-loft [objects (list-of object?)] [a1 real?] [m1 positive?] [a2 real?] [m2 positive?])
```
Also seen in: AutoCAD, PLaSM

Lofts the shapes in the list passed as the `objects` argument. The version with one argument behaves as if 0 was passed as every argument except the first. The `a1`, `m1`, `a2` and `m2` control, respectively, the draft angle and magnitude of the first and last cross sections of the lofted object.

Mirror

```
(do-mirror [object object?] [plane plane?])
```
Also seen in: AutoCAD, PLaSM

Mirrors an object with relation to a given plane.

Move

```
(do-move [object object?] [vector gvector?])
```
Also seen in: AutoCAD, POV-Ray, GML, PLaSM

Displaces an object in the direction of `vector`.

Offset

```
(do-offset [line object?] [distance real?])
```
Also seen in: AutoCAD, PLaSM

Offsets a line (straight or curved), for a specified `distance`. Offset lines are always parallel (or concentric, if offsetting an arc or circle) to the original object.

Revolution

```
(do-revolve [surface object?] [axis axis?])
(do-revolve [surface object?] [axis axis?] [start-angle real?] [end-angle real?])
```

Revolves a surface along an axis, between `start-angle` and `end-angle`. If the latter arguments are not supplied, they are assumed as 0 and 2π radians, respectively.

Rotation

```
(do-rotate [object object?] [axis axis?] [angle real?])
(do-rotate [object object?] [point point?] [vector gvector?] [angle real?])
```
Also seen in: AutoCAD, POV-Ray, GML

Rotates the specified `object` along the given `axis`, using the axis' point of reference as the origin, for the specified angle. The axis may be given as an `axis` object or as a separate point and geometrical vector.

Ruled loft

```
(do-ruled-loft [objects (list-of object?)])
```
Also seen in: AutoCAD, PLaSM

Creates a ruled loft with the specified objects. The loft will be straight, with sharp edges at the cross-sections.

Scale

```
(do-scale [object object?] [point point?] [factor positive?])
```
Also seen in: AutoCAD, GML

Scales an `object` to `factor` times its original size, using `point` as reference.

Slice

```
(do-slice [object object?] [plane plane?])
```
Also seen in: AutoCAD, POV-Ray

Slices the `object` along the specified `plane`, keeping the portion which is in the plane's normal direction.

Subtraction

```
(subtract [object object?])
(subtract [object object?] . [args (list-of object?)])
```
Also seen in: AutoCAD, PLaSM, GML

Subtracts from the first argument the union of all the other arguments, yielding the resulting object. In the version with only one argument, the result is a procedure which will receive as arguments the objects to subtract.

Sweep

```
(do-sweep [surface primitive?] [path primitive?])
(do-sweep [surface primitive?] [path primitive?] [twist real?] [scale positive?])
```
Also seen in: AutoCAD, GML, PLaSM

Similar to an extrusion but aligns the `surface` with the `path`. A sweep can also be parameterized with a `twist` angle (the amount of twist the surface will suffer along the path) and a `scale` factor. The `twist` and `scale` parameters have a default of 0 and 1, respectively.

Thicken

```
(do-thicken [line object?] [width positive?])
```
Also seen in: AutoCAD, GML

Creates a 3D solid from a 2D surface or line, by thickening it.

Transform

```
(do-transform [object object?] [matrix matrix?])
```
Also seen in: AutoCAD, POV-Ray, GML

Transforms an object according to a 4x4 transformation matrix.

Union

```
(unite [args (list-of object?)])
```
Also seen in: AutoCAD, PLaSM, GML

Yields an object representing the union of all the objects passed as arguments.

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