ILLUSTRATED PROGRAMMING

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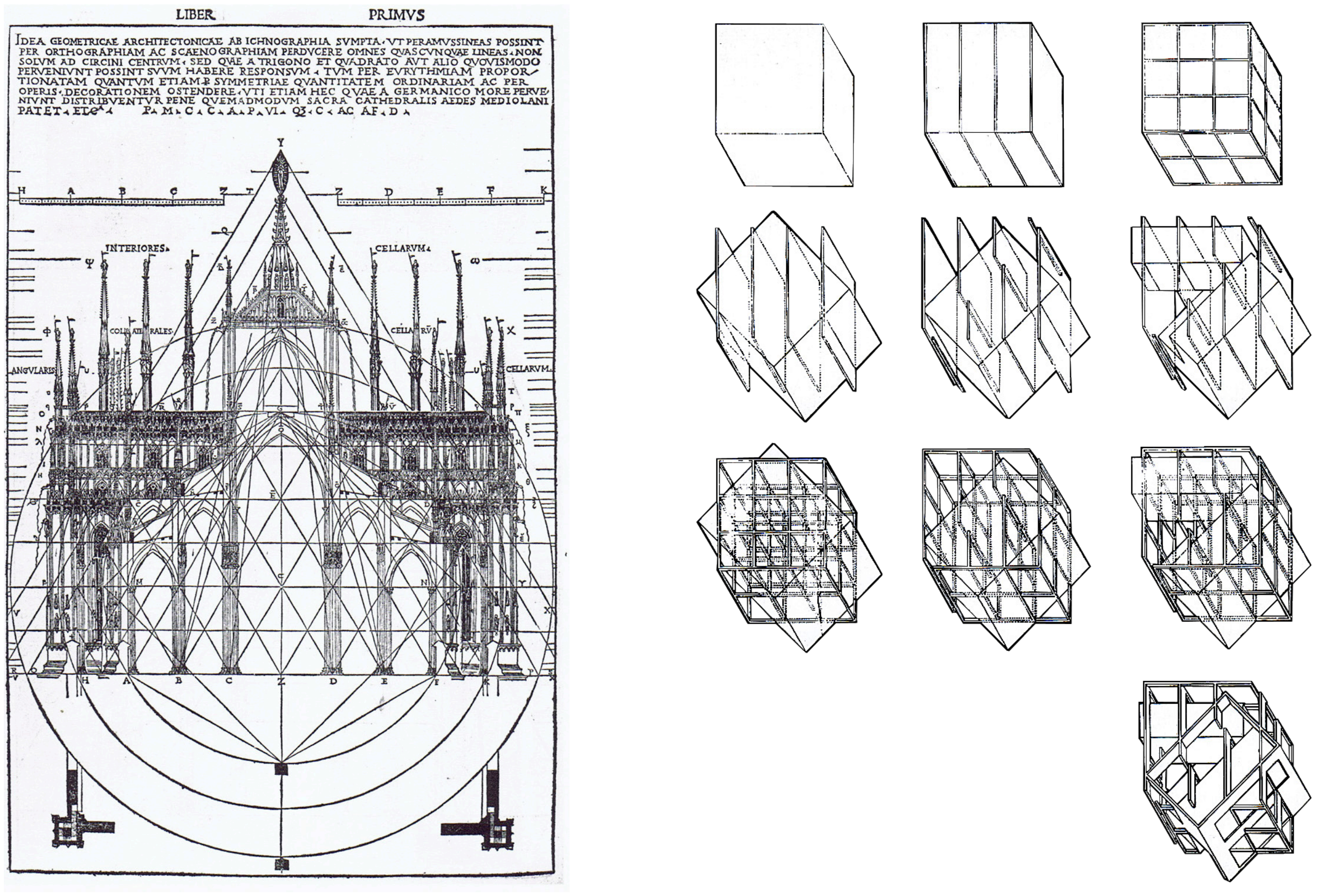
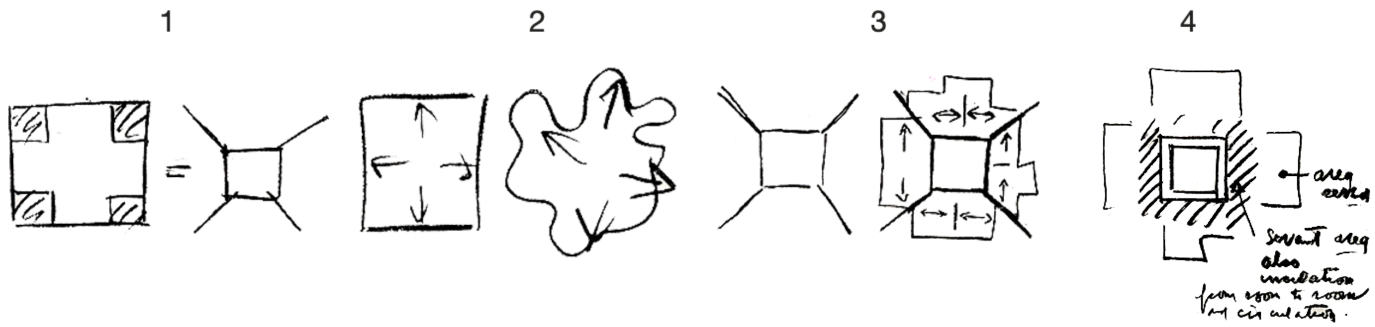


1 On the left, the geometric structure and system of proportions of Milan's cathedral, depicted by Cesare Cesariano in his translation and illustration of Vitruvius' De Architectura (1521). On the right, Peter Eisenman's (1961-1971) diagrams for House III (Miller House) show the evolution of the concept through a sequence of rotations of orthogonal grids.

ABSTRACT

In the area of *Generative Design*, programs are becoming increasingly complex and harder to understand, communicate, and share, enlarging the gap between them and the architectural concepts they implement. To overcome this problem, we need to develop documentation techniques and program comprehension tools targeted to the *Generative Design* domain. This paper proposes *Illustrated Programming* as a coherent approach for improving program documentation and program comprehension, by establishing a correlation between the intended design, the *Generative Design* program, and the generated model. This correlation is achieved by the inclusion of sketches within programs and by bidirectional traceability and immediate feedback between programs and models.



2 Series of annotated sketches for the Goldberg House design in Rydal, Pennsylvania, United States, by Louis I. Kahn

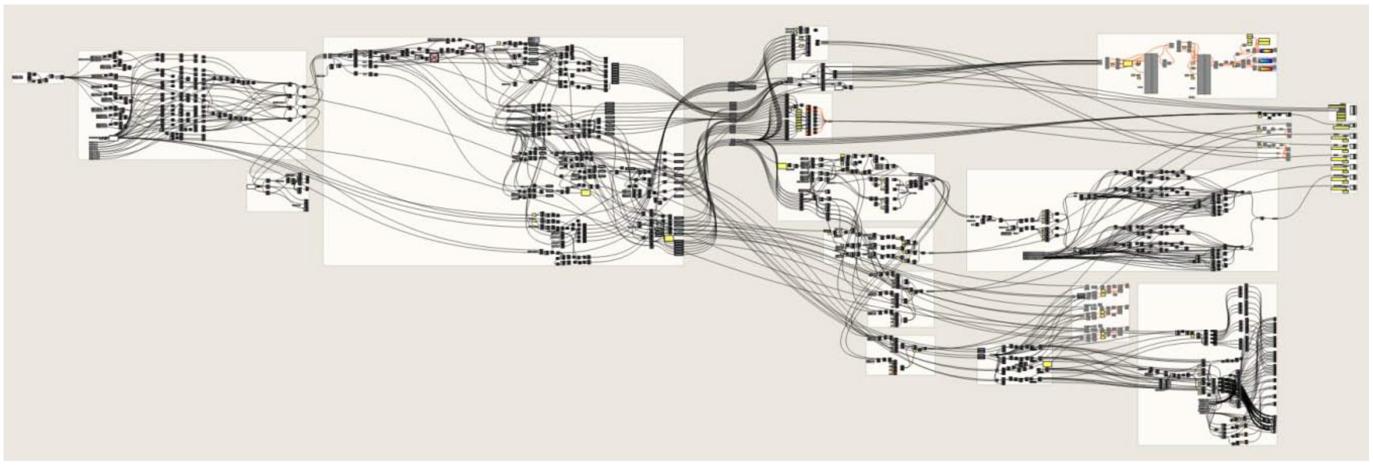
INTRODUCTION

Architects have always been concerned with explaining their designs and, given that most of the architectural work has a strong visual component, it is not surprising that drawings are the preferred media for those explanations. In fact, ever since the invention of linear perspective by Brunelleschi (Tsuji, 1990), the act of *projectum* (interpreted here in its Latin sense of anticipating a reality) has been being quintessential to the architectural practice. As an example, consider (Figure 1), which shows two sets of drawings separated by 440 years of architecture, proving that the importance of drawing has not changed over time in this field.

Drawings are powerful design tools because they convey complex ideas in a compact medium. Although the creative process in architecture is not linear, architects can synthesize the different design steps into a logical sequence of diagrams/sketches, which in the end clearly document the design decisions, the relationships between different parts of the design, and the impact of external factors in the final shape. This kind of illustrated narrative is extremely effective in telling the story of a specific design as well as a way of thinking about and solving design problems (Do et al., 2001), therefore, it has been extensively used, namely, in pedagogical books, empirical studies of drawing in design, and architectural publications and competitions. (Figure 2) shows a sequence of manually sketched diagrams from Louis I. Khan's Goldberg House.

The need for documenting the design process is evident, particularly in architectural projects developed (partially or fully) through *Generative Design* (*GD*) programs. By *Generative Design*, we refer to the use of algorithms, implemented through programming languages, to create geometric shapes. Due to the increased complexity of both *GD* programs descriptions and the shapes those programs can achieve, explaining a program's structure, behavior, and parameters, is critical.

By definition, the *GD* program can itself be considered a description of a design, as it formally specifies the modeling process of the design. Unfortunately, this formal specification can only be easily understood for simple design problems. For any sufficiently complex program, it is additionally helpful to have program documentation and tools for program comprehension. (Storey, 2006)



3 The complete Grasshopper program for the Hangzhou Tennis Stadium

PROGRAM DOCUMENTATION

Program documentation is very important for software development and maintenance (Souza et al., 2005). Unfortunately, writing documentation is perceived as a tiresome task and thus avoided. This negatively affects software development in general and *GD* in particular. In the current state of *GD*, program documentation is generally poor, making it very difficult not only to understand any non-trivial *GD* program, but also to share, adapt, and extend such programs.

In fact, the little documentation that does exist comes in books and research papers, where fragments of programs (McCullough, 2006, Silver, 2006, Preisinger, 2013, Hemmerling, Marco and Lemberski, 2012) or even entire programs (Williams, Chris J. K. and Kontovourkis, 2008) are proudly presented as illustrations or even used as background images. While in many cases these do achieve interesting aesthetic results (Miller, 2011), as is visible in (Figure 3), their explanatory power is limited, and the program that is being illustrated is, in general, much larger than what can reasonably fit in one or two pages. This forces authors to drastically zoom out the program, rendering it unreadable (Castro e Costa, 2012) or to present only a handful of small program fragments (Buell et al., 2011), leaving the rest undocumented. In the end, these programs are not useful as program documentation: they are merely used to show the kind of programming that is used (for example, textual or visual) or the degree of complexity reached in the elaboration of the *GD* program.

When program documentation is poor, obsolete, or absent, the remaining option is to study the program itself, a process known as program comprehension.

PROGRAM COMPREHENSION

Program comprehension is the process of acquiring knowledge about a program (Rugaber, 1995), which allows us to create a mental model of the program's structure and behavior. This is a necessary step before making any modifications to the program. When there is not enough documentation, this mental model must be constructed from reading the program. Unfortunately, due to the large amount of detail required by current programming languages, designers must spend a significant mental effort to extract the relevant architectural ideas from the irrelevant details.

In the field of *GD*, the relevant architectural ideas are conveyed in the form of geometric models. In order to adapt the program to generate a different geometry, it is first necessary to understand the relationship between the program and the generated model.

It is thus important to correctly identify which part of the program is responsible for a given part of the generated model and which parts of the model were generated by a given part of the program. This identification is normally not trivial, but, as we will show, it can be drastically improved with adequate tools.

ILLUSTRATED PROGRAMMING

In order to (1) mitigate the problem of lack of documentation and (2) improve program comprehension, this paper proposes *Illustrated Programming* (*IP*), a programming approach that establishes a correlation between the intended design, the corresponding *GD* program, and the generated models. This correlation encompasses two independent but related ideas:

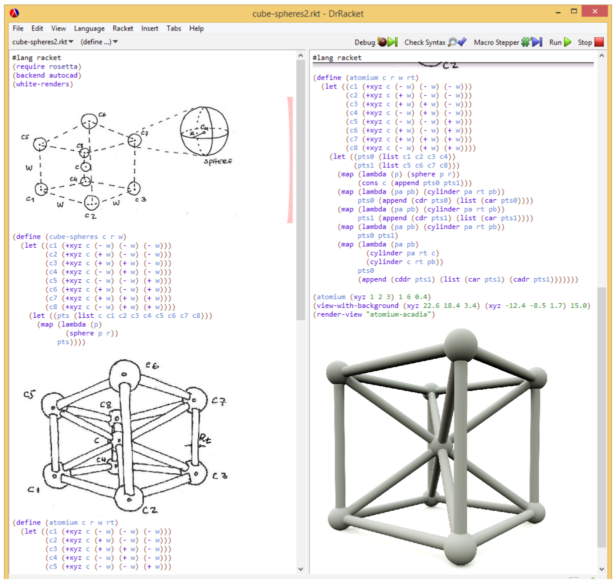
1. Sketch-program correlation, where sketches embedded directly in the program document the correlation between architectural concepts and the corresponding parts of the *GD* program
2. Program-model correlation, where the *Integrated Development Environment (IDE)* allows the user to identify which parts of the program are responsible for which parts of the generated model and vice-versa

In short, the sketch-program correlation provides an explanation for the structure of a *GD* program whereas the program-model correlation provides an explanation for its behavior. In the next sections we detail these two aspects of *IP* and explain its implementation in Rosetta, a development environment for portable *Generative Design* (Lopes, José and Leitão 2011).

SKETCH-PROGRAM CORRELATION

In the past, there were attempts in the field of software engineering to improve the quality of program documentation, most prominently, literate programming, a programming paradigm that promoted the fact that programs are written for people first and foremost, and that documentation should be emphasized just as much as code. Unfortunately, these attempts did not reach the intended goals, mainly because writing good documentation takes a considerable amount of time and effort.

However, the reality in architecture is quite different from that in software engineering: it is part of the design process to produce documentation in the form of sketches. This means that it is not


cube-spheres2.rkt - DrRacket
File Edit View Language Racket Insert Tabs Help
cube-spheres2.rkt (define ...)
Debug Check Syntax Macro Stepper Run Stop
c5
c6
c7
c8
c
c4
w
c1
w
c2
w
c3
Cm
R
sphere
Rt

```
#lang racket
(require rosetta)
(backend autocad)
(white-renders)

(define (cube-spheres c r w)
  (let ((c1 (+xyz c (- w) (- w) (- w)))
        (c2 (+xyz c (+ w) (- w) (- w)))
        (c3 (+xyz c (+ w) (+ w) (- w)))
        (c4 (+xyz c (- w) (+ w) (- w)))
        (c5 (+xyz c (- w) (- w) (+ w)))
        (c6 (+xyz c (+ w) (- w) (+ w)))
        (c7 (+xyz c (+ w) (+ w) (+ w)))
        (c8 (+xyz c (- w) (+ w) (+ w))))
    (let ((pts (list c c1 c2 c3 c4 c5 c6 c7 c8)))
      (map (lambda (p)
             (sphere p r))
           pts))))

(define (atomium c r w rt)
  (let ((c1 (+xyz c (- w) (- w) (- w)))
        (c2 (+xyz c (+ w) (- w) (- w)))
        (c3 (+xyz c (+ w) (+ w) (- w)))
        (c4 (+xyz c (- w) (+ w) (- w)))
        (c5 (+xyz c (- w) (- w) (+ w)))
```

```
#lang racket

(define (atomium c r w rt)
  (let ((c1 (+xyz c (- w) (- w) (- w)))
        (c2 (+xyz c (+ w) (- w) (- w)))
        (c3 (+xyz c (+ w) (+ w) (- w)))
        (c4 (+xyz c (- w) (+ w) (- w)))
        (c5 (+xyz c (- w) (- w) (+ w)))
        (c6 (+xyz c (+ w) (- w) (+ w)))
        (c7 (+xyz c (+ w) (+ w) (+ w)))
        (c8 (+xyz c (- w) (+ w) (+ w))))
    (let ((pts0 (list c1 c2 c3 c4))
          (pts1 (list c5 c6 c7 c8)))
      (map (lambda (p) (sphere p r))
           (cons c (append pts0 pts1)))
      (map (lambda (pa pb) (cylinder pa rt pb))
           pts0 (append (cdr pts0) (list (car pts0))))
      (map (lambda (pa pb) (cylinder pa rt pb))
           pts1 (append (cdr pts1) (list (car pts1))))
      (map (lambda (pa pb) (cylinder pa rt pb))
           pts0 pts1)
      (map (lambda (pa pb)
             (cylinder pa rt c)
             (cylinder c rt pb))
           pts0
           (append (cddr pts1) (list (car pts1) (cadr pts1)))))))

(atomium (xyz 1 2 3) 1 6 0.4)
(view-with-background (xyz 22.6 18.4 3.4) (xyz -12.4 -8.5 1.7) 15.0)
(render-view "atomium-acadia")
```

4 Two strips of an illustrated program containing the initial sketches, the source code, and also a final rendering

necessary to write huge amounts of textual documentation to explain a *GD* program. We only need to annotate the already existing sketches and combine them with the program, thus providing visual explanations of what the program is supposed to do.

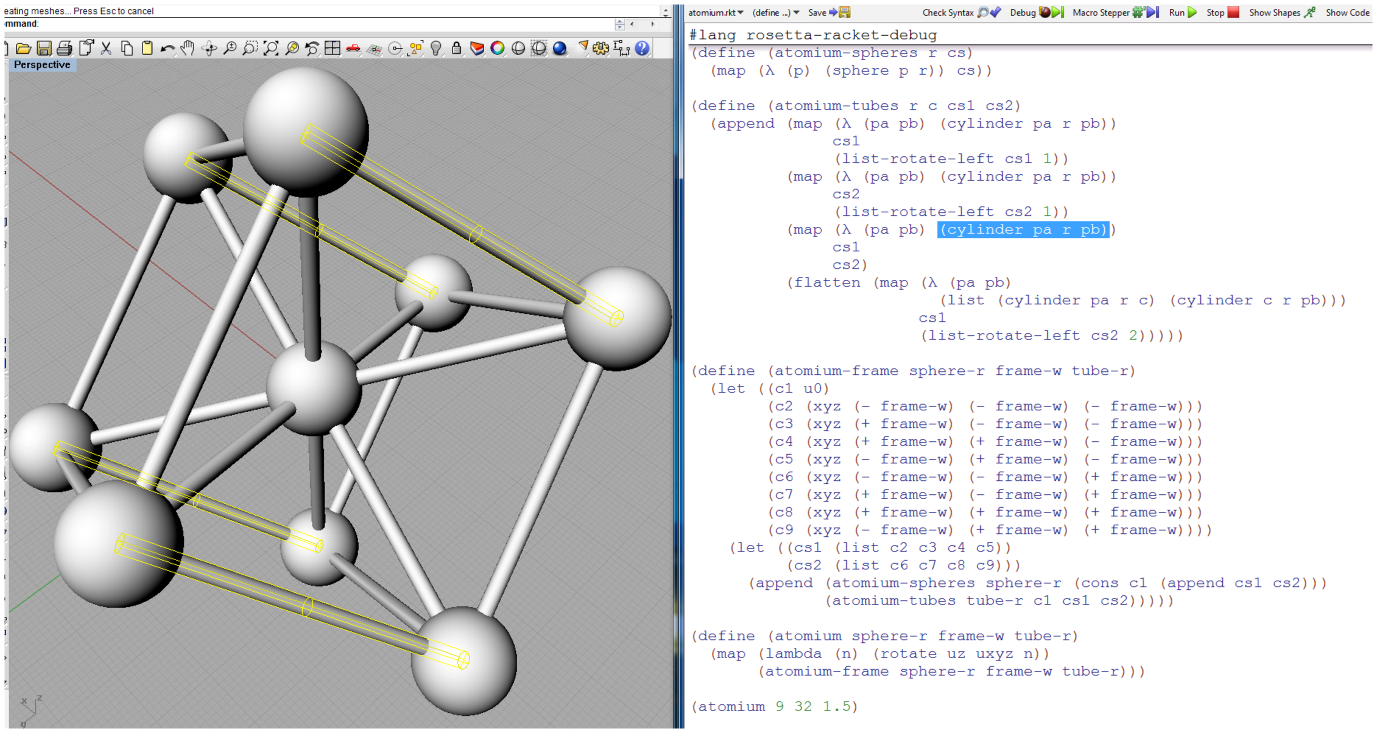
(Figure 4) shows Rosetta, which runs in DrRacket (a descendant of DrScheme (Findler et al., 2002), implementing this process. In the image, we can see sketches developed by the designer for the Atomium building, that explain to the programmer the intended design, alongside the program that implements it. Note the annotations on the sketches, which clearly identify the parameters of the program.

Although, in many cases, a designer and a programmer are a same person, this is not strictly necessary. Actually, this approach also promotes collaborative design processes, where each participant assumes a different role (Santos et al., 2012). In the presented case, the designer and the programmer were in fact in two different continents.

Using sketches as documentation and combining them with the *GD* program allows us to establish a Sketch-program correlation. However, this correlation does not tie in any way the program code with the produced 3D model, which we discuss in the following section.

PROGRAM-MODEL CORRELATION

In *GD*, the designer interacts with a computer program, which can be seen as an intermediary between the concept the designer wants to achieve and the geometric model produced by that



```
#lang rosetta-racket-debug
(define (atomium-spheres r cs)
  (map (λ (p) (sphere p r)) cs))

(define (atomium-tubes r c cs1 cs2)
  (append (map (λ (pa pb) (cylinder pa r pb))
               cs1
               (list-rotate-left cs1 1))
          (map (λ (pa pb) (cylinder pa r pb))
               cs2
               (list-rotate-left cs2 1))
          (map (λ (pa pb) (cylinder pa r pb))
               cs1
               cs2)
          (flatten (map (λ (pa pb)
                          (list (cylinder pa r c) (cylinder c r pb)))
                        cs1
                        (list-rotate-left cs2 2)))))

(define (atomium-frame sphere-r frame-w tube-r)
  (let ((c1 u0)
        (c2 (xyz (- frame-w) (- frame-w) (- frame-w)))
        (c3 (xyz (+ frame-w) (- frame-w) (- frame-w)))
        (c4 (xyz (+ frame-w) (+ frame-w) (- frame-w)))
        (c5 (xyz (- frame-w) (+ frame-w) (- frame-w)))
        (c6 (xyz (- frame-w) (- frame-w) (+ frame-w)))
        (c7 (xyz (+ frame-w) (- frame-w) (+ frame-w)))
        (c8 (xyz (+ frame-w) (+ frame-w) (+ frame-w)))
        (c9 (xyz (- frame-w) (+ frame-w) (+ frame-w))))
    (let ((cs1 (list c2 c3 c4 c5))
          (cs2 (list c6 c7 c8 c9)))
      (append (atomium-spheres sphere-r (cons c1 (append cs1 cs2)))
              (atomium-tubes tube-r c1 cs1 cs2)))))

(define (atomium sphere-r frame-w tube-r)
  (map (lambda (n) (rotate uz uxyz n))
       (atomium-frame sphere-r frame-w tube-r)))

(atomium 9 32 1.5)
```

5 Relating program expressions to the generated shapes. The highlighted cylinders (on the left, in yellow) are generated by the highlighted program text (on the right, in blue).

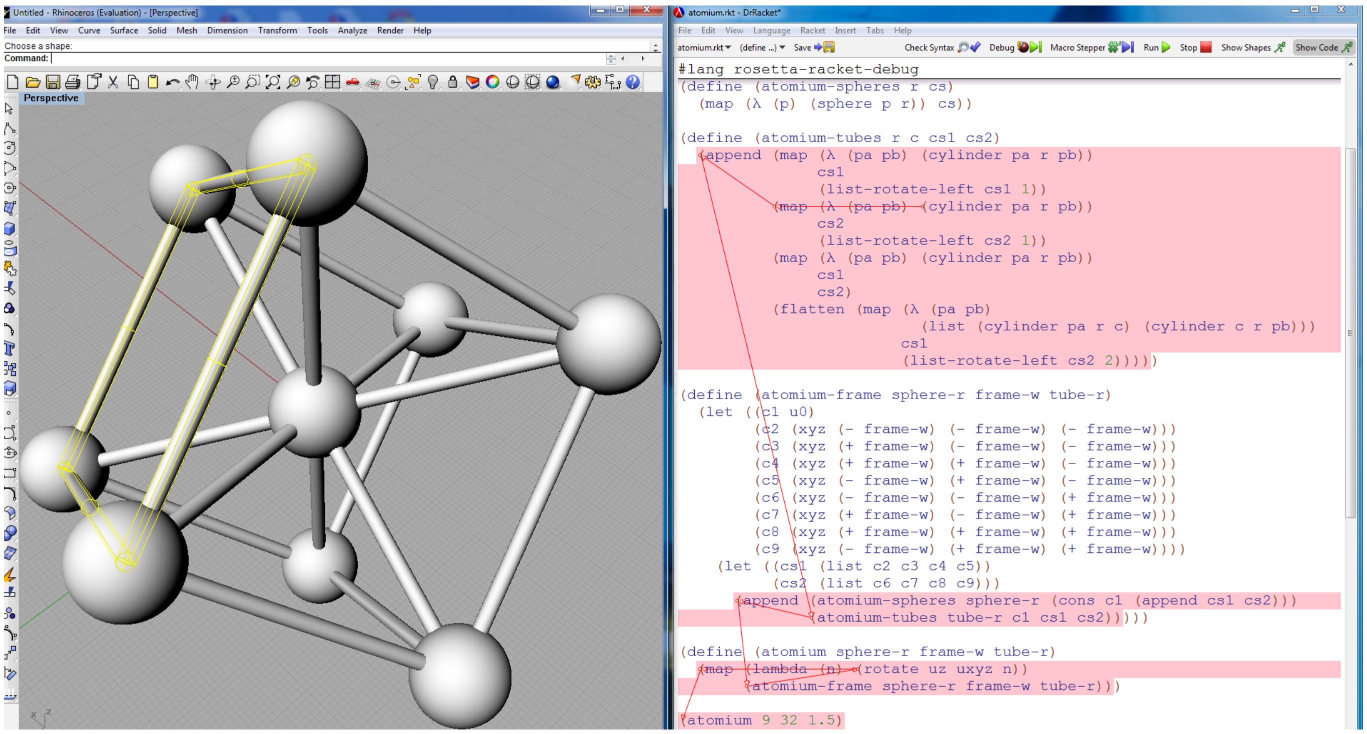
program. However, current programming languages require a large amount of details, which are directly related to the programming language and not to the design. Therefore, they complicate programs and interfere with their comprehension, making it harder to understand the relationship between program and the generated geometric model. In order to overcome this problem, we resort to the concepts of traceability and immediate feedback.

TRACEABILITY

Traceability is the ability to establish a relationship between the elements of the program and those of the model, and it is particularly important for program comprehension, maintenance, and debugging. Without it, it can be difficult to understand the causes of errors, the changes needed to adapt a *GD* program to different purposes, or the impact of changes to a program.

Various techniques have been employed to improve traceability in *GD*. For example, in *Grasshopper*, when the user selects a component that generates geometry, the corresponding part in the model is highlighted. Even more helpful would be the converse association, that is, selecting a shape in the model to automatically highlight the corresponding program component, but, unfortunately, this is not supported.

Moving from visual to textual programming languages, such as, *Rhino*Script or AutoLisp, the situation becomes considerably worse. In general, there is no traceability at all, at least, not one that relates the program with the model.


Untitled - Rhinoceros (Evaluation) - [Perspective]
File Edit View Curve Surface Solid Mesh Dimension Transform Tools Analyze Render Help
Choose a shape:
Command:
Perspective
atomium.rkt - DrRacket*
File Edit View Language Racket Insert Tabs Help
atomium.rkt (define ...) Save
Check Syntax Debug Macro Stepper Run Stop Show Shapes Show Code

```
#lang rosetta-racket-debug
(define (atomium-spheres r cs)
  (map (λ (p) (sphere p r)) cs))

(define (atomium-tubes r c cs1 cs2)
  (append (map (λ (pa pb) (cylinder pa r pb))
               cs1
               (list-rotate-left cs1 1))
          (map (λ (pa pb) (cylinder pa r pb))
               cs2
               (list-rotate-left cs2 1))
          (map (λ (pa pb) (cylinder pa r pb))
               cs1
               cs2)
          (flatten (map (λ (pa pb)
                          (list (cylinder pa r c) (cylinder c r pb)))
                        cs1
                        (list-rotate-left cs2 2)))))

(define (atomium-frame sphere-r frame-w tube-r)
  (let ((c1 u0)
        (c2 (xyz (- frame-w) (- frame-w) (- frame-w)))
        (c3 (xyz (+ frame-w) (- frame-w) (- frame-w)))
        (c4 (xyz (+ frame-w) (+ frame-w) (- frame-w)))
        (c5 (xyz (- frame-w) (+ frame-w) (- frame-w)))
        (c6 (xyz (- frame-w) (- frame-w) (+ frame-w)))
        (c7 (xyz (+ frame-w) (- frame-w) (+ frame-w)))
        (c8 (xyz (+ frame-w) (+ frame-w) (+ frame-w)))
        (c9 (xyz (- frame-w) (+ frame-w) (+ frame-w))))
    (let ((cs1 (list c2 c3 c4 c5))
          (cs2 (list c6 c7 c8 c9)))
      (append (atomium-spheres sphere-r (cons c1 (append cs1 cs2)))
              (atomium-tubes tube-r c1 cs1 cs2)))))

(define (atomium sphere-r frame-w tube-r)
  (map (lambda (n) (rotate uz uxyz n))
       (atomium-frame sphere-r frame-w tube-r)))

(atomium 9 32 1.5)
```

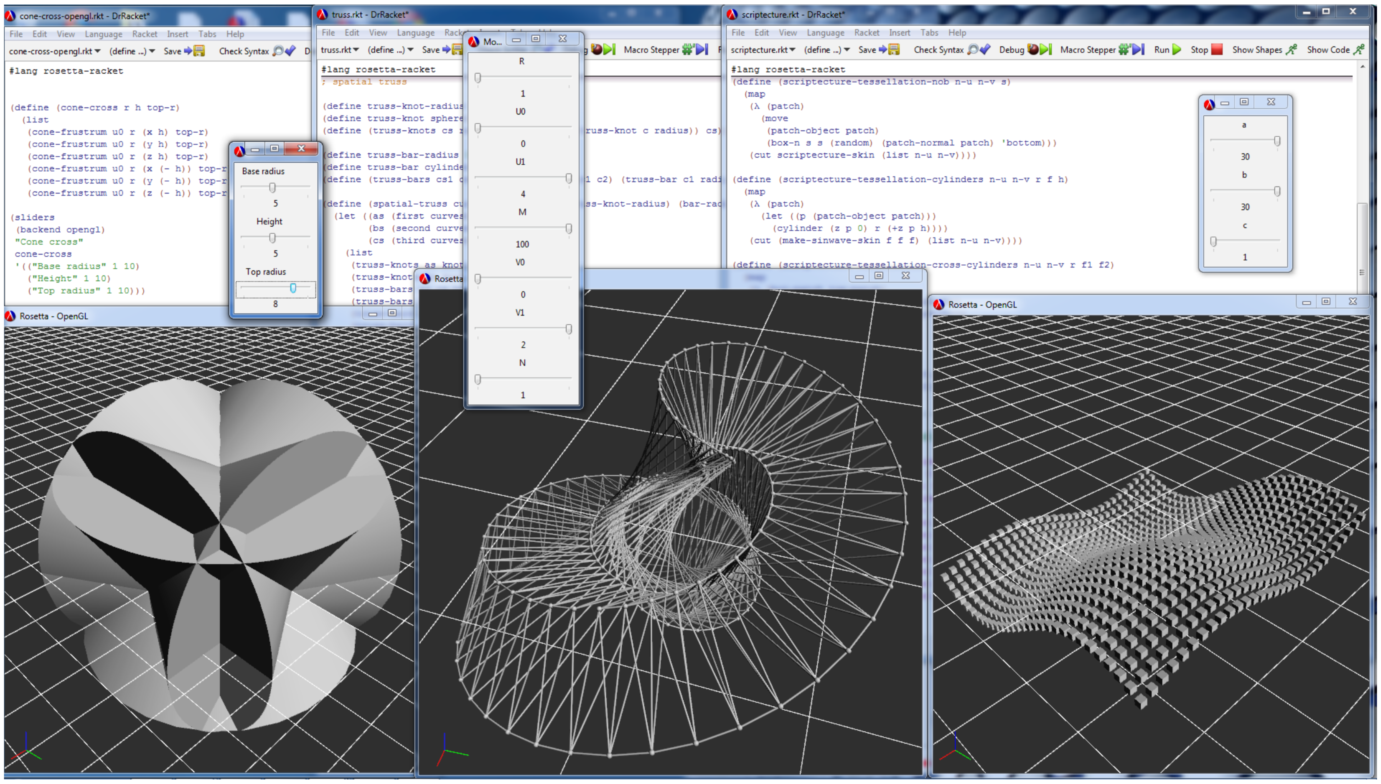
6 Relating shapes to the program expressions that generated them. The highlighted cylinders (on the left, in yellow) are generated by the highlighted program flow (on the right, using red arrows).

In order to improve *GD* traceability, we implemented in Rosetta a bidirectional link between the program and the model. Starting from the model, it is possible to point to some shape element and immediately identify the part of the program that was responsible for its creation. Starting from the program, it is possible to identify which elements of the model were generated from each element of the program. This is shown in (Figure 5) and (Figure 6).

(Figure 5) illustrates a typical scenario where the user selects an expression in the program and Rosetta shows the set of shapes that resulted from that expression. Note that this set contains all shapes that were created by the expression during the complete execution of the program. (Figure 6) shows navigation in the opposite direction: selecting an element of the model in the *CAD* tool instructs Rosetta to highlight the program elements that were responsible for its creation.

Note that the correlation between the program and the generated model allows the designer to use both approaches at the same time, moving from one to the other as he sees fit, thus speeding up the comprehension process. Moreover, traceability can be selectively enabled on a per-module basis. As a result, modules for which traceability is enabled highlight the entire trace, whereas, modules for which traceability is disabled are treated as a black-box, that is, only the entry/exit points are shown. This is especially useful for reducing the amount of visual noise in the highlight and focus only on the parts of the program that are relevant.

The current implementation of traceability uses instrumentation, which consists of adding instructions to the program such that each entry/exit point of a function can be recorded and later reconstructed to show a trace. Program performance is sensitive to this technique because the more entry/exit points exist the more instrumentation is used. For example, a program that produces hun-


cone-cross-opengl.rkt - DrRacket*
File Edit View Language Racket Insert Tabs Help
cone-cross-opengl.rkt (define ...) Save Check Syntax
Base radius
5
Height
5
Top radius
8
Rosetta - OpenGL
truss.rkt - DrRacket*
truss.rkt (define ...) Save Macro Stepper
Mo...
R
1
U0
0
U1
4
M
100
V0
0
V1
2
N
1
scriptecture.rkt - DrRacket*
scriptecture.rkt (define ...) Save Check Syntax Debug Macro Stepper Run Stop Show Shapes Show Code
a
30
b
30
c
1

```
#lang rosetta-racket


(define (cone-cross r h top-r)
  (list
   (cone-frustrum u0 r (x h) top-r)
   (cone-frustrum u0 r (y h) top-r)
   (cone-frustrum u0 r (z h) top-r)
   (cone-frustrum u0 r (x (- h)) top-r
   (cone-frustrum u0 r (y (- h)) top-r
   (cone-frustrum u0 r (z (- h)) top-r

(sliders
 (backend opengl)
 "Cone cross"
 cone-cross
 '(("Base radius" 1 10)
   ("Height" 1 10)
   ("Top radius" 1 10)))
```

```
#lang rosetta-racket
; spatial truss

(define truss-knot-radius
(define truss-knot sphere
(define (truss-knots cs r                    russ-knot c radius)) cs)

(define truss-bar-radius
(define truss-bar cylinde
(define (truss-bars cs1 c                    1 c2) (truss-bar c1 radi

(define (spatial-truss cu                    ss-knot-radius) (bar-rad
  (let ((as (first curves
        (bs (second curve
        (cs (third curves
    (list
     (truss-knots as knot
     (truss-knot
     (truss-bars
     (truss-bars
```

```
#lang rosetta-racket
(define (scriptecture-tessellation-nob n-u n-v s)
  (map
   (λ (patch)
     (move
      (patch-object patch)
      (box-n s s (random) (patch-normal patch) 'bottom)))
   (cut scriptecture-skin (list n-u n-v))))

(define (scriptecture-tessellation-cylinders n-u n-v r f h)
  (map
   (λ (patch)
     (let ((p (patch-object patch)))
       (cylinder (z p 0) r (+z p h))))
   (cut (make-sinwave-skin f f f) (list n-u n-v))))

(define (scriptecture-tessellation-cross-cylinders n-u n-v r f1 f2)
```

7 Using sliders to interactively generate different models. The examples are, from left to right, Orthogonal Cones, Moebius Truss, and ScrIPtecture.

dreds of shapes in a single function will run faster than a similar program that produces the same shapes spread across hundreds of functions. At the moment, we are working on this problem and intend to improve performance in the future.

IMMEDIATE FEEDBACK

Traceability allows an architect to understand the correlation between a *GD* program and the generated model. However, it does not allow the designer to easily understand the correlation between the program inputs and outputs. To this end, the program must be re-executed for each different set of inputs and the model re-visualized, a slow-pace process that will bore even the most patient architect. Immediate feedback attempts to solve this problem by allowing the designer to quickly visualize the impact of changes to the program inputs. With this mechanism, the designer adjusts the program inputs, which have an immediate effect on the generated model, until this model reflects his intentions. This not only allows for better correlation between the program and the model but also allows designers to endeavor in design exploration.

Many design tools acknowledge the usefulness of immediate feedback. This can be seen in the ability of some *GD* tools, such as, *Grasshopper* and Rosetta, to connect program inputs to specialized widgets, such as sliders, that react to changes by recomputing the generated design. Each change in a slider causes Rosetta to recompute the design. However, this re-computation process only operates in real time for very simple *GD* programs. Complex programs can take a considerable amount of time to re-compute and the interactive use of input widgets can become annoying, a problem that affects both *Grasshopper* and Rosetta.

Unfortunately, this problem cannot be easily solved because not all program operations can compute in constant time. A more reasonable assumption is that computation time grows linearly with the input size. This is what happens, for instance, with *Grasshopper* components that map a given operation over a sequence of values: we can expect the computation time to be at best proportional to the length of the sequence. However, in the case of multiple sequences operated in cross-reference, the computation time becomes at best polynomial, making it difficult to have immediate feedback. Adding recursion to the program can make it more difficult still, as it opens the door for computations that require exponential time (or worse). As a result, immediate feedback will never scale to arbitrarily large inputs, particularly when we depend on *CAD* tools that were designed for the speed of human operation, and not for the large volume of operations generated by *GD* programs.

This situation can be improved by sidestepping most of the functionality of traditional *CAD* tools and focusing only on the generation and visualization of a geometric model. To this end, Rosetta includes a backend that does not depend on a full-fledged *CAD* application. Instead, it connects almost directly to the graphics device of the computer, using the *OpenGL* graphics library. (Figure 7) shows several Rosetta programs and the corresponding models in this backend.

This backend allows much faster rendering and, as a result, the designer can enjoy immediate feedback for larger inputs and more complex designs. Once satisfied with the design, he or she can then switch to a normal *CAD* backend, such as, *Rhino*ceros or Auto*CAD*, and continue working as before. Note that, by using Rosetta, switching backends does not entail any change to the *GD* program being developed. (Table 1) presents the time needed by different backends for updating identical geometry, clearly showing that the *OpenGL* backend is considerably faster than the others.

Example/ Backend	AutoCAD	*Rhino*	*OpenGL*
Orthogonal Cones	1022	191	1
Moebius Truss	24253	6094	217
ScrIPtecture	10712	2994	67

Table 1: Time (in milliseconds) needed to update the generated design.

At this moment, the *OpenGL* backend is still being developed and only supports a subset of the functionality that is provided by the other backends. However, our evaluation which is summarized in (Table 1) shows promising results.

RELATED WORK

The idea of *Illustrated Programming* was inspired both by Literate Programming (Knuth 1984) and Learnable Programming (Victor 2012a, 2012b).

Literate Programming (LP) is a programming paradigm invented by Donald Knuth in 1984. At that time, substantial improvements had been made in programming methodology but little progress had been made in program documentation. To significantly advance this aspect of programming, Knuth advocated that programs should be considered works of literature, written using prose and a good presentation order, for a human audience. Then, two different tools were used: *weave* produced a nicely formatted and indexed document for human consumption, while *tangle* extracted and composed the source code so that it could be compiled and executed by a computer.

LP was not widely adopted due to the considerable effort needed to write good prose and a good explanation of a program. However, *GD* is a specific domain where sketches already carry an important explanatory role and usually exist beforehand. By including them in *GD* programs, we make those explanations easily available to anyone that wants to understand the program, while avoiding the considerable effort needed for writing extensive textual documentation.

There are other domain specific languages for *GD*, such as *Grasshopper*, which, given their visual nature, allow to treat the development environment as a canvas where both drawings and programs can coexist. Unfortunately, for non-trivial programs, this canvas tends to become huge, making it difficult to navigate within the program and understand its structure and behavior (Leitão et al., 2012). It is possible to reduce the apparent size and complexity of a program through the use of clusters and wireless connections, but it still remains difficult to understand large and complex programs.

In the case of textual programming languages used in *GD*, such as *Rhino*Script, AutoLisp, and DesignScript, they do not support the inclusion of images in the code. Rosetta does not have this limitation, as it takes advantage of the support provided by DrRacket for literate programming (Flatt et al., 2009) and for inclusion of images in programs, thus significantly improving sketch-program correlation.

Regarding program-model correlation, we observe that some visual *GD* programming languages support, at least partially, traceability and immediate feedback. In the case of traceability, both *Grasshopper* for *Rhino* and *Dynamo* for Revit/Vasari can highlight the particular geometry generated by a selected set of components/nodes. However, the opposite, for example, selecting the geometry and highlighting the parts of the code that generated it, is still not possible.

Immediate feedback is also supported in *Grasshopper* and *Dynamo* via sliders and live programming. Each change in a slider re-executes the program using, as input, the values of all sliders, allowing the visualization of the impact of different inputs in the final output. Live programming re-executes the program on each program change, allowing the designer to build the program incrementally while visualizing its output. In the domain of textual languages for *GD*, both Autodesk's DesignScript (Aish, 2012) and *Rhino*'s Yeti (Davis et al., 2012) support live programming. Although DesignScript does not fully support sliders, its integration with the *Dynamo* platform overcomes this limitation.

Compared to the previous languages, Rosetta provides almost the same features but goes even further in the case of traceability, by providing full bi-directionality. Regarding immediate feedback, Rosetta contains an *OpenGL* backend, which is much faster than the usual *CAD* software at the expense of only providing visualization services. Rosetta currently does not allow live programming, but there are live programming experiments using DrRacket (McLean et al., 2010) that we plan to explore in the future.

There are other studies that confirm our point of view, for example, Programming-in-the-model (*PIM*) (Maleki, Maryam and Woodbury, 2013). *PIM* uses three views over a single design, namely, the model, graph, and the script. The model view is the one normally shown in *CAD* software, the graph view shows the dependencies through a node-link diagram similar to that of visual languages, and the script view shows the code. These views are synchronized such that changes in one view are reflected in the others. Also, the correspondence between elements is highlighted in the different views when a component is selected.

There are two important differences between *Rosetta* and *PIM*. First, *PIM* promotes live programming, which requires either very simple *GD* programs or inordinate amounts of computational power, while *Rosetta* only uses traceability and immediate feedback on demand, thus supporting more complex programs in common computers. Second, in spite of the use of multiple views, *PIM* does not seem to allow the inclusion of sketches in the code.

CONCLUSION

Generative Design is reaching a point where the programs are becoming so complex that it is now important to develop good tools for program documentation and program comprehension.

Based on Literate Programming and Learnable Programming, we introduce the concept of *Illustrated Programming*. This concept states that a good *GD* Programming Environment should help the designer in establishing a strong correlation between the design, the *GD* program, and the generated model.

To this end, we extended *Rosetta*, a tool for portable *GD*, to allow the integration of sketches in the *GD* program and to provide traceability and immediate feedback. Sketches are used as program documentation, establishing a link between the intended design and the program. Traceability allows the visualization of the bi-directional link between the *GD* program and the generated geometry. Finally, immediate feedback allows the user to quickly visualize the impact of changes to the program inputs.
With *Illustrated Programming*, we improve the quality of *GD* programs by offering a visual explanation of the structure and behavior of the program. This facilitates development, understanding, and maintenance of programs. Moreover, it promotes program sharing, communication, and collaborative work throughout the design process.

We are currently evaluating *Illustrated Programming* in large case studies to understand the extension of its benefits and to diagnose and correct its limitations. We plan to improve the Sketch-program correlation with a better mechanism for updating a sketch (currently, the updated sketch needs to be manually reinserted in the program) and with a visual notification of the up-to-date status of program fragments and corresponding sketches. Regarding the Program-model correlation, we will improve immediate feedback by optimizing the *OpenGL* backend implementation and by introducing live programming. However, we believe that the live programming mode should be optional and only available in the *OpenGL* backend so that it can have an acceptable performance for larger *GD* programs

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Figure 4-7. Image credit to Authors (2014).

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