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Editing Graphical Objects Using Procedural Representations

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Abstract

Traditionally, people have created computer-generated images by writing programs in a programming language that supports graphics. More recently, interactive graphics editors have become commonplace. Graphics editors are easy to use but lack many of the capabilities found in graphics programming languages. This deficiency is intrinsic to graphics editors; it is not a result of neglect or incompetence by the implementer.

Tweedle is a graphics editor that attempts to bridge this gap by using a program as its internal representation for a picture. During an editing session the user can modify either the picture itself or the program representation; the editor modifies the other to keep the two consistent. The language used by the editor contains features that allow the editor to incrementally execute parts of a program in response to a change so that the picture can be regenerated without completely reexecuting the program.

The use of a procedural representation allows the user to create pictures with structure, repetition, recursion, and calculated point values. It further allows him to define parts of a drawing as variants of other parts; these variants can differ from their original objects in quite arbitrary ways but still respond to changes made to the original. The language supports linking different parts of the picture together to maintain connections between parts as the picture changes.

A working prototype of Tweedle has been implemented under the X Window System.

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Table of Contents

1. Introduction

People have used computers to create pictures nearly as long as computers have existed. These pictures range from crude character graphics on a line printer to the sophisticated output of today's laser printers. Traditionally, people created these pictures by writing a program in some computer language that supported graphics, usually through some kind of subroutine library. Interactive drawing programs, or graphics editors, are an alternate way of creating pictures, and in the past decade these editors have gone from being an interesting novelty to an accepted part of computer systems. Each approach has advantages and disadvantages, and in many cases these are complementary: the disadvantages of programs are the advantages of editors, and the disadvantages of editors are the advantages of programs.

My goal is to integrate these two approaches by creating a graphics editor that uses a program as the underlying representation for a picture. This allows a user to use the editor to interactively create pictures while still having the capability to fall back upon programming when necessary.

1.1. Overview

Tweedle is a system that combines a graphics editor, Dee, with a programming language, Dum. Any graphics editor must use some kind of data representation to store the picture internally during execution and externally between executions; in Dee this representation is a program written in the Dum language. Executing the program produces the picture.

Dee presents the user with two windows, one containing a picture to be edited and the other containing the text of the program that represents the picture. The user can change the picture by selecting parts of it with a mouse and issuing commands through menus, or can change the text using a standard text editing interface. Changes to the picture are reflected immediately by corresponding changes to the program so that the modified program will produce the modified picture; changes to the text take place in the picture when a *Do Changes* operation is selected.

Tweedle contains several innovative ideas. Most important, it extends procedural representations into the domain of interactive programs. Up to now, procedural representations have been batch oriented; programs that used them manipulated them as a whole. In Tweedle, the representation is constantly changing in response to user input, and acceptable interactive response precludes fully reexecuting the representation in response to every change. Tweedle's interpreter is able to incrementally execute changed representations, executing only a subset of the program but producing the same results as if the program had been fully reexecuted. The interpreter automatically determines how much of the program is affected by a program change; in order to make this work well, Dum was designed to allow this determination be done through a static structural analysis of the program.

Dum programs are structured by defining and calling drawing procedures that create subparts of a picture. These subparts, called *objects*, can later be manipulated by the program in order to change the picture. Dum thus combines the simplicity of the drawing procedure approach with the flexibility of the segment approach to graphics languages.

The procedural representation facilitates a variation hierarchy of graphical objects. This hierarchy allows a user to define a new object as a variant of an existing object by describing the procedure used to change the original object into the variant. Any later changes to the original object will also affect the variant. Variant objects make it easy for a user to create different objects with a similar style and to keep these objects consistent should the style change.

Objects in Dum can define *control points* that other object can use for positioning. Control points can allow arrows to connect to boxes, captions to be centered under pictures, or, since control points are gravity active in the editor, objects to line up on a grid. The interpreter ensures that whenever an object is changed that all parts of the program that depend upon the values of the object's control points are properly reexecuted so that the positioning relationships continue to hold.

1.2. Graphics languages and graphics editors

Graphics editors are one type of "what you see is what you get", or WYSIWYG, program. The picture on the screen directly reflects the picture in the final output, and changes to the picture take place as soon as they are specified by the user. These editors are easy to use and quite sufficient for many pictures; however, they have some limitations. Because the editor is constrained to show exactly the current picture, structuring information is either invisible to the user or simply not present at all. Frequently different parts of the picture should bear some spatial relationship to each other, and unless these relations are explicitly described somewhere they are likely not to hold as the parts of the picture are moved around. Some pictures require points with exact or computed values, and these are difficult to create with an editor. Other pictures are most easily expressed using iteration or recursion, facilities absent in graphics editors.

Figure 1-1 shows some examples of pictures difficult to create with a traditional graphics editor. The binary tree, Figure 1-1a, contains a great deal of structuring information not evident in the picture. If one node gets moved, its children should perhaps also move; the lines connecting the nodes should definitely move; and even the points at which the lines connect to the nodes should change so that the lines continue to be directed to the center of the nodes. Figure 1-1b shows a bar graph in which the heights of the bars should correspond to some given values. In most editors the user would be forced to just make a guess at the appropriate heights. The graph in Figure 1-1c requires iteration and computation; few people would even be tempted to use a graphics editor for this. Figure 1-1d's rosette uses computation both to divide the circle into thirteen equal parts and to determine the appropriate gray scale value for each segment and also uses iteration to construct and place each segment. The snowflake fractal, Figure 1-1e, is most easily created using recursion to draw each side.

A different problem arises when dealing with collections of pictures. Books and papers often contain many illustrations, and the author usually wants them all to have the same style. Sometimes that style will change, requiring, perhaps, bolder lines or a different style of arrows. Using a graphics editor to change each picture can be very tedious. Many of the shortcomings of graphics editors are discussed by Jon Bentley in his article "Little Languages" [8].

Graphics languages have none of these difficulties. It is easy to structure a picture, and parts that depend upon each other can use common variables to gain consistency. Exact and computed values pose no problems, and iteration and recursion are expressed naturally within a language. Modifying a collection of pictures is also easy since one can use a standard text editor to effect the change.

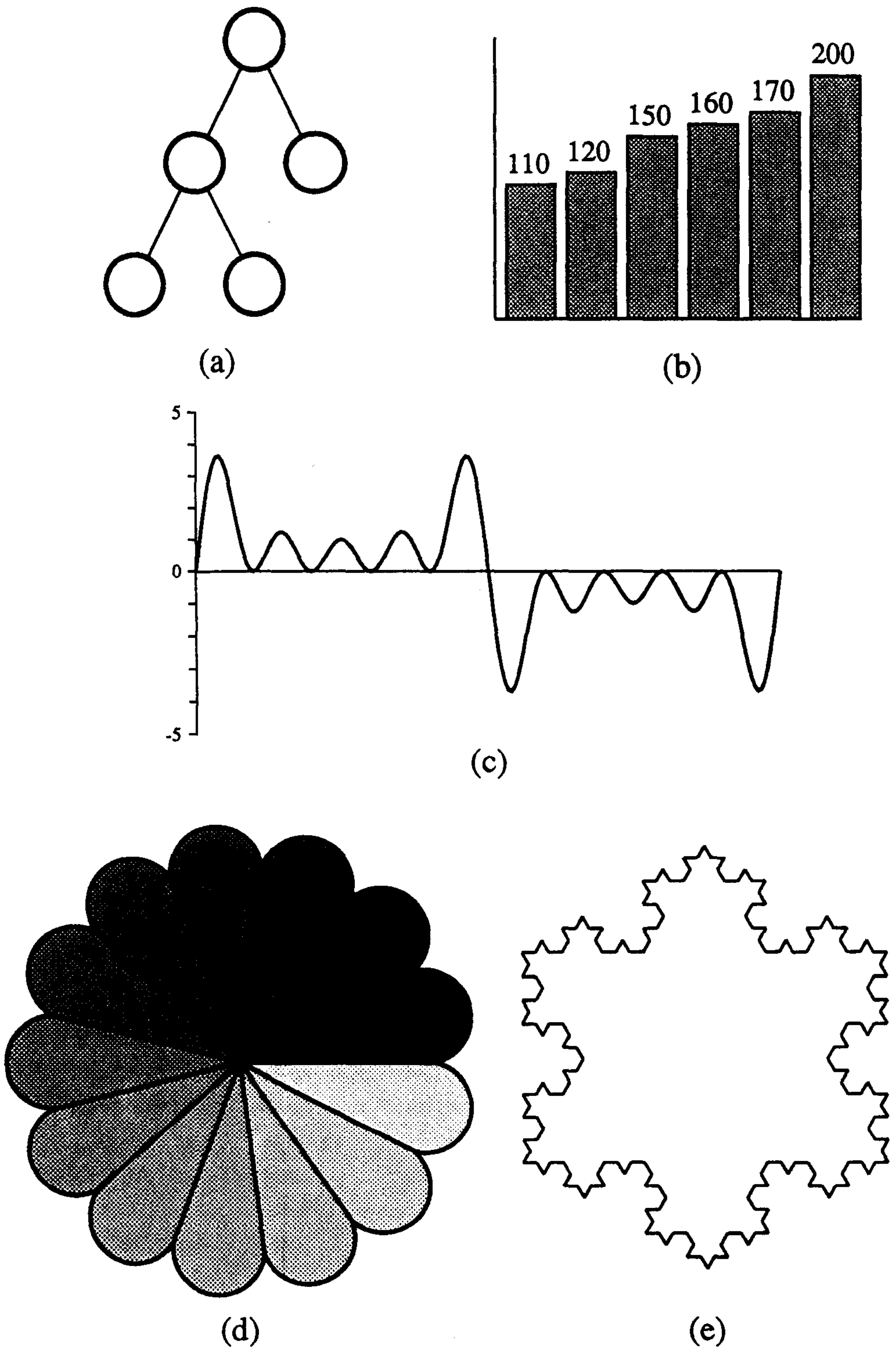


Figure 1-1: Pictures difficult to draw with a graphics editor

Languages are not, however, without their own problems. The overhead involved in writing even a simple program can be daunting. Interactive behavior must be specifically coded into each program; without it getting the desired output can be a tedious repetitive cycle of editing, compiling, running, and looking at the output. The flip side of allowing exact point values is requiring them, even when the programmer has only a vague idea of what they might be.

These problems most often show up in positioning. It is easy to write a program that draws a tree, but difficult to place the nodes for a pleasing result without interactive feedback. Drawing a graph or plot is easy; finding the best place for titles and legends is not. Freehand drawing and layout require user interaction to prevent total frustration.

Tweedle combines the ease of use of a graphics editor with the completeness and extensibility of a graphics language; the limitations of graphics editors are overcome by giving the user the full power of a language for writing extensions, structuring pictures, and specifying exact or computed values. The editor can manipulate user-defined objects like the five pictures in Figure 1-1 as easily as it can manipulate predefined objects like lines, circles, and rectangles. Both are represented as procedures that use low-level graphics primitives to do drawing; the only difference is that the definitions of predefined objects are implicitly included in each drawing. Users can store their own objects in libraries and thereby make them available to multiple drawings, so it is easy to maintain consistency across drawings.

Of course Tweedle does not require its user to use the language to define new objects; in many cases the new objects can be created within the editor by combining already existing objects. Most of the time the user can use the editor without caring that his picture is represented as a program, but when he encounters the limits of the editor he can edit the program representation instead. A given picture can combine objects created by the graphics editor and objects created by the text editor indiscriminately.

1.3. Procedural and nonprocedural representation languages

Computers rarely operate upon real world entities; instead they manipulate representations of these entities. A *representation* is a well-defined data structure that maps properties of these real entities to computer-operable information. A *language* is a set of rules that defines which data structures form valid representations. The distinction between languages and representations is largely artificial, and which term is used frequently depends upon the scale of the problem. When the rules describing the data structure are simple, as with a binary tree representing a sorted list, one usually focuses on the data structure itself and calls it a representation. When the rules are complex, as with a stream of characters representing an algorithm, one focuses on the rules instead and calls it a language.

In some cases a data structure is complex enough to be called a language, but so clearly describes a real world object that "representation" still seems appropriate. Languages in this class are often called, logically enough, *representation languages*; examples include the knowledge representation languages used in expert systems, document description languages, and page description languages. These representation languages fall into two classes: *nonprocedural* languages, which describe the desired end result but not how to achieve it, and *procedural* languages, which describe the end result by describing how to achieve it. Nonprocedural languages are also sometimes called *descriptive*, *declarative*, or *very high level* languages.

Arguments about whether procedural or nonprocedural languages are most appropriate for a problem have been going on for quite some time [22]. Nonprocedural languages allow the program writer to concentrate upon the end result without worrying about implementation details. This makes them easier to use, especially for nonprogrammers. Conversely, the language implementor is free to use whatever means are most appropriate to a particular implementation to achieve these results.

The most severe limitation of declarative languages is that they do not extend gracefully. As long as the user is trying to describe the kinds of things the designer envisioned when he created the language, there are no problems, but as soon as he tries to do anything else he finds himself in trouble. If the language cannot describe it, the user cannot write it; this is sometimes called ''running into the edges of the representation.'' Some nonprocedural languages solve this by allowing extensions to the language, but the language used for the extensions is usually quite different from the original language.

Procedural languages can solve the extensibility problem by having low level primitives and control structures for combining them; however, these primitive operations can make it easy for the user of such a language to become enmeshed in a web of details irrelevant to the problem he is trying to solve. Most procedural representation languages have facilities for defining macros or procedures that represent high level constructs; programs that uses these are often indistinguishable from descriptive programs. Procedural languages can thus masquerade as declarative ones, but not vice-versa.

Procedurality, it must be noted, does not automatically guarantee extensibility. Command stream languages consist of a series of operations and are thus procedural, but they do not have the ability to compose these operations in an extendible way. Early text formatting programs provide a good example of this. In order to format an indented quotation, a user would write something equivalent to

```
Skip a line
Set left margin to 2 inches
Set right margin to 6.5 inches
Format the text "This is the body of the quotation"
Set left margin to 1 inch
Set right margin to 7.5 inches
Skip a line
```

(The ''Format the text...'' command would normally be implicit). Page description languages can be similar: ''Move to (500,654). Switch to italics. Print an 'A.' '' Extensible procedural languages contain commands similar to these in order to actually produce results, but they allow the commands to be grouped into subroutines, used in conditionals and loops, and take calculated values as arguments. [34] I will hereafter use ''procedural'' to refer only to languages with these properties, and ''command'' to refer to procedural languages without them.

Of course there is a continuum between purely procedural and purely descriptive languages; even languages like Pascal or C that initially appear totally procedural contain descriptive elements in the form of variable declarations. Nonetheless, most languages fall readily into one class or the other. Concrete comparisons between the two styles are difficult to make since there are so few applications for which there are both declarative and procedural representations. The idea of using a procedural representation for something besides a procedure has only recently started to become popular; the reverse, using a declarative language to represent a procedure, is even more rare. Document description is one area that has substantial examples on each side.

Scribe [30, 31, 32] is a document description language that is almost entirely declarative. The bulk of an input file consists of sections of text enclosed in *environments* that describe the function or appearance of the text they enclose. Typical functional environments are quotations, footnotes, subscripts, and enumerated lists; appearance environments can indicate centering, italics, and so forth. Scribe also contains a few procedural constructs like starting a new page or setting tab stops.

TEX [17, 18] and troff [28] are procedural document description languages. They contain commands to do things like change margins, skip vertical space, and change type faces, and also contain commands that manipulate esoteric things like registers, parameters, marks, insertions, diversions, and traps. Neither raw TEX nor raw troff is a particularly hospitable environment for anyone but the most dedicated hacker; fortunately both provide macro facilities that allow the messy details to be hidden from the casual user.

LATEX [20] is a popular macro package for TEX. A document written using LATEX doesn't look much different from one written using Scribe; for example, in LATEX one writes a quotation like

```
\begin{quotation}
This is an uninteresting quote.
\end{quotation}
```

while in Scribe one writes

```
@begin(quotation)
And this one isn't much better.
@end(quotation)
```

The actions taken by the document compiler are, however, very different in each case. In LATEX the `\begin{quotation}` and the `\end{quotation}` get expanded as macros into series of low-level TEX commands; these commands skip the appropriate space above and below and change the margins. In Scribe, `@begin(quotation)` causes a database lookup to find the attributes of the `quotation` environment. This lookup tells the compiler that the quotation's text should be offset with vertical space above and below and should have narrower margins. The difference is subtle but important. The definition of a LATEX macro can contain arbitrarily complicated TEX commands such as conditional expressions, mathematical computations, or recursive macro calls. The definition of a Scribe environment, on the other hand, gives the settings of predefined text parameters. A TEX user can produce novel layout effects by including new macro definitions in his input file; in Scribe these could only be produced by modifying the compiler to add new features.

This distinction is intrinsic to representation languages for any sufficiently complex system. There will always be things that require computation to represent cleanly, and any language that includes computation is, by definition, procedural. Any particular feature can be added to a declarative language by extending the language definition, of course, but before long the language starts to lose any coherence it originally had. Descriptive languages excel at well-defined, closed tasks, while procedural languages are needed when the job is open-ended.

All of which returns us to Tweedle. Tweedle's representation language, Dum, includes object definitions that function analogously to macros in TEX. Objects are high level, they can be manipulated by the editor, and there is a large set of predefined objects. Many pictures will never need any direct Dum programming. Dum's low level graphics statements and general purpose programming constructs are analogous to low-level TEX commands: you can use them to build up your own objects if you need something unusual.

Figure 1-2 shows some of the flexibility gained by this approach. Each line is an instantiation of a different object. Each object definition takes two points as arguments; what it does to get from one point to the other varies from object to object. Computation allows the objects to slightly modify the circle, square, or dash size in order to assure that the space gets filled with an integral number of elements.

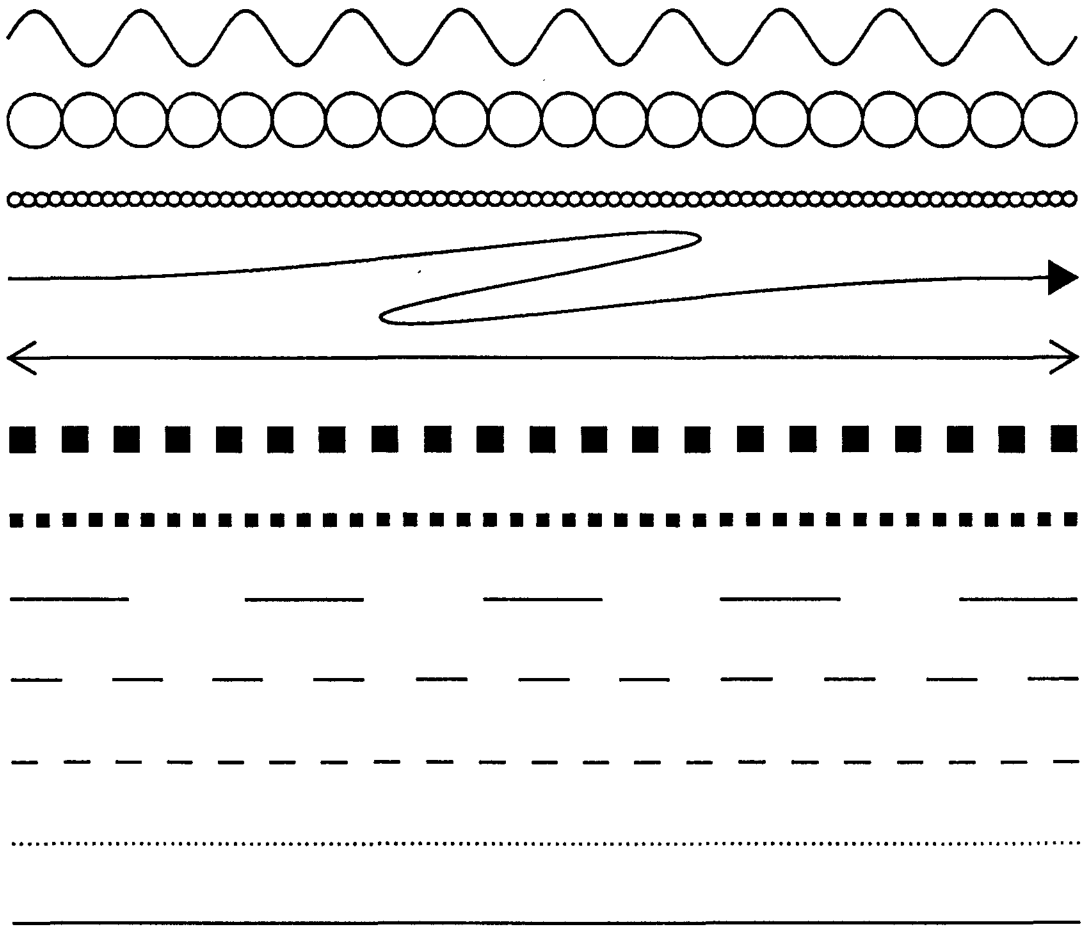


Figure 1-2: Sample line styles programmable within Tweedle

1.4. What Tweedle isn't

Although it resembles one in some superficial ways, Tweedle is not an automatic programming system. The Dee editor generates Dum code in response to user operations, and, in fact, many Dum programs are completely written by the editor. But there are many programs that the editor cannot automatically generate and many that it cannot fully understand. Things easy to do by modifying text but hard to express through a graphics editor interface are done by modifying the text — that's why it is there. Conversely, the claims in Section 1.2 about the transparency of user-written code hold only as long as the program conforms to some minimal structuring conventions. Dee happily accepts non-conforming programs and generates the right picture, but the user will find that some kinds of editing will not work.

This particular implementation of Tweedle is not a production quality graphics editor; its goal was to be demonstrative, not comprehensive. Many things have been left out, and many simplifying assumptions have been made. The implementation is, however, quite usable: except for occasional screen dumps showing Dee in operation, all the illustrations in this thesis were drawn with Dee.

1.5. A note on the cast of characters

Some readers may have difficulty keeping Tweedle, Dee, and Dum distinct. Tweedle is the general name for the entire system; it includes both Dee and Dum. Dee is the graphics editor (it allows one to *de*sign pictures) and Dum is the programming language (it is passive, mute, *dumb*).

2. Previous Work

2.1. Procedural representations in graphics systems

Procedural graphics representations can be generally divided into two classes: segment-based representations and display procedure representations. Segment-based representations include such popular standards as Core and GKS [37, 38]. These representations contain explicit graphical objects, usually called *segments* or *symbols*, that are identified by name and are manipulated by predefined operations. A program first creates a segment, then adds primitive objects like lines and curves to it. When the segment is complete, the program closes it and then explicitly draws the segment on the display. A program may or may not be able to modify an existing segment once it has been closed. The structure of the program that manipulates the segments is entirely independent of the structure of the picture; this makes segment-based representations well-suited for applications that change the picture based on user interaction.

In a display procedure representation, subparts of the picture are represented by procedures that draw them. The main program consists of a series of procedure calls, and when the program has finished running, the picture is complete. Procedure-based representations are conceptually simple but they are poorly suited to many interactive applications since the program must be changed and reexecuted in order to change the picture. Their big advantage is flexibility: a segment can be rotated, scaled, or otherwise transformed but otherwise always looks the same, while a procedure can alter its flow of execution to produce different results depending upon its input arguments, the current graphics state, or global style parameters [25].

This last feature turns out to be very important for computer flight simulation, which requires rapid rendering of a constantly changing image. This image will typically contain many small distant objects and only a few large close ones. The close objects must be rendered in detail to obtain realism, and the distant objects must be rendered quickly to obtain the needed speed. Display procedures are ideal for this application since they can readily adapt their output to show a level of detail appropriate to their size in the image.

In this environment John Gaffney and John Warnock produced the Evans and Sutherland Design System [14]. This language combined the image model used in other Evans and Sutherland systems with a simple stack-based semantic model. Although the Design System has never been described in the literature, it had an enormous impact upon later work. John Warnock moved to Xerox PARC and together with Martin Newell created an interactive graphics system called JaM [41]. JaM combined the Design System's execution model with a slightly different graphical model.

Several years later, work began at PARC to develop a successor to Xerox's page description language, Press [27]. Press was a device-independent representation that had been implemented on various raster printers and achieved widespread use in the academic community; however, it had a very limited set of graphical capabilities. JaM became the base for this successor, Interpress [42]. During this time Chuck Geschke and John Warnock left PARC to form Adobe Systems and there they designed the PostScript language [1], also based upon JaM.[1].

[1]This history is given in gloriously gory detail by Brian Reid in a famous ARPANET Laser-Lovers message [33]

These languages are all more similar than they are different. Each is a stack oriented token based language; a program consists of a series of operands to push upon the execution stack and operators that act upon them. Certain operators allow the definition of new operators while others provide graphic operations, arithmetic functions, control structures, and so forth. Programs in these languages structure their pictures by defining and calling drawing procedures.

Special purpose graphics languages are designed to represent a particular class of drawings. Most of these are too limited in scope to be interesting, but one, PIC, provides an interesting mix of descriptive and procedural operations [15, 16]. PIC addresses itself to the boxes-and-arrows illustrations so common to technical writing. It contains primitive operations like *box*, *circle*, *ellipse*, and *arrow*. A typical PIC program consists of a series of invocations of these operators:

```
ellipse "PIC" "source"
arrow
box "PIC"
arrow
ellipse "TROFF" "code"
```

This would produce a picture similar to Figure 2-1. The PIC interpreter takes care of the spacing between boxes, the positioning of labels, and other similarly menial tasks. Its defaults can be overridden by supplying extra arguments to the operators, and the interpreter accepts arguments in a wide variety of syntaxes, for example

```
arrow right from 1/3 of the way between last box.ne and last box.se
```

The ''.ne'' and ''.se'' in this example function similarly to control points in Tweedle but are restricted to a small set of predefined values. In addition to high level operations like ''box'' and ''ellipse,'' PIC supplies a full set of procedural operations like *for* and *if*. A user can define macros, but these are treated quite differently from the built-in operations. PIC is very good at boxes-and-arrows pictures but can be difficult to use in other situations.

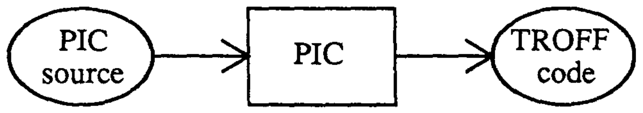


Figure 2-1: PIC sample output

2.2. Graphics editors

I define an *editor* as a program that allows a person to interactively edit the representation of some object. A useful distinction can be drawn between *internal* and *external* representations: an internal representation is how the editor stores the object while working on it, and an external representation is how the editor stores the object between executions. Most editors use external representations that are just versions of the internal representation capable of being stored on a file system; unless otherwise mentioned this is true of all editors discussed here.

Particularly interesting are editors that constantly present the user with an image of the current state of the object being edited; these are called "what you see is what you get", or WYSIWYG editors.[2] There are three main classes of WYSIWYG editors, each requiring successively more abstract representations: text editors, document editors, and graphics editors.

[2]Some people use a more restrictive definition of WYSIWYG, reserving it for editors that use a pointing device.

WYSIWYG text editors are sometimes just called screen editors. Typical of these are the various implementations of Emacs [39, 13]. The representation being manipulated in text editors is really just the text file itself.

Document editors provide the same type of formatting as the document description languages discussed in the last chapter. A section of the current document is displayed upon the screen and the user manipulates it by chosing sections of text and altering such attributes as font, size, margins, and line spacing. Bravo [21] was one of the earliest examples of a document editor. It was actually ''what you see is almost what you get'' since the screen size and available resolution precluded showing a full page's width of characters: a document's line breaks on the screen occurred at different places from those in the printed output. Document editors are now commonplace, a typical example being MacWrite [4]. Their representation for the document is generally some form of command language with commands to change the text attributes interspersed with the text of the document.

Since it is impossible to store a picture as such in a computer, a graphics editor's representation must be more abstract than the others'. Some graphics editors, often called *paint programs*, use bitmaps as representations; among these are Markup [26], a pioneering effort, and MacPaint [3]. Bitmaps have three main disadvantages as representations, size, nonportability, and lack of structure. A bitmap representation's size is proportional to the size and not the complexity of the image; this is an advantage only for very small or extremely complicated images. Bitmap images cannot take advantage of the improved resolution of most printers; lines, curves, and letters will be printed at the screen resolution rather than the printer resolution. Bitmaps are also very difficult to scale by other than an integral amount and to rotate by other than multiples of ninety degrees. The general transformation algorithms are slow and the results are usually disappointing. Perhaps the most severe limitation is the lack of structure. While paint programs have commands to add lines, rectangles, or circles to the picture, once these things have been added they are just bits in the bitmap. It is impossible to later operate upon these objects as themselves; the user can only manipulate the bits that make up the objects.

Most graphics editors use some sort of static hierarchical data structure to represent the picture. The image is kept as a list of picture items, each of which is either a primitive item or another list. One of the first such editors was Draw from Xerox PARC [7]; MacDraw is a popular current example [5]. These editors frequently feature grids to help users make accurate drawings; grids force points in the image to coincide with points in a rectangular grid. Grids can help in many cases, but even such a simple image as an equilateral triangle is beyond their capabilities.

Some editors gain some additional power by using an external representation that is human readable. In these systems the user can use a standard text editor to achieve results that would be impossible or tedious in the graphics editor. Bell Labs' PED [29] is one such system.

Constraints are an alternate representation that have been used in several interesting editors. In a these systems the user gains precision in his picture by placing geometric constraints upon the points used to define it. Typical examples include constraining two points to be coincident, constraining three points to be collinear, constraining two points to be the same distance apart as two other points, constraining two points to lie on a line parallel to the line through two other points, and constraining two points to lie upon the same horizontal or vertical line. To create a rectangle the user would first define four points A, B, C, and D in approximately the right positions, draw the line segments AB, BC, CD, and DA, and then place the following constraints on the points:

```
    AB is parallel to CD
    AB is the same length as CD
    AC is the same length as BD
```

(Other sets of constraints are possible.) The first constraint forces the quadrilateral ABCD to be a trapezoid, the second forces it to be a parallelogram, and the third forces it to be a rectangle by making the diagonals equal in length.

Constraints have many attractive features. Standard numerical analysis algorithms can be used to resolve them. They represent the types of relations common in drawings in a natural, consistent fashion. Finally the interface to constraint systems is straightforward: the user uses a pointing device to select points in the picture and chooses a constraint from a menu to apply to these points.

These advantages are countered by some serious problems. Getting the constraints right for a picture can be a difficult task roughly equivalent to trying to draw the picture using a compass and straightedge. The constraint solver satisfies the constraints by moving points in the picture; care must be taken to assure that it does not move the wrong points. Similarly, a given set of constraints can have many solutions. In the rectangle example, above, the constraints would be solved by *any* rectangle; the editor must provide some way of making sure that the solver produces the one the user had in mind. A combinatorial explosion occurs as more and more constraints are added requiring mutual satisfaction, so the user must carefully structure his picture hierarchically to allow the solver to limit itself to just a few constraints at one time. Unless the editor allows the user to define his own constraints, some pictures will be tedious or even impossible to draw. Without user-definable constraints, it is usually impossible to constrain line segments to have a particular length, angles to have particular values, or distances to have a calculated relation to each other. This makes pictures like the bar graph and equation plot in Figure 1-1 intractable. As in other declarative systems, iteration, recursion, and computation are only awkwardly expressed.

The first constraint system was Ivan Sutherland's seminal Sketchpad [40]. Sketchpad stored constraints as functions that return how far their arguments are from satisfying the constraint; the constraint solver varied the arguments until all the error terms became zero. As an example, the procedure for a constraint forcing two points to be horizontal might return the absolute value of the difference of the points' x coordinates. New constraints types could only be added by modifying the editor. Although primitive by today's standards (it had, for example, no curves, and constraints were selected by flipping switches on the front panel of the computer) Sketchpad provided nearly all the features found in graphics editors today.

Alan Borning's Thinglab [10] is actually a general simulation environment using constraints to describe the things being modeled. A Thinglab constraint is a Smalltalk class with certain special properties; since Smalltalk is an interactive interpreted language the addition of new constraint types is an easy process. Thinglab constraints contain methods that the interpreter can use to try to satisfy the constraint; for example, the constraint for the midpoint relation might look like

```
midpoint := (point1 + point2) / 2             OR
point2 := point1 + 2 * (midpoint - point1)    OR
point1 := point2 + 2 * (midpoint - point2)
```

Here the interpreter has the choice of three different methods to use for satisfaction. The ordering of the methods indicates that the solver should first try to satisfy the constraint by assigning `midpoint`; if that fails it should attempt to assign `point2`, and if that fails it should attempt to assign `point1`.

Although not usually considered a graphics editor, METAFONT [17, 19] by Don Knuth can be used as such. In a METAFONT session the user explicitly adds, modifies, and deletes constraints on named points in the picture. METAFONT's interface is strictly textual, and the user can define his own constraints.

Juno [24], by Greg Nelson, is perhaps Tweedle's closest relative. A Juno picture is represented as a program in the Juno language, and the user can interactively edit either the picture or the program. Juno differs from Tweedle in that its language is very restrictive. A statement in Juno takes the form of a guarded command:

```
LET variables | constraints IN commands END
```

This introduces a set of point variables (all variables in Juno represent points), forces their values to satisfy the constraints, and uses them in the commands. The commands can contain drawing commands like `fill` and `stroke` as well as additional guarded commands. The variables in the outer guarded command are available within the inner, but their values cannot be changed by the constraint solver. Juno has a very limited set of constraints, and they may not be extended. It attempts to find the ''right'' solution to multiply-valued constraints by allowing an initial guess of the value; the solver starts with this guess as its solution and tries to satisfy the constraints by moving the points as little as possible. The guess starts out as the actual position of an input point, and, after the constraints have been solved, it is replaced by the actual value found for the point. This allows subsequent solutions to be found very quickly.

Daedalus [6] is a VLSI editor that uses constraints to represent the spatial relationships of the components. The layout is represented as a LISP program, and the user is able to change either the picture or the program. Only a small set of predefined constraints are available.

The CMU Tutor system [35, 36] is similar in some ways to Juno and to Tweedle. This is a programming environment designed to assist people in producing computer assisted instruction programs. CMU Tutor shows simultaneously the program to produce the current page of the CAI program and the present state of the current page. A graphics editor for the current page generates the source code required to produce the desired output; changes to the current page are incrementally compiled by the system. The level of editing available is quite primitive; the CMU Tutor editor allows the user to add objects easily, but once they are added they can only be modified by selecting sections of code and giving new values to the points included therein.

A novel approach to attaining accuracy in drawings occurs in the Gargoyle editor from Xerox PARC [9]. In many graphics editors, the pointing device is attracted to existing points in the picture when it moves near them. This is called *gravity*, and allows the user to more easily connect up parts of the picture. Gargoyle extends the concept of gravity to non-visible alignment objects. The user can select parallel lines, circles, or lines with specified angles; these greatly facilitate the drawing of many pictures. Gravity is also active when the user transforms parts of the picture, thereby enabling him to gain precise alignment. This form of gravity, called *snap-dragging* by its creators, would make a welcome addition to Dee.

One final editor of interest is the Adobe Illustrator [2]. Illustrator is noteworthy in that it uses a directly executable PostScript program as its external representation. Details of its internal representation are unavailable; however, there is nothing to suggest that it is other than a standard hierarchical description. A user can edit the resulting PostScript file if he desires, but he must take care that he does not use any PostScript operators other than those in the limited set Illustrator understands.

3. The Programming Language

In normal use, the Dum programming language appears to play a subordinate role to the Dee editor. The user is creating a drawing, not writing a program, and so can, for the most part, ignore the language except in the rare occasions that he needs to edit the text. This view is a carefully cultivated illusion; the true relationship is just the opposite.

Dee's internal structure looks more like a programming environment than a graphics editor. When the user performs some editor operation, the editor alters the program so that it will produce the required change, then incrementally executes the program to update the picture (Figure 3-1). It is therefore important to understand the language in order to understand the editor.

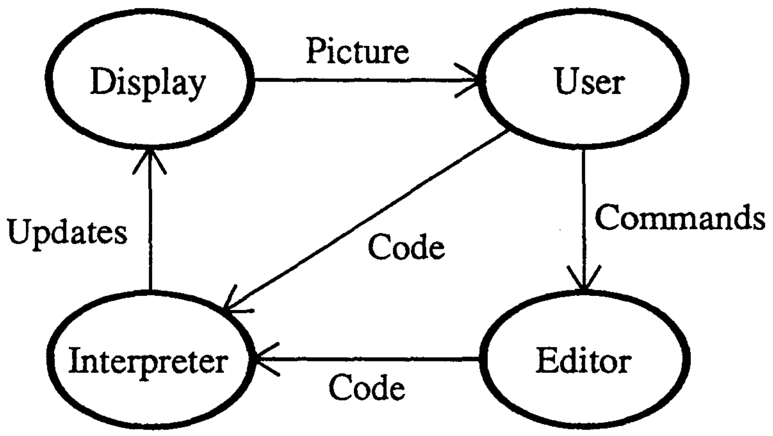


Figure 3-1: The flow of information during an editing session

Conversely, the Dum language must be considered in the context of the editor in order to understand its design. The program text is constantly being changed, both by the editor and by the user, so the language should be simple to parse and to interpret. Furthermore, the amount of work done in response to a program change should be proportional to the size of the change, not to the size of the program. Finally the language must have constructions analogous to the operations of the graphics editor in order for the variation hierarchy to exist.

3.1. Language design goals

The most basic goal in Dum was to have it be based upon standard imperative programming language features. Other systems, notably Juno [24] showed that a multiple-view editor is possible by using an unconventional language; the goal in Tweedle was to make it work using a conventional one so as to make it as easy to program as possible. Dum should contain variables, functions, iteration, alternation, and so forth.

The syntax of Dum was designed to be very simple. Whenever the user changes the picture through either the text or the graphics interface, new code must be parsed and executed. The turn-around time must be short for good interactive response; this precluded the use of a complicated language. Pragmatics further dictated simplicity: Dum remained in a state of flux for much of the development, and changes to a simple parser are easier to make than those to an elaborate one. Finally, syntax design is not really germane to the project; it draws attention away from the deeper issues involved.

It is generally acceptable for a major change to a picture to require several seconds to take place, but small, common changes like adding, moving, or deleting objects must take place quickly. This is achieved in Tweedle through *incremental execution*, the ability to selectively execute parts of the program so that the picture appears as it would had the entire program been reexecuted in response to the change. Doing this efficiently requires avoiding language constructs that allow the execution of one part of a program to make state changes that would affect the results of unrelated parts of a program, so many important features of Dum programs can be discovered through static semantic analysis of the program text.

The object variation hierarchy allows one object to be defined as a variant of another. This mechanism is quite general: a variant object can add, delete, move, or change the subparts of the original object. The variant is described by the list of changes done to the original to make it into the variant; therefore Dum needs a means to describe all these types of changes.

3.2. Language overview

The syntax of Dum superficially resembles that of LISP:[3] a program is a series of lists whose elements are either atoms or other lists. This syntax is easy to parse, and the resulting parse tree is very easy to manipulate. Dum is, however, not an applicative language since its lists are frequently just convenient ways of grouping together similar items and of delimiting statements.

Dum's types are summarized in table 3-2. Numbers are either integers or floating point and are converted from one to the other as required. They are also used as boolean values with zero representing false and any other value representing true. Points are pairs of numbers; they are just a convenient method of keeping *(x,y)* pairs together. Strings are immutable but can be of any length. Arrays are dynamic collections indexed by integers with no restrictions placed upon the types of the individual elements. A paint describes something that can be used to draw with; in the current implementation they are restricted to shades of gray but could also represent colors or fill patterns. Object variables are used to refer to subparts of the picture and will be discussed fully in section 3.3.

Datatype	**Sample constants**
number	`2    3.14    -4e10`
point	`[0 0]    [100 -100]    [1 1.5]`
string	`"hello, world"    ""    "nice new rattle"`
array	*none*
paint	*none*
object	*none*

Figure 3-2: Basic types in Dum

Expressions are written exactly as in LISP: the operation name is followed by the arguments. Each argument is evaluated and the operation is called with the resulting values. Point expressions occur so frequently that there is a bit of syntactic sugar to represent them: `[x y]` is shorthand for `(makepoint x y)`. Here are some sample expressions:

[3]A complete description of Dum syntax can be found in Appendix I.

```
17
[(* r (cos theta)) (* r (sin theta))]
(sqrt (+ (* x x) (* y y)))
(concat (translate [100 100]) (rotate 45))
```

Dum contains most of the features found in any ALGOL-like language; it just uses more parentheses to express them than usual. A program can contain *if*, *for*, *while*, *begin*, and assignment statements. Variables must be defined before they are used; however, data definition statements can be freely mixed with executable code. Since arrays can contain values of different types, all type-checking in assignments and routine calls is done at runtime.

There are two types of subroutines in Dum, functions and object definitions. Object definitions can, to a first approximation, be thought of as functions that return objects. Two features guarantee that subroutines act as strict mathematical functions: arguments are always passed by value, and no non-local references are allowed. Since there are no side effects, a change in a subroutine can only affect those parts of the program that use the subroutine's value. This locality allows the incremental execution mechanism to bound the amount of the program that needs to be reexecuted in response to a change. Furthermore, the behavior of a subroutine is totally specified by its parameters, so the interpreter can call subroutines without worrying about the global context.

An example of a function definition may help to make the syntax more concrete. Consider the following absolute value function:

```
(function abs
    (returns number)
    (args (number i))
    (method
        (if (< i 0)
            (:= abs (neg i))
            (:= abs i)
        )
    )
)
```

This declares a function `abs`. `Abs` takes one argument, a number, and returns a number. The *method* clause contains the body of the code, which in this case is a single *if* statement. The first sublist of the *if* statement is the condition, the second is the true branch, and the third is the false branch. In this case the function assigns either `-i` or `i` to `abs`, depending upon whether or not `i` is less than zero.

Dum provides a full set of predefined functions for arithmetic, trigonometry, graphical transformations, point manipulation, and assorted other uses; these are described in Appendix II. Two functions that are worth noting at this point since they will be used frequently in examples are `grayscale`, which returns a paint representing a particular shade of gray, and `arr`, which returns an array containing its arguments. Programs can also include libraries of functions and object definitions; these allow sets of programs to create consistent sets of drawings easily.

3.2.1. Graphics operations

Dum's graphics primitives are based upon the *path* model used by PostScript [1]. A path is an abstract construct that represents a geometric shape; it consists of a sequence of line segments, curves, and arcs. The current path is part of an executing program's state and is modified by path construction statements like *moveto*, *lineto*, *curveto*, and *arc*. Unlike PostScript paths, which use Bezier cubics, Dum paths use a single point to specify curved segments and rely upon other points in the path to condition the curve. This was done primarily out of expediency: the X Window System that was used to implement Dee only supports simple splines [12].

Dum programs produce graphical output by executing *drawpath* and *fillpath* statements. These are compound statements; within them path construction statements define the path to be drawn or filled. Options such as the line width and the fill paint are specified as part of the statement. If a path contains another path, the options of the subpath override those of the main path for the duration of the subpath and the main path's options are restored when the subpath is over. Paths can also contain objects, to be discussed fully in the next section.

Graphical transformations are represented as six-element arrays and are provided by various built-in functions. The available transformations are summarized in Figure 3-3; standard graphics texts contain a full discussion of transformations and matrices [11, 25]. The current coordinate system is modified using the *with* statement, which takes a transformation followed by statements to execute with that transformation. After the end of the *with* statement the coordinate system is restored to what it was before.

Dum function	**Matrix form**	**Array representation**
`(translate [x y])`	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ x & y & 1 \end{bmatrix}$	[1 0 x 0 1 y]
`(scale [x y])`	$\begin{bmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & 1 \end{bmatrix}$	[x 0 0 0 y 0]
`(rotate a)`	$\begin{bmatrix} \cos a & -\sin a & 0 \\ \sin a & \cos a & 0 \\ 0 & 0 & 1 \end{bmatrix}$	[cos a sin a 0 -sin a cos a 0]
`(concat A B)`	$B \cdot A$	

Figure 3-3: Summary of transformations in Dum

When one *with* statement is nested within another, the inner *with* is done relative to the outer. These transformations are performed in the order in which they are encountered, and modify the global coordinate system. For example, the code fragment

```
(with (translate [100 100])
    (with (rotate 45)
        ...draw picture...
    )
)
```

first translates the origin to (100,100), then rotates the axes by 45°. The order is important; this is not the same as rotating the axes and then translating the origin. It is sometimes more helpful to think of what happens to the picture before it gets drawn on the page, and in that case the transformations are performed from the inside out: here the picture is rotated by 45° and then translated by (100,100).

The current transformation, the current path, and the current values of the path options collectively determine the graphic state of an executing program. These can only be changed by the *with*, *drawpath*, and *fillpath* statements, and all revert to their previous values upon the completion of the controlling statment. Changes to the graphic state are thus statically limited by program constructs, so it is possible for the interpreter to save the state at the time of some subroutine execution and to restore it should the subroutine need to be reexecuted at a later time. Unrelated parts of the program cannot affect the state, so the interpreter can know that the saved state is still correct.

The current graphic state is quite invisible to program execution since there are no functions that query it. This has both advantages and disadvantages. Operations that query the global state are really just global variables in disguise; were they included, subroutines would no longer be mathematical functions. Different invocations with the same arguments might yield different results. On the other hand, the current system lacks adaptability. One advantage of procedurality is that objects can modify their appearance based upon their context, showing more or less detail, for example, depending upon their size. This ability is lost since there is no way for the object to determine what the current transformation actually is.

3.3. Object semantics

The *object* is the central mechanism in Dum for structuring pictures and in Dee for controlling incremental execution. Objects represent distinct manipulable portions of the drawing, and are thus somewhat similar to segments in Core or GKS [37, 38]. More concretely, an object is a binding of a path with a transformation to place the path in the picture. If an object represents a piece of text, a character string and a font replace the path.

It is important to keep distinct several related concepts involving objects. An *object definition* is a section of code that defines the appearance and behavior of an object. An *object instance*, also called an *instantiation* or simply an *object*, is the above mentioned path and transformation pair. The *type* of an object is its definition; two objects are of the same type if they are both instantiations of the same object definition. An *object reference* is a pointer to an object, and an *object variable* is a variable that holds an object reference. Object references can also be stored in arrays, so anywhere an object variable is required an array element can also be used.

An object can contain other objects as parts; a component part is called a *subobject* and the containing object the *parent object*.

While segments in Core or GKS and objects in Dum can be manipulated in similar ways, their definitions are very different. A segment has a name, and a program defines the appearance of a segment by calling subroutines that add displayable objects to the segment. Code that defines a particular segment could be scattered throughout the program that uses it. In Dum, an object definition is just a procedure that draws the object. When an object definition is called, the interpreter creates a new object with an empty path and a copy of the current transformation. *Draw*, *drawpath* and *fillpath* statements inside the object do not modify the display but instead add their paths to the object's path. The value of a call to an object definition is a reference to the object that was just created. The object's path is actually drawn when a reference to it is used in a *draw* statement.

This separation of object creation and object drawing arises because there are times when a program needs to defer drawing. Filled objects are opaque, and objects drawn later obscure objects already on the display. Furthermore, certain positioning information about an object is available to the program whether the object has been drawn or not.

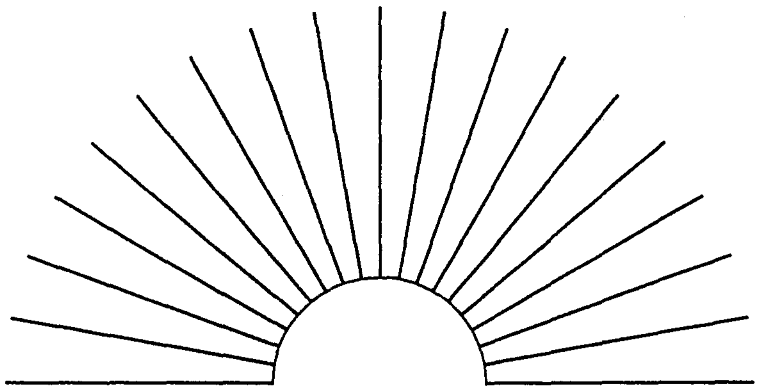


Figure 3-4: A sunburst

The center of a circle is one example of this positioning information, and it was used to create the sunburst in Figure 3-4. This picture was made by creating an opaque circle but not drawing it, then using the center of the circle to position the outward radiating lines. The circle was then drawn, covering the center portions of the lines.

The positioning information takes the form of *control points*, point values defined within an object definition but accessible outside. The control points for a rectangle object might be the four corners, the centers of the sides, and the center of the rectangle. The primary uses for control points are to specify points that other objects can use for alignment and to specify which points will be gravity active in the editor. The first use is the most common and allows, for example, arrows to point to sides of boxes, captions to center themselves, and, in the above sunburst example, the radiating lines to use the center of the circle as an endpoint. The effect of gravity will be described in the chapter on the Dee editor.

Within an object definition a control point acts just like any local point variable. Outside, the program obtains its value by using the *getpoint* operation, `(getpoint <object reference> <control point name>)`. *Getpoint* is not a function since its second argument is not a normal value. The value of a *getpoint* operation is the value assigned to the control point within the object definition, transformed by the object's transformation, and then inversely transformed by the current transformation. For example, consider the code shown in Figure 3-5. Here, the object `circle` has defined the control point `center` and assigned it the value `[0 0]` in its definition. The main program instantiates a circle with a translation of (100,100) and calls it `a_circle`. It then changes the coordinate system to a translation of (250,100) and draws a line from (0,0) to the center of `a_circle`.[4] (0,0) in the new translated coordinate system becomes (250,100) in device coordinates. The value of the control point must be the value that, when transformed by the current transformation, will yield the center of the

[4]The *using* statement surrounding the *lineto* statement will be described shortly and can be ignored for now.

circle; so the value of the control point, (0,0), is transformed by the transformation of the object, `(translate [100 100])`, to give the point (100,100) in device coordinates; this value is then transformed by the inverse of the current transformation to yield the value (-150,0), which is the value of the control point.

```
(defineobject circle
    (args (number radius))              # one argument, the radius
    (control center)                    # defines the control point
    (method
        (:= center [0 0])               # the center is the origin
        (drawpath                       # draw a path that is
            (arc center radius 0 360)   # an arc from 0-360 degrees
        )
    )
)

(function main
    (method
        (with (translate [100 100])          # translate to (100,100)
            (object a_circle (circle 50))    # create a circle
            (draw a_circle)                  # and draw it
        )
        (with (translate [250 100])          # translate to (250,100)
            (drawpath                        # and draw a line from
                (moveto [0 0])               # (0,0)
                (using a_circle              # to a_circle's center
                    (lineto (getpoint a_circle center))
                )
            )
        )
    )
)
```

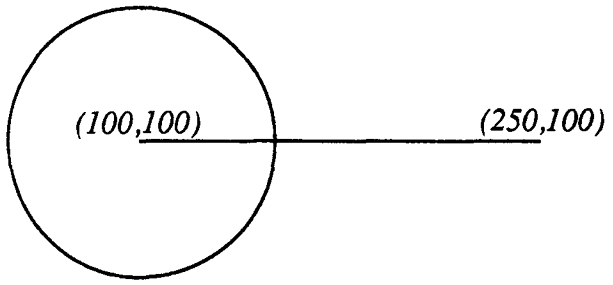


Figure 3-5: Sample code illustrating control points

Dum contains five statements that modify already existing objects, *delete*, *raise*, *lower*, *transform* and *recall*. *Delete* removes a drawn object from the display. *Raise* and *lower* change an object's stacking order, that is, the way in which it obscures other objects with which it overlaps. *Transform* changes the transformation associated with the object, causing it to appear in a different location. *Recall* replaces an object with a different object, and will be discussed in detail later.

These statements at first appear to be superfluous, since the effects of these statements could be achieved by modifying the original text. Rather than using a *delete* statement, the object could never be drawn; rather than using *raise* and *lower* the order of the draw statements could be changed, and rather than using a transform statement the transformation that controls the creation of the object could be changed. This is frequently the case, but there are times when doing this would require a fairly deep understanding of the program. Multiple instances of an object may be created within a *for* or *while* loop, and the appropriate modification in this case is difficult to discover.[5] More important, these statements allow the object variation hierarchy to exist.

In the object variation hierarchy, one object is defined to be a variant of another; these objects are called the *variant* and the *original* objects. The definition of a variant object is a list of operations to perform on the original in order to change it into the variant. These operations can include adding new subobjects, moving around existing subobjects, or even replacing these subobjects with others. When the interpreter is called upon to execute the definition of a variant object, it first executes the code of the original object and then, using the same values for all local variables, executes the code of the variant. The variant can thereby use the values of any variables in the original. A variant takes the same argument list as its original, followed optionally by some additional parameters.

This variation mechanism is very powerful, since it allows the variants to follow later changes made to the original. As long as all the variables that the variant depends upon are defined the variant will continue to make sense; if they are not, a runtime error occurs. An additional advantage of variants is that they inherit the control points of the original object. A node in a graph could define itself as a variant circle and thereby inherit whatever control points have already been defined for circle.

Figures 3-6 and 3-7 show an example of the variation mechanism. The object defined in Figure 3-6 draws a label centered in an oval; this was used in various figures throughout this thesis. It consists of two subobjects, a scaled circle to generate the oval and a label.[6] The variant object is the same except that it shows two lines of text in the oval. The original line of text is moved to a new position, and then the new second argument is used to generate the second line of text. Since the two-line module is a variant object, changes to the original like alterting the line width or using a different font will automatically apply to the variant.

The transformation of an object is bound when the object is created, not when the object is drawn. The most important reason for this is to assure that an object's control points have values, even though the object itself has not yet been drawn. A second reason is that some structured types of drawings may want to pass objects to other objects and have them drawn there. This is best illustrated by an example.

Figure 3-8 show a program to draw a binary tree. The main program creates all the nodes, placing them as it wishes. The structure of the tree is built by passing to each tree the two trees it should use as its left and right subtrees. The code that defines the tree creates a node for itself, draws connecting lines to the subtrees, draws the subtrees,[7] and finally draws its own node. The main program has only to draw the final tree and the entire structure appears. Since the transformations are bound at creation time, the code for the tree need not worry about positioning the two subtrees.

---

[5]*For* causes fewer problems since the index variable can be tested; *while* loops are virtually impossible.

[6]The exact arguments to the `circle` object are irrelevant here.

[7]Once again, ignore the *using* statement for now.

```
(defineobject module (args (string legend))
  (control left right top bottom ne nw se sw center)
  (method
    (with (scale [1.5 1])
      (object oval (circle [1 25] 2))
      (draw oval)
    )
    (number f (getfont "times" 14))
    (number w (strwidth legend f))

    (with (translate [(* -0.5 w) -5])
      (object the_label (text legend f))
      (draw the_label)
    )

    # code omitted that assigns the control points
  )
)
```

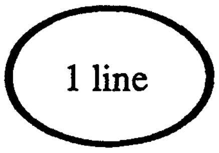


Figure 3-6: A labelled oval

```
(defineobject 2_line_module (variant module)
  (args (string line2))
  (method
    (transform the_label (translate [(* -0.5 w) 2]))
    (:= w (strwidth line2 f))
    (with (translate [(* -0.5 w) -13])
      (object 2nd_label (text line2 f))
      (draw 2nd_label)
    )
  )
)
```

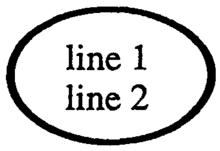


Figure 3-7: A variant with two lines of text

The editor can change an object's transformation either by changing the transformation in effect at the object's creation or by adding a *transform* statement to the end of the program. Whichever method is used, the editor then has the job of making sure the picture looks as if the object had always been in its new location. Simply moving the object is not enough; since the calculation of a control point's value includes its object's transformation, the values of the object's control points change. If the picture is to remain consistent, all parts of the program whose results depend upon the values of these control points must be reexecuted.

In order to do this the interpreter creates for each object a list of code segments whose results depend upon the object's control point values. Each of these segments needs to be complete; that is, any part of the program not in the list of segments must execute in the same way no matter what the values of the control points may be. In many cases the segments are both obvious and quite self-contained. Most *getpoint* operations occur in path construction statements or as arguments to other objects, and in both of these cases the interpreter has no difficulty in determining how much code needs reexecution: in the first case it is the path construction statement, in the second, the object invocation. Neither reexecution can cause distant sections of code to become incorrect, although if an object gets reinvoked the values of its control points can in turn change, causing ripples of reexecution to spread throughout the program. The true difficulty occurs when the value of a control point affects later execution. A program can test a control point in an *if* statement, for example, or assign its value to a point variable and use the variable later in the program. In these cases a changed control point can cause later execution to change in arbitrary and unpredictable ways. While these uses of control points are rare, they are

```
(defineobject tree
    (args (object left right))          # left and right subtrees
    (control center)
    (method
        # the node is a filled circle, centered at the origin,
        # through the point [25 0], line width 2, fill paint white
        (object node (filled_circle [25 0] 2 (grayscale 1)))

        # my center is the circle's center
        (:= center (getpoint node center))

        # if there is a left subtree, connect to it and draw it
        (if (not (null left))
            (begin
                (using left
                    (drawpath
                        (moveto [0 0])
                        (lineto (getpoint left center))
                    )
                )
                (draw left)
            )
        )

        # ditto for right
        (if (not (null right))
            (begin
                (using right
                    (drawpath
                        (moveto [0 0])
                        (lineto (getpoint right center))
                    )
                )
                (draw right)
            )
        )

        # finally draw myself
        (draw node)
    )
)

(function main
    (method
        # create the nodes
        (with (translate [50 25])
            (object tree1 (tree (nullobj) (nullobj))))
        (with (translate [150 25])
            (object tree2 (tree (nullobj) (nullobj))))
        (with (translate [100 125])
            (object tree3 (tree tree1 tree2)))
        (with (translate [200 125])
            (object tree4 (tree (nullobj) (nullobj))))
        (with (translate [150 225])
            (object tree5 (tree tree3 tree4)))

        # finally draw the whole tree
        (draw tree5)
    )
)
```

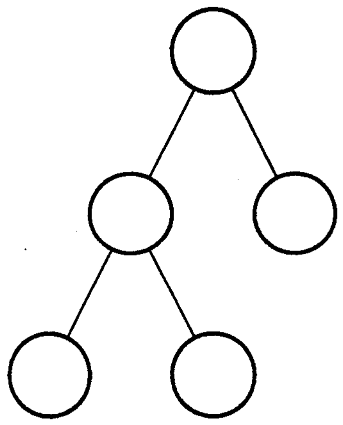


Figure 3-8: A program to draw a binary tree

useful; for example, a program might want to test an object's position, and, depending whether the object is above or below a particular point, draw an arrow to the bottom or the top of the object.

Figure 3-9 shows an example of the flexibility gained this way. This code computes the relative positions of `obj1` and `obj2` and determines the best way to connect them: the left edge of `obj1` to the right edge of `obj2`, the right edge of `obj1` to the left edge of `obj2`, the bottom edge of `obj1` to the top edge of `obj2`, or the top edge of `obj1` to the bottom edge of `obj2`. It first calculates the *x* and *y* displacements between the centers of the objects, and determines the best connection by comparing their magnitudes and signs. If the *x* displacement is larger in magnitude than the *y* displacement, `obj2` is closer to being to the left or right of `obj1` than it is to being above or below it, and either a left-right or right-left connection is appropriate depending upon the sign of the *x* displacement. Figure 3-10 shows several connections generated this way. Whenever either of the objects moves, the entire section of code needs reexecution.

```
(point c1 (getpoint obj1 center))
(point c2 (getpoint obj2 center))

(number dx (- (px c1) (px c2)))
(number dy (- (py c1) (py c2)))

(if (> (abs dx) (abs dy))
    (if (> dx 0)
        (with (translate (getpoint obj1 left))
            (draw (arrow (getpoint obj2 right)))
        )
        (with (translate (getpoint obj1 right))
            (draw (arrow (getpoint obj2 left)))
        )
    )
    (if (> dy 0)
        (with (translate (getpoint obj1 bottom))
            (draw (arrow (getpoint obj2 top)))
        )
        (with (translate (getpoint obj1 top))
            (draw (arrow (getpoint obj2 bottom)))
        )
    )
)
```

Figure 3-9: Code to determine the best connection strategy

Examples like this can be detected automatically only through dynamic dependency analysis. In keeping with the goal of using static mechanisms whenever possible, Dum instead contains a language construct to indicate the relevant portions of the program. All sections of code that depend upon the location of an object must be enclosed within a *using* statement, `(using <object reference> <code>)`. A *using* statement has no immediate effect on the execution of the program; it just informs the interpreter to store the code within it as something that needs execution if the *using's* object is transformed.

The Dee editor automatically includes appropriate *usings* in code that it produces, and it is not difficult to see where they belong in user-written code. In the common cases described above, the path construction statement and the statement with the object invocation need to be wrapped in a *using*. If the dependency is more complex, as with the control point being used in an *if* statement, the author needs to think about the semantics of the program and encapsulate those sections that depend upon the control points in *using* statements.

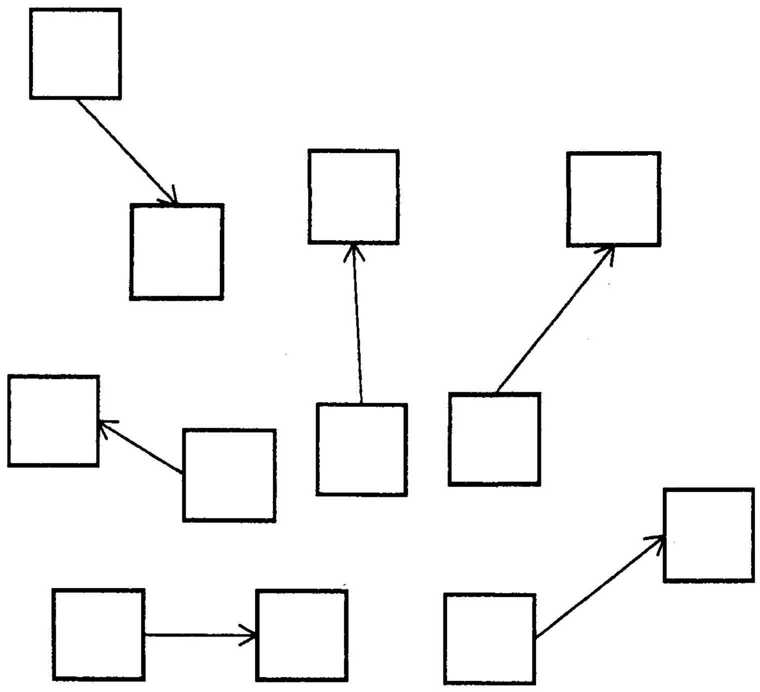


Figure 3-10: Several connections using this scheme

When an object gets moved, all the *using* statements for it get reexecuted. Figures 3-11 and 3-12 show this in action. The picture in Figure 3-11 is composed of two squares with an arrow connecting the right side if the first square with the left side of the second square. The definition of `arrow`, not shown, draws an arrow from (0,0) to the point passed to it as an argument. Here, the arrow is translated to the right side of the first box and passed the left side of the second box as an argument. Since the translation involves a control point, the entire *with* statement must be wrapped in a *using* statement for the first box. Inside the *with*, the invocation of the arrow is wrapped within another *using* since it uses another control point. In Figure 3-12 a *transform* statement has been added that changes the position of the right square. Since the arrow invocation is wrapped in a *using* for that square the invocation is reexecuted, this time with the new value for the control point, and the arrow continues to be attached correctly. If the left box were moved instead, the interpreter would reexecuted the entire *with* statement. This example was fully generated by the Dee editor and illustrates its correct insertion of *using* statements.

If the object was passed any objects as arguments, all the *using* statements in it for objects that were passed as parameters also must be reexecuted. The calculation of a control point's value involves both the current transformation and the transformation of the object whose control point is being used. When an object is transformed, the current transformation changes for all *using* statements inside its definition, so these *using* statements must be reexecuted.

It is important for the interpreter to be alert for potential loops when reexecuting a *using* statement. These arise when code within a *using* statement attempts to transform the *using's* object, since this action normally triggers the reexecution of the *using* statement. The situation can be even more difficult to detect since the loop could involve two or more objects:

```
(with (translate [200 0])
  (object sq1 (square 50)))
(draw sq1)

(with (translate [300 0])
  (object sq2 (square 50)))
(draw sq2)

(using sq1
  (with (translate (getpoint sq1 right))
    (using sq2
      (draw (arrow (getpoint sq2 left)))
    )
  )
)
```

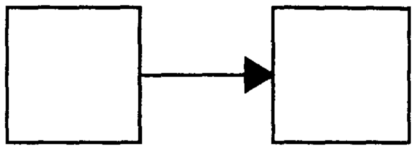


Figure 3-11: A picture illustrating *using*

```
(with (translate [200 0])
  (object sq1 (square 50)))
(draw sq1)

(with (translate [300 0])
  (object sq2 (square 50)))
(draw sq2)

(using sq1
  (with (translate (getpoint sq1 right))
    (using sq2
      (draw (arrow (getpoint sq2 left)))
    )
  )
)
(transform sq2 (translate [325 25]))
```

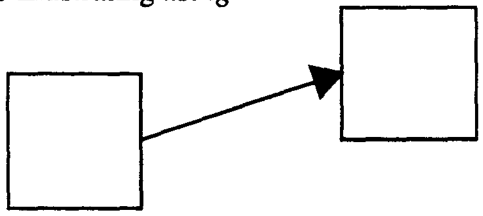


Figure 3-12: The same after translating the right square

```
(using A
    (transform B ...)
)
(using B
    (transform A ...)
)
```

To avoid this problem transform statements are illegal within *using* statements and any attempt to execute one results in a runtime error. This is more restrictive than it needs to be, since it disallows many perfectly safe transformations; the interpreter could maintain a list of objects whose *using* statements are currently being reexecuted, check any object being transformed against this list, and only signal an error if a loop should occur.

There is an additional advantage to having the control point dependency be explicitly stated with *using* statements rather than having it be implicitly discovered. Enclosing a control point use with a *using* tells the interpreter that the control point value should be updated if it ever changes. In some cases the user might not want the value to change; for example, the user could want an arrow to point to the place where a corner of a box is currently located but not want the arrow to change if the box is moved. This is particularly useful when control points are used to implement grid-like mechanisms: objects use control point values for initial placement but should not be constrained to always using these values. By leaving out the enclosing *using* statement, the user tells the interpreter that the control point access should not change value if a transformation occurs.

Frequently in editing one subobject in an object gets replaced by a new object which fills the same role in the picture. Dee allows its user to change the type of a particular instance of an object into a new type so that the object can be edited separately from other instances or to change the fill pattern or line width of an instantiation. These changes cannot be reflected in the program by simply using a *delete* statement and a new invocation because *using* statements in the parent object for the old subobject should now apply to the new subobject. Dum contains the *recall* statement to handle these cases. *Recall* takes an object reference and an object invocation, `(recall <old reference> <object invocation>)`, and assigns the result of the invocation to the reference after deleting the reference's object from the picture. In addition, any *using* statements for the original object are reassigned to the new object. Runtime errors can occur if the new object does not define all the control points of the old object.

```
(defineobject underlined_label
  (args (string s))
  (method
    (object lab (label 12 "times" s))
    (draw lab)

    (point u [0 3])        # underline offset
    (using lab
      (drawpath
        (moveto (p+ (getpoint lab left) u))
        (lineto (p+ (getpoint lab right) u))
      )
    )
  )
)
```

Underlined Label

Figure 3-13: An underlined label

```
(defineobject larger_underlined_label
  (variant underlined_label)
  (method
    (recall lab (label 18 "times" s))
  )
)
```

Underlined Label

Figure 3-14: A variant with larger text

For a practical example of how this is useful, consider Figures 3-13 and 3-14. Figure 3-13 defines an object that draws an underlined label; it first draws the label then draws the line under it. The variant object in Figure 3-14 has replaced the label with an one in a larger font. In order for the underline to continue to be correct, the control points used to draw it must apply to the new label instead of the old one, and this is precisely what *recall* does.

Pictures frequently contain repetition, and in a Dum program this takes the form of multiple invocations of an object definition with identical argument lists but different transformations. Since objects are functional, these calls will all yield the same path, and executing the code more than once is wasted effort. Dum programs can avoid this work by using the built-in function *new*; this function takes an object reference as a parameter and returns a reference to an object with the same path but a different transformation. These two objects actually share the same path, so the amount of space and computation needed by a highly repetitive objects is drastically reduced. In the recursive snowflake picture in Figure 3-15 each distinct path segment is computed and stored only once. The use of *new* allows this picture to be drawn in a linear amount of time and space as a function of the maximum recursion depth; without *new* it would require exponential time and space.

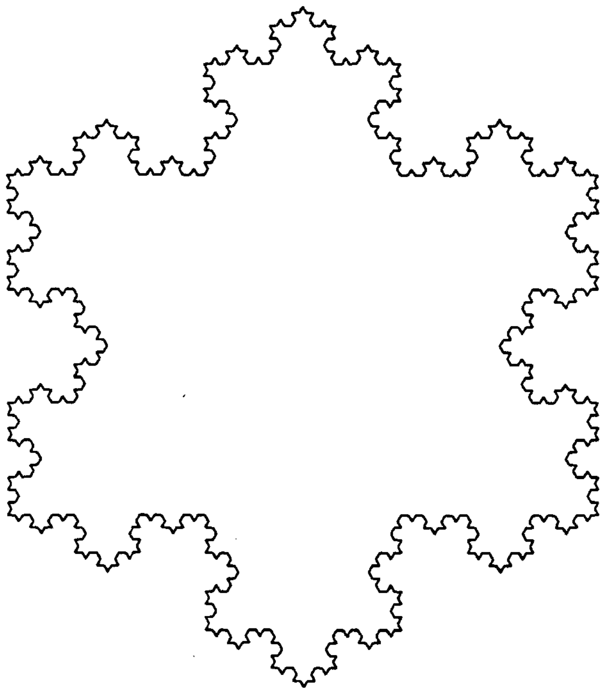


Figure 3-15: A picture with a high degree of repetition

Using *new* is completely transparent; the new object appears and behaves exactly as it would have had it resulted from a call to the appropriate object definition. If the arguments to the object being *new*'ed contain any object references, the *new* function actually does call the appropriate definition. This is because the object being called presumably uses some of the control points of the passed object, and the relation between the called object and the passed object will be different in the two cases. This is also completely transparent; the program can always call *new* with impugnity.

This path sharing among different instances of an object places some restrictions upon the way transformations are stored in an object. In particular, the transformations of subobjects must be stored relative to the transformation of their parent object. Using relative transformations has the additional benefit that when objects are moved, the editor need not update the transformations of subobjects. When drawing, a transformation stack is maintained so that local coordinates can be mapped into global coordinates.

One unfortunate side effect of using relative transformations arises when an object is drawn by an object other than the one that created it; this occurs in the binary tree example on page 24. This is a manifestation of the classic funarg problem that arises in programming languages when functions that have been passed to other functions attempt to do non-local references. To resolve this problem, an object must maintain enough information to enable the drawing routines to find its creator.

3.4. Why a new language?

One question not yet addressed is whether or not a new language is actually necessary. Would another language serve equally well? One likely candidate is PostScript [1], a language, like Dum, explicitly designed to represent images. PostScript is especially attractive since many programs produce it as output, and being able to interactively edit these files would be a valuable tool. Although Dum and PostScript share some parts of their imaging models, there are some fundamental differences that make PostScript unsuitable as an interactive representation. A review of Dum's language design goals will show how Dum satisfies these goals and why other languages, particularly PostScript, do not.

The first goal is conventionality. Dum contains all the features commonly found in standard imperative programming languages: variables, arrays, functions, assignments, *for* and *while* loops, and *if* statements. PostScript also has these features; their syntax and underlying semantics may be unusual but the features themselves are not.

Another goal is simplicity, and both Dum and PostScript succeed here. A Dum program is a sequence of lists containing other lists and atoms, while a PostScript program is just a sequence of stack-based operations and their operands. The need for simplicity is the primary thing that keeps other languages from being appropriate.

The biggest difference between Dum and PostScript is Dum's use of static structure to facilitate incremental execution. Many program properties that would require simulated execution to discover in PostScript can be found in Dum programs through static semantic analysis of the source text. All changes to the graphics state of a Dum program are statically bounded by *drawpath*, *fillpath*, and *with* statements, so the interpreter can determine the graphics state at any point by inspecting the program. If the program is changed to modify the graphics state the interpreter can tell just what part of the program is affected by the change. This is very different from the way PostScript handles state changes since PostScript programs change the graphic state by executing operators that can be anywhere. For example, the PostScript code

```
i 0 eq                  % test if i = 0
{
    45 rotate           % and rotate axes by 45 degrees
} {
    100 100 translate   % or translate origin to (100,100)
} ifelse                % depending upon the value

% what is the current transformation now?
```

leaves the current transformation rotated by 45° if the value of `i` is 0 and translated to (100,100) if it isn't. These state changes may even be tucked away inside drawing functions:

```
/box {                  % start definition of box
    ...                 % do some drawing operations
    10 10 translate     % translate the origin
} def                   % and finish the definition

100 100 translate       % translate origin to (100,100)
box                     % draw a box

% origin is now translated to (110, 110)
```

Another way Dum uses static structure is to have all subroutines act as mathematical functions. The nesting structure of graphics state changes already guarantees that subroutine calls cannot change the graphical state, and disallowing non-local references guarantees that they cannot change the program state. Since subroutines cannot have side effects, the interpreter can call them freely without causing incompatible changes to the program state, and since they cannot use non-local variables, the amount of context associated with a call is limited to the values of the subroutine's parameters and local variables.

The final application of static structure is the *using* statement. *Using* allows the interpreter to determine all parts of a program that rely upon the position of an object so that it can reexecute them if that position changes. As will be seen in the next chapter, *using* also enables the incremental execution mechanism to find what parts of a program require reexecution if the definition of an object changes. PostScript has no formal notion of graphical objects, so it has no construct analogous to *using*.

The last goal is having an object variation hierarchy. Dum allows an object's subobjects to be manipulated with statements like *transform*, *recall*, and *raise*; these permit the program to change the graphical output of an object interactively. The idea of having subparts of the picture change after they have been drawn is dramatically different from PostScript's graphics model. PostScript uses a simulated paint model for graphics: the picture is created by placing areas of opaque ink upon the current page, and once the ink is on the page it cannot be erased or moved. There are no commands in PostScript to manipulate a picture once it has been produced.

Although Dum and PostScript differ greatly semantically, they share many statements and functions. This enables anyone familiar with PostScript to understand and write Dum code with few difficulties. Further, many programs that generate PostScript for hard copy could easily be changed to generate Dum instead and thereby produce pictures that can be edited with Dee.

4. The Graphics Editor

Figures 4-1 and 4-2 illustrate the basic difference between the structure of conventional graphics editors and the structure of the Dee editor. The Dum language interpreter forms the heart of the Dee editor; whenever the user changes the picture the editor generates new code and passes it to the interpreter for execution. The execution of this code in turn generates changes to the displayed picture. This chapter will describe the editor, concentrating on how the interpreter incrementally executes program changes to keep the picture consistent.

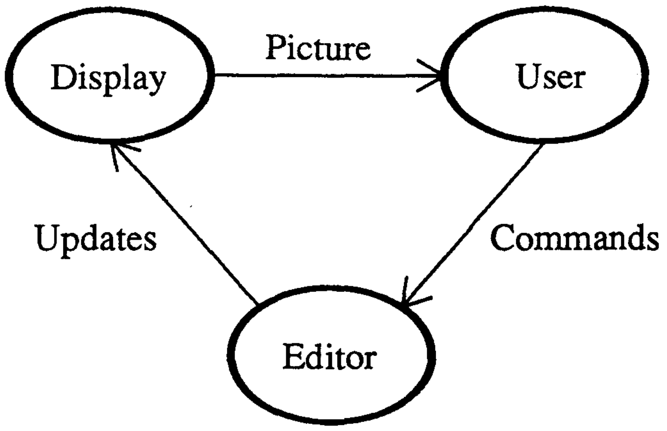


Figure 4-1: The flow of information in a conventional editor

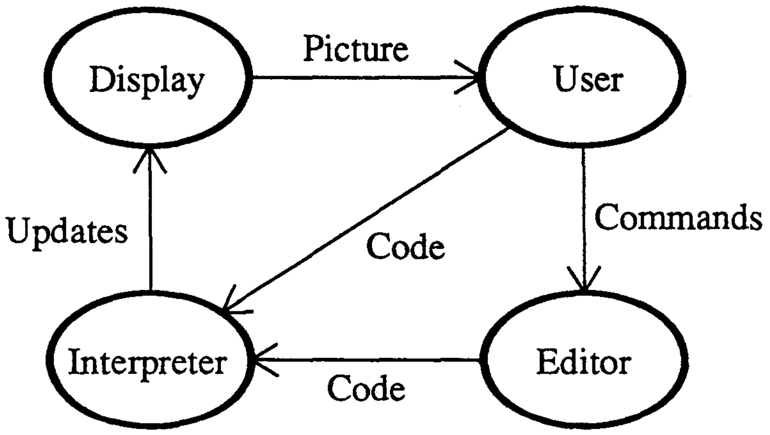


Figure 4-2: The flow of information in the Dee editor

4.1. Incremental execution

The execution of any program in any language can be thought of on two levels. It is first a series of transformations upon some set of objects that collectively comprise the internal state of the system. But it is also a series of side effects like printing values or drawing on a screen, and it is the production of these side effects that is often the real goal of running the program. The line between these effects is sometimes a little fuzzy; updating a file can be thought of as changing the state if the file is considered as part of the state or as a side effect if it is not. In Dum programs the division is quite clear: a program modifies its variables and it produces a picture as a side effect.

When a program changes, it needs to be rerun so that the resulting picture will reflect the changes to the program. Since every editing operation in Dee corresponds to some change to the underlying Dum program, these changes occur very frequently and good interactive response requires that the resulting reexecution be done quickly. Any individual change can have two kinds of effects: it can change the way the program transforms the internal state, and it can change the side effects that the program generates. Having the interpreter produce the correct side effect changes is a fairly straightforward exercise in manipulating data structures; the next chapter will discuss how it does this. Handling internal state changes is a much more interesting problem.

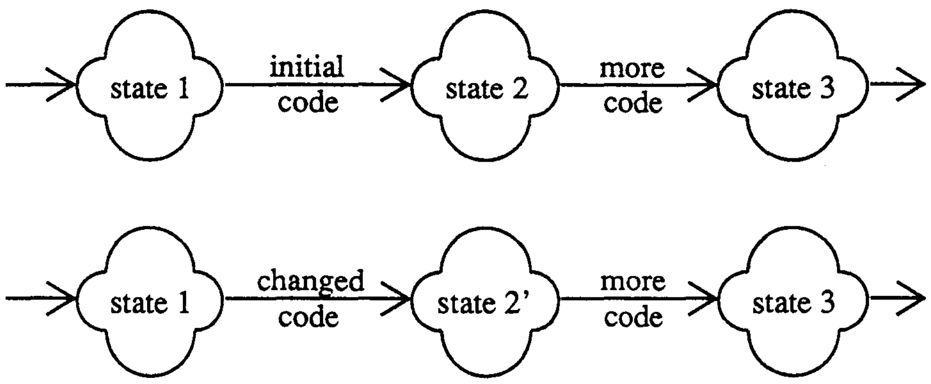


Figure 4-3: How changing code affects the program state

It is useful at this point to distinguish between two types of program changes: *structural* changes and *content* changes. Structural changes affect the way various program components fit together. These can include deleting subroutines, changing objects definitions into functions or *vice versa*, changing the return types of functions, and changing the number or types of subroutine arguments. Content changes, on the other hand, change the internal code of subroutines or add new subroutines but do not change how the subroutines interconnect. When a structural change occurs the editor reexecutes the program in its entirety; however, with content changes it can often get by by executing only a subset of the program. Structural changes are quite rare, so the extra time needed to respond to them is not a problem.

Figure 4-3 shows how the interpreter can avoid executing the entire program in response to a content change. Initially the program contains a block of code that transforms state 1 into state 2, and this is followed by some additional code that transforms state 2 into state 3. If the first block is changed, state 1 gets transformed into a new state, state 2', which may be different from the original state 2. After execution of the following code, however, the state may once again be the same as it was in the original execution. Any side effects produced before the program entered state 1 will be the same as before because the changed code has not yet been encountered, and any side effects produced after state 3 will be the same as before because the program is proceeding from the same state.

The challenge here is identifying the second block of code, that is, to identify how much of the program after the change needs to execute in order to return the state to what it was in the original execution. In some cases, no amount of extra code will satisfy the requirement; the state remains different even after executing the rest of the program. Dum, however, was designed so that common editing operations change the state only in carefully controlled ways so the interpreter needs to execute very little extra code to restore its state. Frequently state 2' is the same as state 2, and in these cases no extra code needs execution.

As discussed in the previous chapter, Dum's static structure bounds changes to the graphics state and forces subroutines to have no side effects. The first feature mostly comes into play in determining the extent of the effects when the user modifies the text of the program. If graphics state changes were unbounded, the user could change the code segment

```
    (object a_shape (triangle))
    ...
```

into

```
    # this is not legal Dum code
    (translate [20 20])            # translate origin by (20,20)
    (object a_shape (triangle))
    ...
```

and thereby change the position of not only the object a_shape but also the position of every object that was created later in the program. The problem here is that the affected part of the execution is not bound by the change to the text. In Dum, however, the user would change the code either into

```
    (with (translate [20 20])
        (object a_shape (triangle))
    )
    ...
```

to translate just the triangle, or into

```
    (with (translate [20 20])
        (object a_shape (triangle))
        ...
    )
```

to translate the triangle and everything following. In either case, the change embraces all the code affected by the change; there are no lingering after effects.

This is less important when the editor changes the code since it could limit itself to changes that have no long term effects. In the above example using nonexistent state changing statements, the editor could change to code into something like

```
    # this is not legal Dum code either
    (gsave)                        # save the graphics state
    (translate [20 20])            # translate origin by (20,20)
    (object a_shape (triangle))
    (grestore)                     # put it back
    ...
```

The functional nature of object definitions is much more important. Since an object definition cannot modify nonlocal variables, the editor can insert an object invocation anywhere in the program without worrying what effects it will have on the code that follows: it will have no effects whatever. It can also change the code within an object definition as much as it wishes, knowing that these changes cannot affect anything besides the actual invocations of that definition. Finally, since the definition cannot look at nonlocal variables or at the graphics state, changes to an object definition cannot affect the subobjects as long as their argument lists are unchanged.

A primary issue in incremental execution is establishing the appropriate granularity. When a piece of code changes, the interpreter must reestablish the program state somewhere before the code and execute until it can be sure that the program state is consistent with what it was before.

The interpreter must therefore save the program state at appropriate intervals during the initial execution and use these saved states in incremental execution. The question is how frequently these states should get saved. Saving them too infrequently leads to extra code being executed both before and after the change; saving them too frequently slows down execution too much and uses a lot of storage.

The storage problem can be partially alleviated by using data compaction. Each individual section of code is likely to change only a small part of the state, so the interpreter could save the entire state in some places and save only the changed parts in between. The problem with this approach is that reestablishing the state now requires reconstructing it from multiple sources; doing this is likely to be nearly as slow as executing extra code.

Dee's solution is to save the state at the beginning and the end of each execution of an object definition. Saving at the beginning is easy; it only requires saving the values of the arguments. Saving at the end is done by maintaining the program execution stack as a linked list of stack frames; when an object invocation exits its stack frame is removed from the stack and saved in the object. This allows the final variable values to be saved without doing any copying. The initial saved state allows the interpreter to reexecute each invocation of a changed object in isolation from the rest of the program; the final state allows it to avoid completely reexecuting the definition when the only change has been to add code to the end.

As discussed in the previous chapter, there are only a few ways a Dum program can use object references: it can *draw* them, *delete* them, *raise* them, *lower* them, *transform* them, and *recall* them. In particular, the only way a program can use their values to affect the flow of further execution is through their control points; these can be used like any other point value. But the interpreter knows what parts of the program depend upon the control points; these are just the parts of the program delimited by *using* statements for the changed object.

Thus, when an object definition changes, it suffices to reexecute each invocation of the object. The original values of the control points for each invocation are compared to the new values, and, if they vary, the *using* statements associated with these invocations each get reexecuted.[8] Since the interpreter also maintains the final state of each invocation to an object, it can extend the executions of the objects rather than completely reexecuting them when additional code gets added to the end of a definition. Further, when an object that has variants is changed or extended, the interpreter must also reexecute invocations of the variant objects.

There are three other kinds of content changes possible to a program: the definitions of functions can change, the main program can be extended, and the main program can change internally. The second of these cases is easily handled by saving the final state of the main program and restoring it before executing the added code. The other two situations cause more difficulties, and, should they occur, the interpreter abandons incremental execution and just reexecutes the entire program.

[8]No comparison is done in the current implementation; it just assumes that the control point values always change.

The problem with function definitions is that changing a definition is likely to change its value, and changing its value can affect the later execution of the program in unpredictable ways. Since most of the code in Dum programs is dedicated to producing a picture, functions are used primarily as support operations peripheral to the main thread of execution. This means that, in practice, function definitions change much less frequently than object definitions, so the extra overhead incurred when functions change is not a problem. In particular, the editor never changes functions; the only time they change is when the user changes them explicitly through the text editor. Call graph analysis could eliminate some of these full executions by reexecuting only objects that actually use the changed function, but this was not done in the current implementation.

The problem is more severe with the main program since it changes more frequently. Many full executions could be avoided by saving additional state checkpoints between some of the statements in the main program, especially towards the end where changes occur most frequently. About half of the main program changes are to the statements just added to the program by the most recent editor operation, so saving even one checkpoint would eliminate many full executions. The current implementation, however, does not do this.

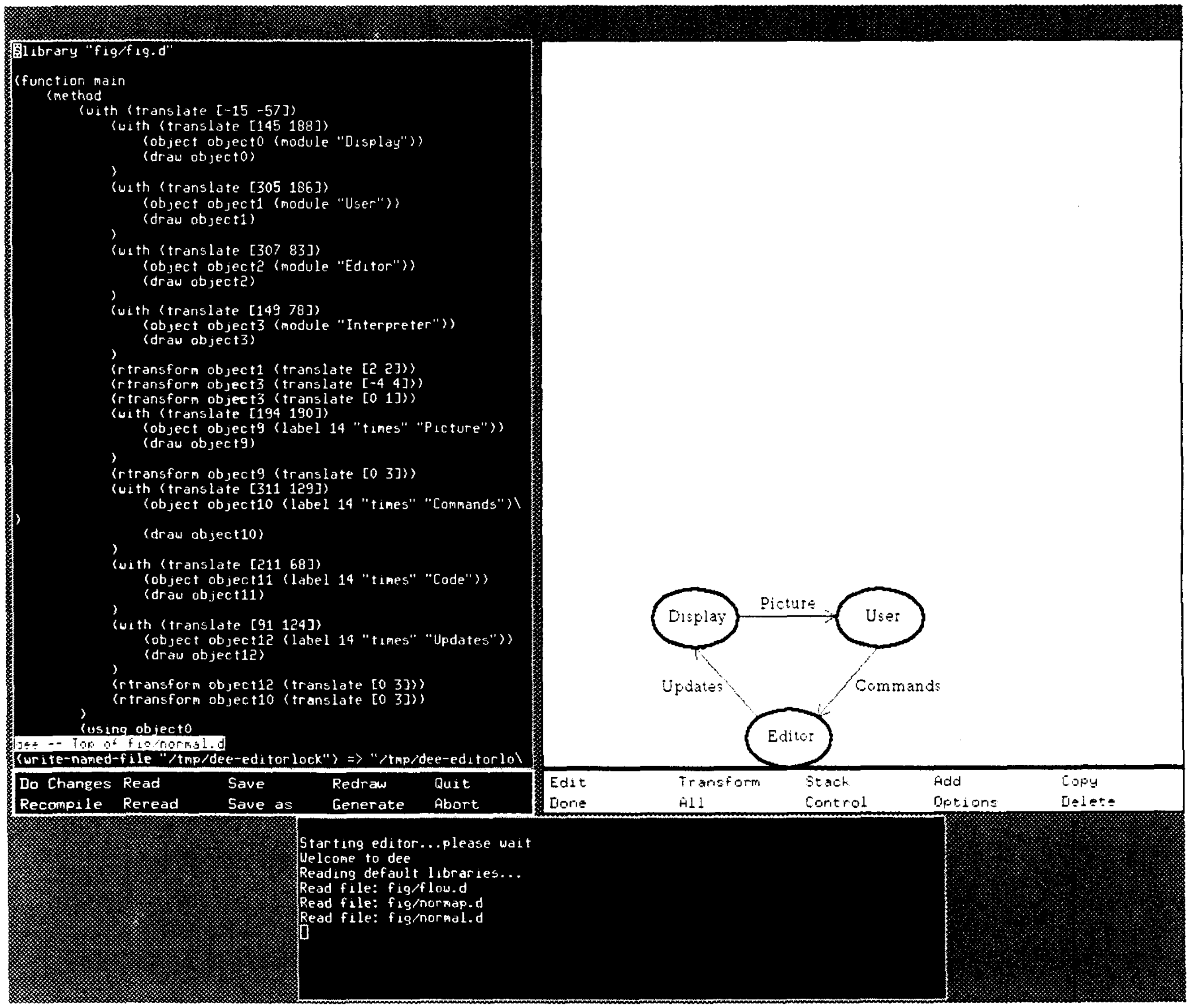
4.2. User interface

Figure 4-4 shows a snapshot of the screen as it appears during an editing session with Dee. On the left is a window containing the text of the current program, and below it are buttons for commands that operate upon the picture as a whole. On the right is a window with the picture and buttons for graphics editor operations. At the bottom a dialog window provides an area for Dee to display messages and for the user to enter responses.

A text editor runs in the left window to allow the user to modify the program text. The current implementation uses a version of Emacs [13] with some customized functions to streamline editing, but Dee does not rely upon any particular features of Emacs so other editors would serve equally well. The buttons below provide the standard editing functions *Read*, *Reread*, *Save*, *Save as*, and *Quit*. There are also several functions unique to Dee: *Do Changes*, which tells the interpreter to use incremental execution to execute the changes made manually to the text, and *Recompile*, which tells the interpret to fully reexecute the program. *Recompile* is actually superfluous since *Do Changes* will always discover when full reexecution is necessary; however, it is sometimes useful for debugging purposes to force reexecution even when no changes have occurred. Other operations are *Redraw*, to refresh the screen, *Generate*, to generate a PostScript file for hard copy, and *Abort*, to stop the execution of a running Dum program.

The user begins a session by using the *Read* function to read in some saved Dum program. An empty drawing can be obtained by reading a nonexisting file; in this case Dee initializes the drawing with an empty main program. The interpreter executes the program, and the resulting picture appears in the window on the right. The user is then free to manipulate the picture either by using the graphics editor or by editing the source.

The graphics editor uses the familiar select-then-operate mechanism: a subset of the objects in the picture comprise the *selection* and the various operations act upon all selected objects. The user modifies the selection by pointing at objects and clicking a mouse button; depending upon which button is pushed the pointed-to object *becomes* the selection, is *added* to the selection, or



```
library "fig/fig.d"

(function main
    (method
        (with (translate [-15 -57])
            (with (translate [145 188])
                (object object0 (module "Display"))
                (draw object0)
            )
            (with (translate [305 186])
                (object object1 (module "User"))
                (draw object1)
            )
            (with (translate [307 83])
                (object object2 (module "Editor"))
                (draw object2)
            )
            (with (translate [149 78])
                (object object3 (module "Interpreter"))
                (draw object3)
            )
            (rtransform object1 (translate [2 2]))
            (rtransform object3 (translate [-4 4]))
            (rtransform object3 (translate [0 1]))
            (with (translate [194 190])
                (object object9 (label 14 "times" "Picture"))
                (draw object9)
            )
            (rtransform object9 (translate [0 3]))
            (with (translate [311 129])
                (object object10 (label 14 "times" "Commands")\
)
                (draw object10)
            )
            (with (translate [211 68])
                (object object11 (label 14 "times" "Code"))
                (draw object11)
            )
            (with (translate [91 124])
                (object object12 (label 14 "times" "Updates"))
                (draw object12)
            )
            (rtransform object12 (translate [0 3]))
            (rtransform object10 (translate [0 3]))
        )
        (using object0
dee -- Top of fig/normal.d
(write-named-file "/tmp/dee-editorlock") => "/tmp/dee-editorlo\
```

```
Starting editor...please wait
Welcome to dee
Reading default libraries...
Read file: fig/flow.d
Read file: fig/normap.d
Read file: fig/normal.d
```

Figure 4-4: A sample editing session

is *removed* from the selection. By clicking the button more than once without moving the mouse, the user can select objects that lie behind other objects in the picture. Initially the user can only select objects defined in the main program; an object's component subobjects are not individually selectable. Selected objects are indicated by displaying small blocks around the bounding boxes of the selections. Figure 4-5 shows the selection boxes for various figures.

Buttons for graphics editing functions are located below the picture. The user can *Edit* selected objects, *Transform* them, *Stack* them, *Copy* them, or *Delete* them. There are also two functions that act independently of the selection, *Transform All* and *Add.* The following paragraphs will describe how these operations appear to a user; the next section will describe how they modify the program text.

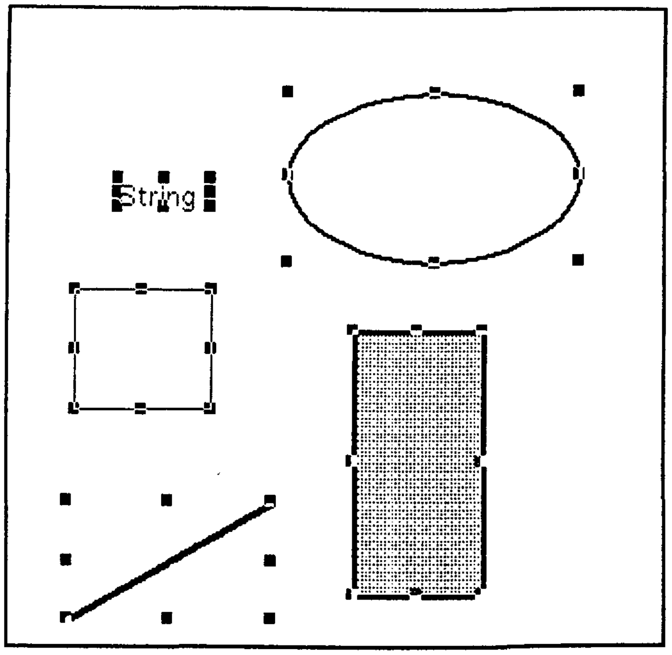


Figure 4-5: Various selected objects

Editing requires all objects in the selection be invocations of the same object type.[9] A pop-up menu offers three varieties of editing: the object definition can be changed, causing all instances of this object to change; the selected instances can be changed into instances of a new object that is a variant of the original object; or the selected instances can be changed into instances of a new object that is initially the same as the original object but is not a variant. The current selection is stacked, and one of the selected objects becomes the prototype for the change. At this point only objects that are subobjects of the object being changed can be selected, and they can then be operated upon using any of the editing functions. Changes to the object definition take place immediately to all instances of the object. During the editing the user can add new control points to the object by clicking the *Control* button; values for the points are specified using the mouse. When the user has finished editing the object, he clicks the *Done* button, and the selection that was stacked when the *Edit* button was chosen is restored.

Transforms come in six varieties and three flavors. The varieties are *translate*, *rotate*, *scale*, *scale x*, *scale y*, and *stretch*, or nonuniform scale; the flavors are *normal*, *anchored*, and *exact*. In normal transforms the selected objects' bounding boxes are displayed as flashing boxes that the user can drag around with the mouse; to assist in exact placement a small pop-up window appears that shows the current value of the transformation. Rotations and scalings take place around the object's origin, that is, the position on the screen that corresponds to (0,0) in the object's coordinate system. Anchored transforms are just like normal ones except that the user first specifies the center of the transformation with a mouse click; there are of course no anchored translations. In exact transforms the user is prompted for the transform's value in the

[9]As a simplification, the current implementation only allows a single object to be in the selection. The extension to multiple objects is straightforward.

dialog window; the mouse is not used at all. The various types of transforms are selected through a three layer pop-up menu.

Stack allows the selected objects to be either raised or lowered with respect to objects they overlap. If more than one object is selected the stacking is done in the order in which the objects were selected; this is only relevant when the selected objects overlap each other.

Copy duplicates each of the selected objects. As in transforms, the selected objects' bounding boxes are dragged with the mouse.

Delete deletes each of the selected objects from the picture.

Transform All transforms every subobject in the object being edited by the same amount, or, if the main program is being edited, every object in the picture. It is different from the other operations in two ways: first, it ignores the current selection, and, second, it also operates upon the paths in the current object. All the varieties and flavors of regular transforms are also available through *Transform All*. This function is most useful for transforming the entire picture.

Add presents the user with a multiple level pop-up menu of objects that can be added. One pane contains all objects defined in the current program as well as the special entry *new*, and additional panes contain all items defined in libraries included in the program. Several libraries are always included by default; these provide rectangles, curves, labels, arrows, and other common objects. Dee first requests the origin for the object to be added and then requests values for each of its parameters; a parameter name protocol specifies how Dee obtains these parameter values. Certain parameters are provided automatically by Dee depending upon the current values set by the user: these are number parameters named `%linewidth` and `%fontsize`, paint parameters named `%fillpaint`, and string parameters named `%font`. Point valued parameters are input with the mouse, and if an array parameter is named `%pointarray`, Dee will fill the array with a sequence of such points. Objects parameters are picked as in the selection mechanism, and string and number parameters are requested in the dialog window.

Any time Dee requests a point, the user can chose either exact positions on the screen or nearby control points by using different mouse buttons. Control points are thus gravity active; mechanisms like grid points can be provided by including objects in the picture that produce no graphical output but define control points for other objects to use.

4.2.1. Bounding boxes

Dee highlights selected objects by putting small squares on the screen at the corners and edges of their bounding boxes, and gives feedback for interactive transformations by dragging bounding boxes with the mouse. Because of the semantics of objects, these bounding boxes behave in what may be a somewhat unexpected manner.

The bounding box of an object is defined to be the smallest rectangle containing the object with sides parallel to the axes of the object's parent. If the object's parent has been rotated or scaled, however, the bounding box on the screen may not have edges parallel to the edges of the window and may sometimes not even be a rectangle.

For example, consider Figure 4-6. This shows the picture produced by invoking this object definition:

```
(defineobject boxes
    (method
        (with (translate [50 25])
            (object rect1 (rectangle [75 30] 2)))
        (draw rect1)

        (with (concat (translate [175 25]) (rotate 30))
            (object rect2 (new rect1)))
        (draw rect2)

        (with (concat (translate [300 25]) (scale [1.5 .75]) (rotate 30))
            (object rect3 (new rect1)))
        (draw rect3)
    )
)
```

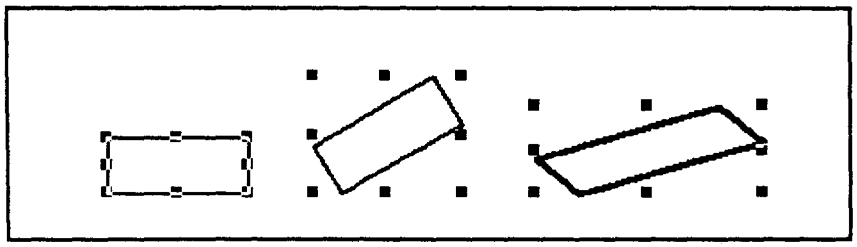


Figure 4-6: Bounding boxes of three objects

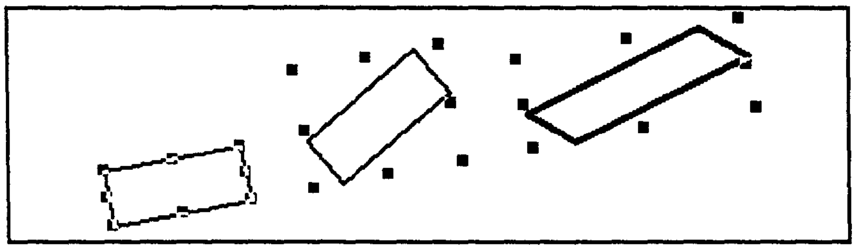


Figure 4-7: The same, in a rotated coordinate system

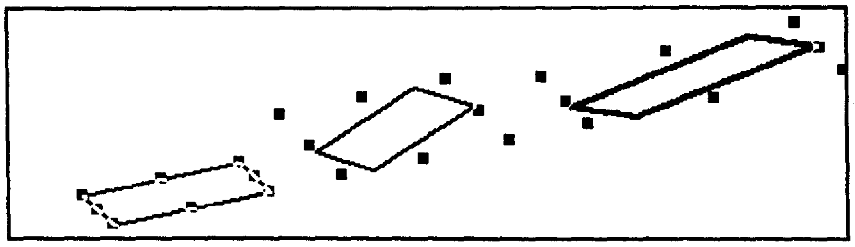


Figure 4-8: The same, in a skewed coordinate system

The three rectangles have been invoked with different transformations: the first was just translated, the second rotated then translated, and the third rotated, scaled, and then translated. In all three cases Dee correctly calculates the bounding box of the rectangle. If the `boxes` object is rotated in the picture, the result is as in Figure 4-7. The bounding boxes are now rotated so that their edges remain parallel to the axes of the rotated object. Figure 4-8 shows the results of a skewed transformation of the boxes object. Here the bounding boxes have become parallelograms.

One result of this is that the bounding box used for dragging in interactive transformations can change its shape. Figure 4-9 shows six snapshots of a rotating bounding box taken in a rectangular coordinate system; the six rotations shown are 20°, 40°, 60°, 80°, 100°, and 120°. Compare this with Figure 4-10, taken in a skewed coordinate system. Here the shape of the bounding box is different for each rotation. The same effect occurs in scaling; Figures 4-11 and 4-12 show scale factors of (0.25,2), (0.5,1.67), (0.75,1.33), (0.75,-1.33), (0.5,-1.67), and (0.25,-2) in snapshots taken in a rectangular and in a skewed coordinate system.

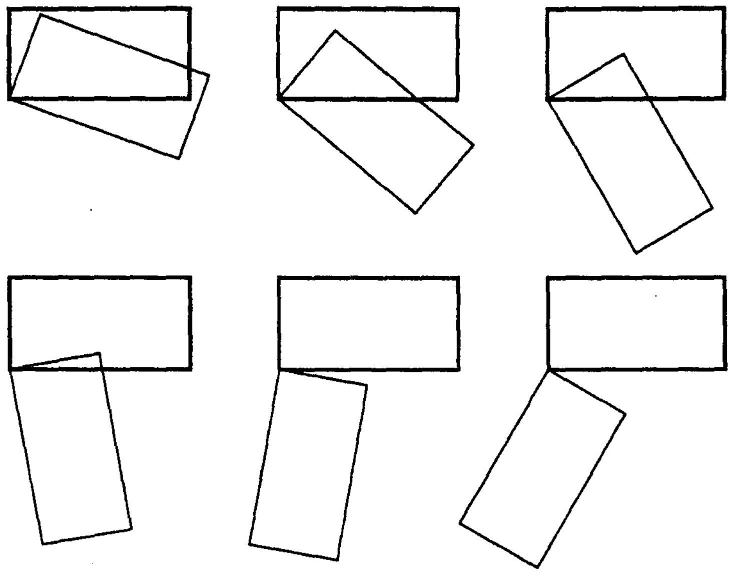


Figure 4-9: A bounding box being rotated

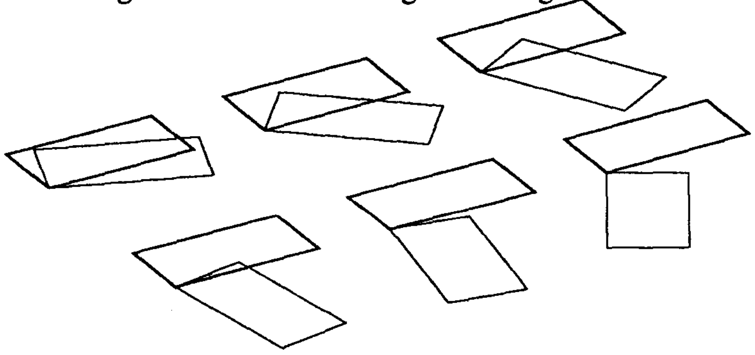


Figure 4-10: The same, in a skewed coordinate system

4.3. Generating code

When the user performs one of the various graphics editor operations, the editor modifies the code of the current program and invokes the incremental execution module to do the changes. This section will discuss the forms that these modifications take.

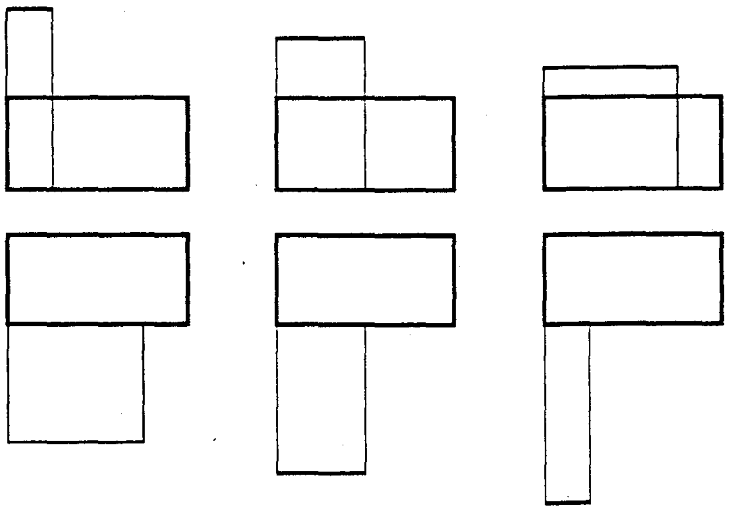


Figure 4-11: A bounding box being scaled

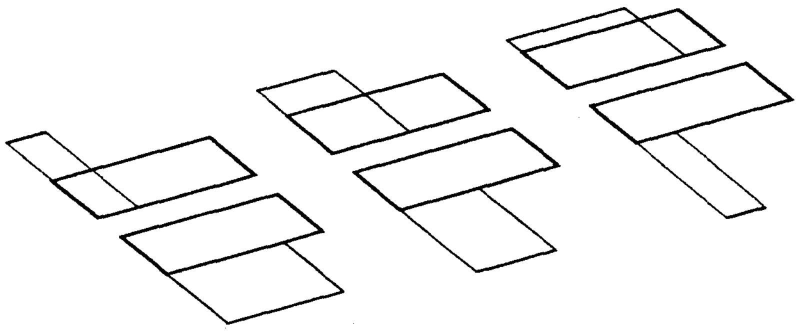


Figure 4-12: The same, in a skewed coordinate system

In many cases it is possible for the editor to modify the code in either of two ways: it could change the original invocation of an object, or it could add extra statements to the end of the invoking routine. For example, assume the program originally contained code that generated a circle with radius 50 translated to (100,100)

```
(with (translate [100 100])
    (object a_circle (circle 50))
)
(draw a_circle)
```

and, through the editor, the user moved the circle to (200,200). The editor could either change the original code to

```
(with (translate [200 200])
    (object a_circle (circle 50))
)
(draw a_circle)
```

or it could append the statement

```
(transform a_circle (translate [200 200]))
```

to the end of the current routine. Which should it chose?

The first has the advantage that it keeps the program much cleaner. Objects are frequently moved around many times before the picture assumes its final state, so programs would become littered with dozens of extra statements at the end. These clutter up the program text, obscure the program flow, and make the program take longer to execute.

Unfortunately, the first solution will not work if the subobject being moved was defined within a loop or if the object being edited is a variant. In these situations the definition is untouchable; the editor must use the second solution. Since it has to do modifications this way when editing objects that are variants, the editor just does it this way all the time.

Using the second solution has two additional advantages. The actual modification of the program text is much easier to do this way since appending to the end of a routine takes less text manipulation than changing the middle of a routine. More important, appending to the end means that the incremental execution module can extend execution rather than redoing it, so the results of the change take place more quickly. The only disadvantage is the cluttering up of the program text; however, this can be solved by manually invoking a source code optimizer upon the program when it gets too messy. The optimizer replaces trailing *transform*, *raise*, *lower*, *delete*, and *recall* statements by the appropriate changes to the invocations whenever possible. The following descriptions of the modifications made by various commands only describes the changes as they actually take place; next chapter contains a section on the optimizer that describes how it transforms the text to remove the trailing editing statements. In all the examples it is assumed that there is only one object in the selection and that the variable `obj` contains a reference to it. If there are multiple objects in the selection the process must be iterated for each one.

The three types of *editing* are all treated slightly differently. The simplest change is choosing to change the definition of an object; this doesn't actually modify the text, it just changes the editor's focus in the program to the particular object definition. If the user chooses to edit the instances as different objects, the editor prompts the user for the name of the new object and appends a *recall* statement

```
    (recall obj (<new name> <parameters to original call>))
```

at the end of the current routine. Before executing the recall statement, it creates the definition for the new object. If the selection is being edited as a variant, the definition is

```
    (defineobject <new name> (variant <old name>)
        (method
        )
    )
```

and if the selection is being edited as an independent object the definition is a copy of the original definition with the new name. The new definition is parsed, and then the recall statement is executed.

Transforms are done by appending a *transform* statement to the program:

```
    (transform obj <new transformation>)
```

This is the same for all flavors of transformation. The value of the transformation for an anchored transform is just a concatenation of a rotation or scaling with a translation.

When *Stack* is chosen, the editor appends either a *raise* or a *lower* statement for `obj` to the program.

The *Copy* operation requires the editor to come up with a name for the new object instance. This new name is then assigned the result of calling *new* on the original object with the appropriate transformation and the result is drawn:

```
(with <transformation of new object>
    (object <new name> (new obj))
)
(draw <new name>)
```

Delete just appends a *delete* statement for `obj`.

Transform All is the one operation that cannot be done by appending statements since it operates on paths as well as objects. It instead wraps the entire body of the routine in a *with* statement

```
(with <transformation>
    <original routine body>
)
```

and reexecutes the routine. Since this involves modification, not appending, it is impossible to do a *Transform All* on an object that is a variant of another object.

Add acts differently depending on whether the object to add already exists or is a totally new object. If the latter, the editor prompts for the new name and creates a new skeleton definition for the object:

```
(defineobject <new name>
    (method
    )
)
```

In either case the editor creates a new name for the instance and appends statements to the program to instantiate and draw the object to be added

```
(with <transformation of new object>
    (object <new name> (<name of object> <parameters>))
)
(draw <new name>)
```

and executes the statements. If any control points were specified as parameters, the new code is wrapped with *using* statements for the objects involved. Finally, if a new type of object is being added, the editor shifts its focus to the new object so that the user can add subobjects to the newly defined object.

4.4. An extended example

To make all this more concrete, here is an extended example that uses most of the interesting features of the Dee editor. Each step shows the changed section of the program as well as the picture thus far produced. The part of the code added in each step is shown in boldface.

The user starts out with an empty program, shown in Figure 4-13. He then selects *Add new* from the menu, specifies that this new object is to be called `car`, and indicates the point (325,25) as the origin for the object using the mouse. Dee transforms the program as shown in Figure 4-14. It creates a skeleton definition for the object `car` and adds an instantiation of `car` in the main program called `a_car`.[10] Since the definition of `car` is empty, the instantiation does not

[10]Dee actually creates variables with uninformative names like `object17`. They have been changed in this example to add clarity.

yield any picture yet. The focus of editing shifts to the definition of `car` so any new objects added will be added to this definition.

```
(function main
    (method
    )
)
```

Figure 4-13: Example: the initial program

```
(function main
    (method
        (with (translate [325 25])
            (object a_car (car)))
        (draw a_car)

    )
)

(defineobject car
    (method
    )
)
```

Figure 4-14: Example: instantiating a `car`

In a step not shown here, the user specifies the default fill pattern to be 50% gray and the default line width to be zero. He then uses *Add* twice to create two instantiations of the library object `filled_rectangle`. `Filled_rectangle` takes three arguments, a point, a number named `%linewidth`, and a paint named `%fillpaint`, and draws and fills a rectangle from the point (0,0) to the passed point with a border width of `%linewidth` and a fill pattern of `%fillpaint`. Because the number and paint parameters are named `%linewidth` and `%fillpaint`, Dee automatically supplies their values. Figure 4-15 shows the result of adding these two rectangles. For each, Dee requests the value for the origin and then the value for the point parameter using the mouse. In the first rectangle, `body`, the origin is at the origin of the `car`, so there is need for a *with* statement to translate it. In the second, `top`, the origin is at the point (25,30), so a *with* statement is required.

```
(defineobject car
    (method
        (object body (filled_rectangle
                [100 30] 0 (grayscale 0.5)))
        (draw body)

        (with (translate [25 30])
            (object top (filled_rectangle
                    [50 25] 0 (grayscale 0.5))))
        (draw top)

    )
)
```

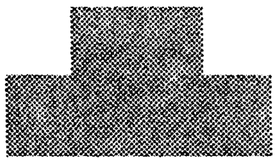


Figure 4-15: Example: adding the car body

The user then changes the default to a white fill and a border width of one. In Figure 4-16 he adds another rectangle, `win1`, using these values.

```
(defineobject car
    (method
        ...

        (with (translate [31 31])
            (object win1 (filled_rectangle
                    [17 20] 1 (grayscale 1))))
        (draw win1)

    )
)
```

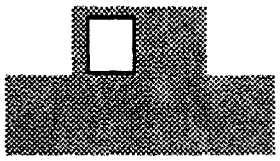


Figure 4-16: Example: adding a window

Figure 4-17 shows the result of a new operation, *Copy*. Here the user copies `win1` to a new location; this location is specified by dragging the bounding box of `win1` to the new position (52,31). Dee creates the new instance by adding a call to *new* with `win1` as the argument and assigning the result to the variable `win2`.

```
(defineobject car
    (method
        ...

        (with (translate [52 31])
            (object win2 (new win1)))
        (draw win2)

    )
)
```

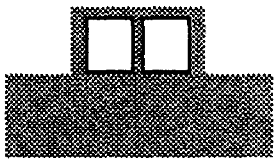


Figure 4-17: Example: copying to make another window

In Figure 4-18 a similar process is used to add two circles for the tires. The `filled_circle` library object draws a circle around its origin though a specified point. After drawing the wheels, the user clicks the *Done* button and the editing focus returns to the main picture.

```
(defineobject car
    (method
        ...

        (with (translate [20 0])
            (object tire1 (filled_circle
                    [0 10] 1 (grayscale 0))))
        (draw tire1)

        (with (translate [80 0])
            (object tire2 (new tire1)))
        (draw tire2)

    )
)
```

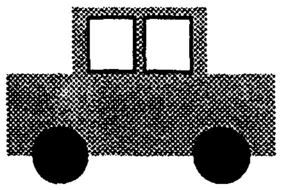


Figure 4-18: Example: adding wheels

The user then uses *Copy* twice to make two copies of the car; this is illustrated in Figure 4-19. The two copies are named 2nd_car and 3rd_car.

```
(function main
    (method
        (with (translate [325 25])
            (object a_car (car)))
        (draw a_car)

        (with (translate [325 100])
            (object 2nd_car (new a_car)))
        (draw 2nd_car)

        (with (translate [325 175])
            (object 3rd_car (new a_car)))
        (draw 3rd_car)

    )
)
```

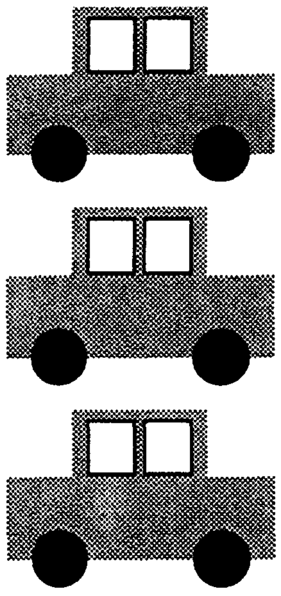


Figure 4-19: Example: creating two more copies of the car

Figure 4-20 shows the result of selecting the middle instance, 2nd_car, and then clicking the *Edit as variant* button. Dee requests a new name for the variant, and when truck is entered it creates a definition for truck as a variant car. 2nd_car is then recalled to be a truck. Since the definition of truck is initially empty, the picture remains unchanged, but the editing focus is now on truck.

```
(function main
    (method
        (with (translate [325 25])
            (object a_car (car)))
        (draw a_car)

        (with (translate [325 100])
            (object 2nd_car (new a_car)))
        (draw 2nd_car)

        (with (translate [325 175])
            (object 3rd_car (new a_car)))
        (draw 3rd_car)

        (recall 2nd_car (truck))

    )
)

(defineobject truck (variant car)
    (method
    )
)
```

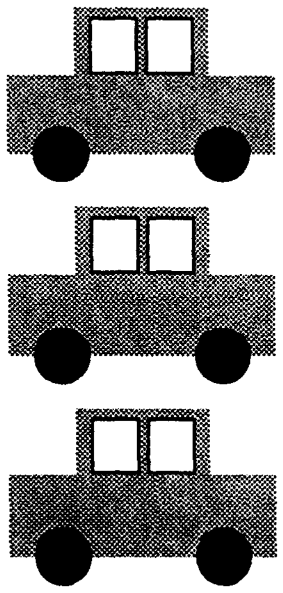


Figure 4-20: Example: turning one copy into a truck

In Figure 4-21 the user makes two changes to the truck definition. He first deletes win2 and then uses a *Scale x* transformation to change the size of the rectangle top. The original transformation of top, (translate [25 30]) is replaced by the new transformation (concat (translate [25 30]) (scale [0.6 1])). After making these changes, the user again clicks *Done* and the focus returns to the main picture.

Next the user selects the top instance, 3rd_car, and chooses *Edit instance* (Figure 4-22). The user supplies wagon as the new name and Dee creates a definition for wagon which is a copy of the definition for car and then adds a *recall* statement for 3rd_car. This is very different from the change made to 2nd_car: truck's definition is a variant of car's while wagon's definition is a copy of it. Again the picture remains the same and Dee changes its focus to the new definition.

```
(defineobject truck (variant car)
    (method
        (delete win2)
        (transform top (concat (translate [25 30])
                (scale [0.6 1])))

    )
)
```

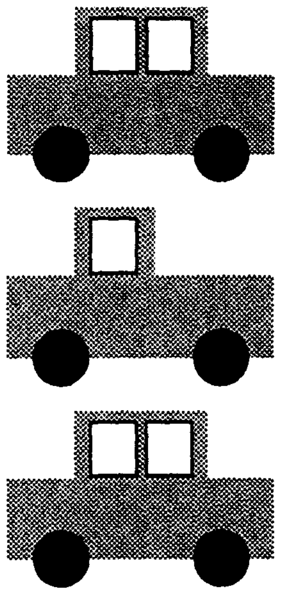


Figure 4-21: Example: editing the car to make it a truck

```
(function main
    (method
        (with (translate [325 25])
            (object a_car (car)))
        (draw a_car)

        (with (translate [325 100])
            (object 2nd_car (new a_car)))
        (draw 2nd_car)

        (with (translate [325 175])
            (object 3rd_car (new a_car)))
        (draw 3rd_car)

        (recall 2nd_car (truck))
        (recall 3rd_car (wagon))

    )
)

(defineobject wagon
    (method
        ...copy of code for car
    )
)
```

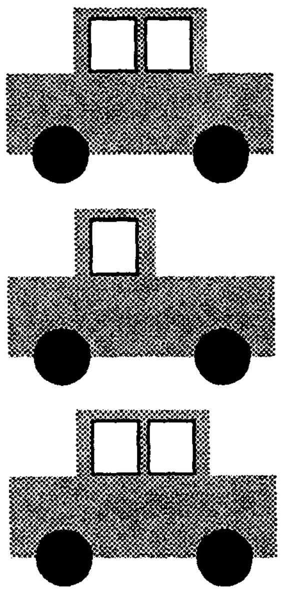


Figure 4-22: Example: turning another copy into a wagon

In Figure 4-23 the user deletes `win1`, `win2`, and `top` from `wagon`. If the optimizer were now invoked, the invocations of these objects would disappear. Again *Done* returns the focus to the main picture.

```
(defineobject wagon
    (method
        ...

        (delete win1)
        (delete win2)
        (delete top)

    )
)
```

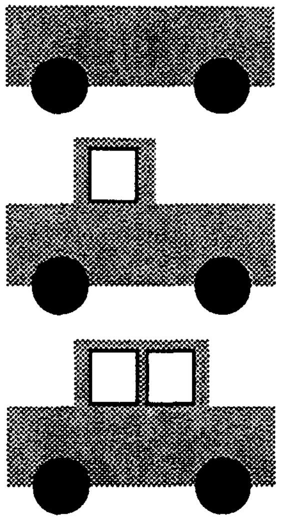


Figure 4-23: Example: editing the car to make it a wagon

The user then selects the original car for editing using *Edit definition*. This change involves adding two small white circles centered on the tires. Figure 4-24 shows the result of this; two things are worth noticing here. The user specifies the center of `tire1` as the origin of `hub1`; this is done by moving the mouse to approximately the right position and clicking the button to find the nearest control point. Since the transformation for `hub1` involves a control point, the entire invocation is wrapped in a *using* statement for `tire1`. This structuring ties the invocations of the hubcaps to the locations of the wheels; if a wheel were moved its hubcap would move with it. The second thing to notice is that the instantiation of `truck`, `2nd_car`, also gains hubcaps since `truck` is a variant of `car`.

In Figure 4-25 the focus is again returned to the main picture and the user does an *Anchored rotate all*, rotating the entire picture around the center of `2nd_car`. Dee computes the appropriate transformation and wraps the entire main program in a new *with* statement. The final version of the program can be found in Figure 4-26.

```
(defineobject car
    (method
        ...

        (using tire1
            (with (translate (getpoint tire1 center))
                (object hub1 (filled_circle
                        [0 5] 0 (grayscale 1))))
            (draw hub1)
        )

        (using tire2
            (with (translate (getpoint tire2 center))
                (object hub2 (new hub1)))
            (draw hub2)
        )

    )
)
```

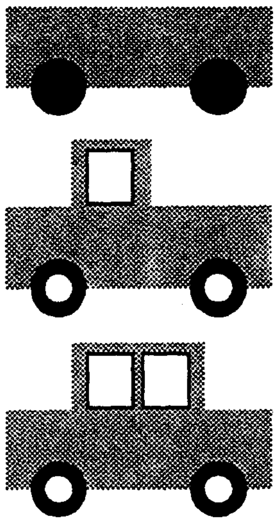


Figure 4-24: Example: adding hubcaps to the car

```
(function main
    (method
        (with (concat (translate [766.46 137.247])
                (rotate 165))

            (with (translate [325 25])
                (object a_car (car)))
            (draw a_car)

            (with (translate [325 100])
                (object 2nd_car (new a_car)))
            (draw 2nd_car)

            (with (translate [325 175])
                (object 3rd_car (new a_car)))
            (draw 3rd_car)

            (recall 2nd_car (truck))
            (recall 3rd_car (wagon))
        )

    )
)
```

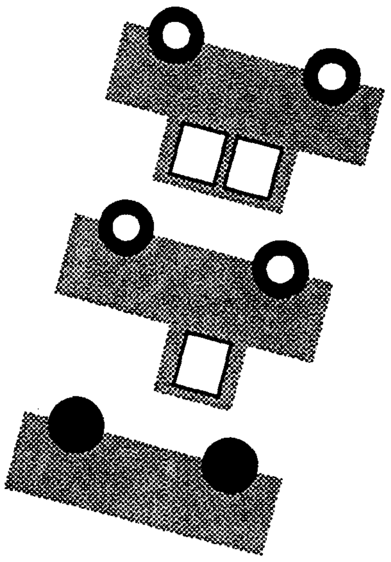


Figure 4-25: Example: rotating the entire picture

```
(function main
    (method
        (with (concat (translate [766.46 137.247]) (rotate 165))
            (with (translate [325 25])
                (object a_car (car)))
            (draw a_car)

            (with (translate [325 100])
                (object 2nd_car (new a_car)))
            (draw 2nd_car)

            (with (translate [325 175])
                (object 3rd_car (new a_car)))
            (draw 3rd_car)

            (recall 2nd_car (truck))
            (recall 3rd_car (wagon))
        )
    )
)

(defineobject car
    (method
        (object body (filled_rectangle [100 30] 0 (grayscale 0.5)))
        (draw body)

        (with (translate [25 30])
            (object top (filled_rectangle [50 25] 0 (grayscale 0.5))))
        (draw top)

        (with (translate [31 31])
            (object win1 (filled_rectangle [17 20] 1 (grayscale 1))))
        (draw win1)

        (with (translate [52 31])
            (object win2 (new win1)))
        (draw win2)

        (with (translate [20 0])
            (object tire1 (filled_circle [0 10] 1 (grayscale 0))))
        (draw tire1)

        (with (translate [80 0])
            (object tire2 (new tire1)))
        (draw tire2)

        (using tire1
            (with (translate (getpoint tire1 center))
                (object hub1 (filled_circle [0 5] 0 (grayscale 1))))
            (draw hub1)
        )

        (using tire2
            (with (translate (getpoint tire2 center))
                (object hub2 (new hub1)))
            (draw hub2)
        )
    )
)
```

Figure 4-26: The final program (continued on next page)

```
(defineobject truck (variant car)
    (method
        (delete win2)
        (transform top (concat (translate [25 30]) (scale [0.6 1])))
    )
)

(defineobject wagon
    (method
        (object body (filled_rectangle [100 30] 0 (grayscale 0.5)))
        (draw body)

        (with (translate [25 30])
            (object top (filled_rectangle [50 25] 0 (grayscale 0.5))))
        (draw top)

        (with (translate [31 31])
            (object win1 (filled_rectangle [17 20] 1 (grayscale 1))))
        (draw win1)

        (with (translate [52 31])
            (object win2 (new win1)))
        (draw win2)

        (with (translate [20 0])
            (object tire1 (filled_circle [0 10] 1 (grayscale 0))))
        (draw tire1)

        (with (translate [80 0])
            (object tire2 (new tire1)))
        (draw tire2)

        (delete win1)
        (delete win2)
        (delete top)
    )
)
```

Figure 4-26, continued

5. Implementation

This chapter covers details of Dee's implementation. Dee consists of about 14,500 lines of C code, 200 lines of MLisp [13] to streamline the editor interface, 500 lines of Dum code to provide the default object library, and 600 lines of PostScript [1] for generating hard copy. Dee uses the X Window System [12] as its graphics support.

Since Dee contains an interpreter, there is potential confusion between the Dum language it interprets and the C language used to implement it. This is particularly severe when talking about how data is stored, since some things are stored as Dum types and some are stored as C types. To avoid confusion, I will use the following conventions when talking about data representation:

Number always refers to a Dum number.
Integer and *float* always refer to C types.
Array always refers to a Dum array.
List always refers to a C array.
Linked lists will always be qualified as such.

In addition, all unions mentioned are discriminated.

5.1. Overview

Figure 5-1 shows the basic structure of Dee. The program text is parsed to produce a parse tree and a symbol table; these in turn are interpreted by the interpreter, creating a history of the execution called the execution tree, a set of object instances, and a display tree representing the structure of the picture. The display module combines the display tree with the object instances to produce a picture upon the display. When the user requests a change to the picture, the graphics editor uses the display tree and the symbol table to construct the appropriate modification to the program.

5.2. Parsing

Dee parses a program using two passes. The input file is first preparsed into a linked list containing tokens and sublists. There are three kinds of tokens: numbers, strings, and names. Numbers and strings represent constants of the appropriate type, and names represent variables, routine names, and keywords. Lists are either normal lists, containing one or more elements, or point expressions, containing exactly two elements. This pass performs no name lookup; it just translates the program text into a linked list representation.

A simple recursive descent parser then makes another pass over the resulting parse tree. This pass replaces names with symbol table pointers and checks the structure of all the language constructs. Because Dum's polymorphic arrays require run-time type checking, the parser does none other than verifying that expressions are used wherever they are required by the language syntax.

Dee maintains a hashed global symbol table containing keywords, subroutine names, and control point names. Since different objects can have control points with the same names, the names stored in the table have the object name and a "$" concatenated to the name; for example, the `top` control point of the `box` object would be stored as `box$top`. Each symbol table entry for

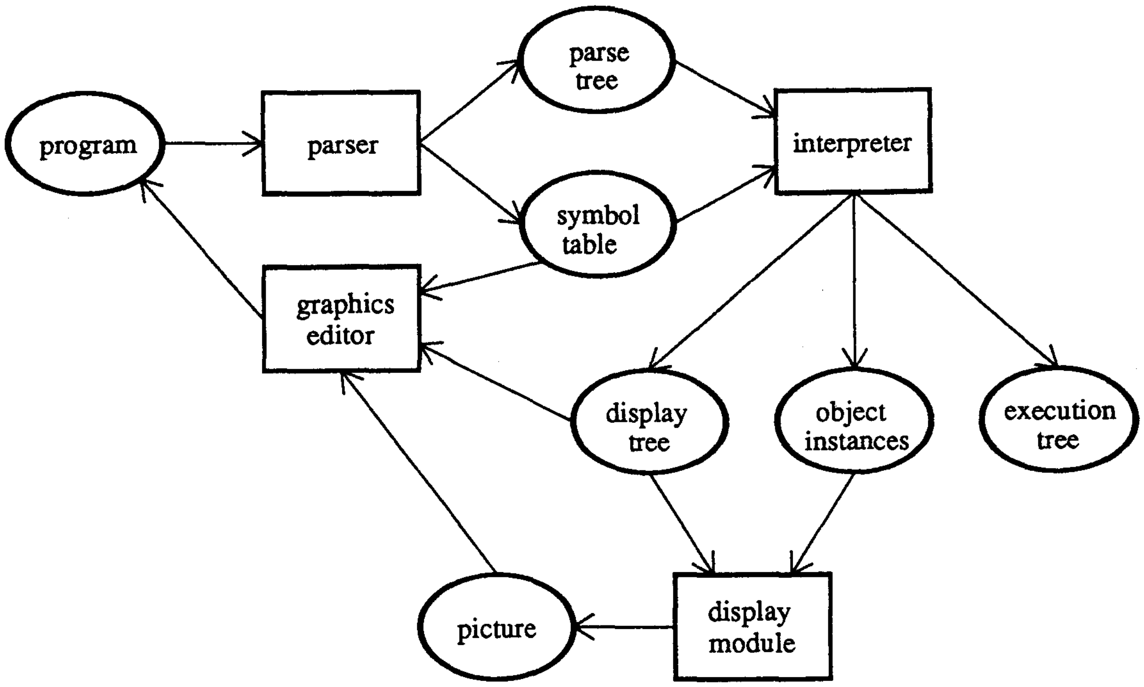


Figure 5-1: The structure of the Dee editor

a subroutine contains a pointer to a routine descriptor that in turn contains a local symbol table for the routine, stored as a sorted binary tree. The local symbol table contains the type and the stack offset for each variable; if the current routine is an object that is a variant of another object the variables all have offsets larger than those in the original object.

Dum's syntax guarantees that the first element of any list in the program is a keyword or routine name, so the parser looks for these in the global symbol table. If the lookup fails, the name is assumed to be an as yet undefined routine. Any other names in the list are local variables, so the parser looks them up in the local symbol table; if this fails and the current routine is a variant object the parser looks in the symbol table for the original. The only exception to this is the control point name argument to the `getpoint` operator, `(getpoint <object> <pointname>)`. Since the type of the object is not known at compile time, the control point name cannot be looked up until runtime.

In addition to the local symbol table, the routine descriptor contains these fields:

The return type of the routine.
The number and types of the arguments.
A list of pointers to the arguments in the local symbol table.
A list of pointers to the control points in the global symbol table.
Parent, child, and next pointers for the object variation hierarchy.
A pointer to the definition of the routine in the parse tree.
A pointer to a list of invocations in the execution tree.

5.3. Data representation

Dee's internal representation for values is fairly straightforward. There is one type of variable, a *value*, not available to programs but used heavily throughout Dee. This is just a union of each of the other types.

Numbers are stored as a union of an integer and a floating point value. Points are pairs of these numbers, and a paint is a number representing a gray scale value. Strings contain a pointer to the text itself and an integer length. The representation for objects will be described in Section 5.6.

Arrays can be stored in either of two ways, represented as a union. The first representation, called a *free* array, is a linked list of index-data pairs. The index is an integer, and the data is a value. The second representation arises because arrays are used so frequently to hold transformations. These arrays, called *transform* arrays, are stored as six element lists of floating point values with indices implicitly defined to be zero though five. The interpreter automatically converts between these representations as necessary.

5.4. Basic execution

The execution module traverses the parse tree creating a new data structure, the execution tree. This tree's nodes represent statement executions, routine calls, expressions, and iterations. As an example, Figure 5-2 shows the execution tree produced by the following short and rather useless program:

```
(function three (returns number)
    (method
        (:= three 3)
    )
)

(function main
    (method
        (number i 1)
        (while (> (three) i)
            (:= i (+ i 1))
        )
    )
)
```

The top node represents the execution of the main function. It has two children for its two statements, a datatype statement and a *while* statement. The datatype statement has an expression child for the initial value of the variable `i`. The *while* statement has two children for each iteration, an expression child for the loop condition, and an iteration child for the statements in the loop. The expression contains a routine call to > that in turn contains an expression for each argument; since > is a built-in function the call contains no statement children. The first argument to > is a call to the routine `three`. `Three` has no arguments, but contains one statement child, an assignment statement. This assignment statement has an expression child for the value being assigned. Back in the *while* loop, each iteration contains an assignment node with an expression child for its value, and the expression contains a call to the built-in routine +. The two expression children of + are the two arguments to the function, `i` and `1`.

The whole purpose of this tree is to provide the necessary bookkeeping for other functions in the editor, done by keeping numerous linked lists of nodes through the tree. For each object

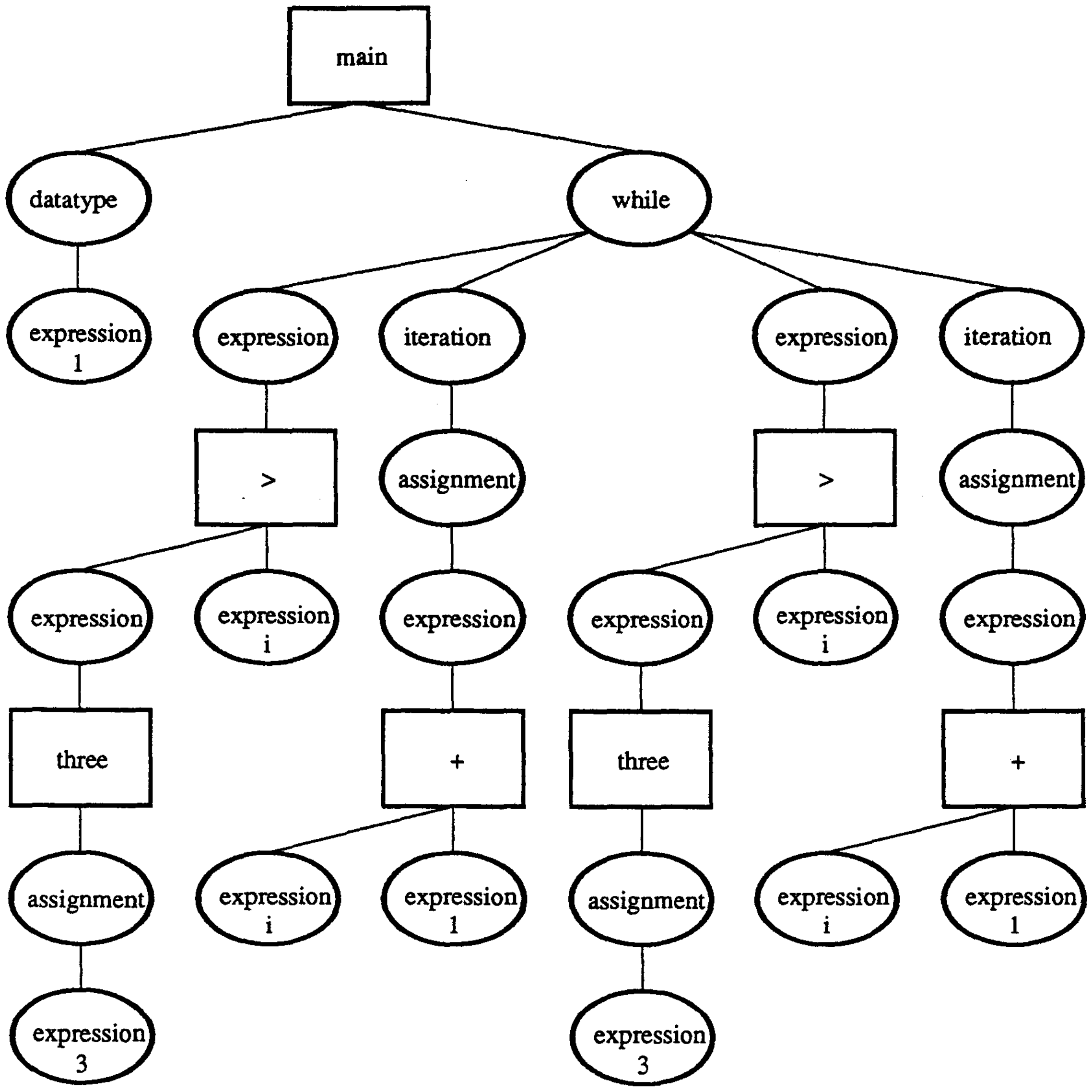


Figure 5-2: A sample execution tree

type, Dee maintains a linked list of instantiations, and for each object instance, it maintains a linked list of all *using* statements for that object and a linked list of all *using* statements for object arguments within the execution of the object. The node for a *using* statement contains some extra information: a copy of the current routine's stack frame, the current graphical transformation, and the state of the current path; these allow the interpreter to restore the program state before reexecuting the *using* statement.

5.5. Paths and the display tree

A path is maintained as a recursive data structure, each instance containing whether or not the path is to be filled, the border width, the fill paint, the path's bounding box, and a linked list of path components. Path components can be simple path construction operators like *moveto*, *lineto*, and *arc*, subpaths, transformation pushes and pops, drawn objects, or *start* and *end* marks.

When the interpreter begins execution of the main program, it creates a new empty path. As the program executes, various path components get linked into the current path. *Drawpath* and *fillpath* statements create subpaths, statements like *moveto* and *lineto* statements add the corresponding path components, and *with* adds a transformation push and pop. Each invocation of an object creates a new empty path, and statements within the object definition add components to this path. Drawing an object links its path into the current path. *Start* and *end* marks are added by the *using* statement to delineate the section of the path created by code within the *using*.

The final top-level path is called the *display tree*. This is used to draw the picture, both initially and when the window system notifies Dee that it needs to refresh its picture window. This tree is also used by the graphics editor interface to find objects pointed to by the mouse.

5.6. Objects and inheritance

An object value consists of a pass count, described later, and a pointer to an object descriptor. This descriptor contains the following information:

The transformation in effect when the object was created.
The pass count when the object was drawn.
The head of the *using* chain for the object.
The head of the *using* chain in the object.
The object's bounding box relative to its parent object.
A pointer to the object creating this object.
A pointer to the arguments in the instantiation call.
A pointer to an object low-level descriptor.

The low-level descriptor in turn contains

The object's path.
A pointer to the object's routine descriptor.
A list of values of the object's control points.
The final values of the object's local variables.

The reason for this distinction is that the low-level descriptor contains all the information common to multiple copies of the object, while the object descriptor contains the information that differs for each copy. When one object is created from another using *new*, the created object gets a new object descriptor, but shares the original object's low-level descriptor.

This sharing can potentially save an enormous amount of time and storage. Figure 5.6 shows the familiar recursive snowflake curve, this time only expanded to two levels, and below it the structure of its display tree. Here the rectangles represent paths, and the ellipses components of the path. The display is represented as a path with three components, each a *side* object. Since the second and third objects were created by calls to *new* rather than by direct calls to *side*, the three objects share the low-level descriptor with the path for the side. This call to side is with the arguments 0, for the current depth, and 2, for the maximum depth. The definition of *side* calls itself recursively with an increased depth parameter, `(side 1 2)`, and calls *new* with the result three times to create the four segments of the side. They again share a low-level descriptor, and the process recurs until the depth parameter is equal to the maximum parameter, `(side 2 2)`. In this case *side* just draws a simple line segment.

Without the path sharing, this structure would be a very bushy tree. Dee can compute and draw the snowflake expanded to three levels in 2 seconds using 61 kilobytes of data storage. If the program is rewritten without *new*, the same picture requires 9 seconds and 1023 kilobytes of storage. Expanding the snowflake to four levels requires 10 seconds and 151 kilobytes using *new* and cannot be drawn without running out of virtual memory without *new*.

Text objects are created using a built-in function, *text*, that returns an object reference. The low-level descriptor for a text object contains a string and a font instead of a path.

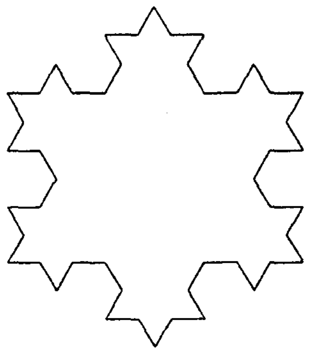
When an object is linked into a path, a reference to the object descriptor is put in the path component. This means that object descriptors must stay around, even if no variables in the program refer to them. Objects may also be multiply referred to if one object variable is assigned to another. These facts make it rather difficult to determine exactly when object descriptors should be deallocated. To simplify things, all object descriptors and low-level descriptors are kept in linked lists and deallocated only before a program is fully executed.

Whenever the interpreter executes an object definition it creates a stack frame to hold the definition's variables. The frame is a list of values (recall that a value is the union of all other types); having each entry be the same size simplifies addressing. If the object being executed is a variant of another object, the frame is large enough to hold the variables of both the original and the variant objects. Before executing the variant definition the interpreter executes the definition of the original using the variant's stack frame. Since, as described above, the variables in the variant all have offsets different from those in the original, the variant can use both its own variables and the variables of the original.

5.7. Display and funargs

The display module generates the picture through a simple traversal of the display tree. When it encounters an object, it must convert the object's relative position to an absolute position. To do this it maintains a stack of transformations; each stack entry contains both the new transformation and the cumulative product of all transformations thus far.

As mentioned in Chapter 3, funarg problems arise with transformations whenever an object gets drawn by an object other than the one that created it. Since objects can only be passed down as parameters, not up as return values, the creator's transformation must be on the transform stack somewhere. The display module needs to find this transformation and make a branch in



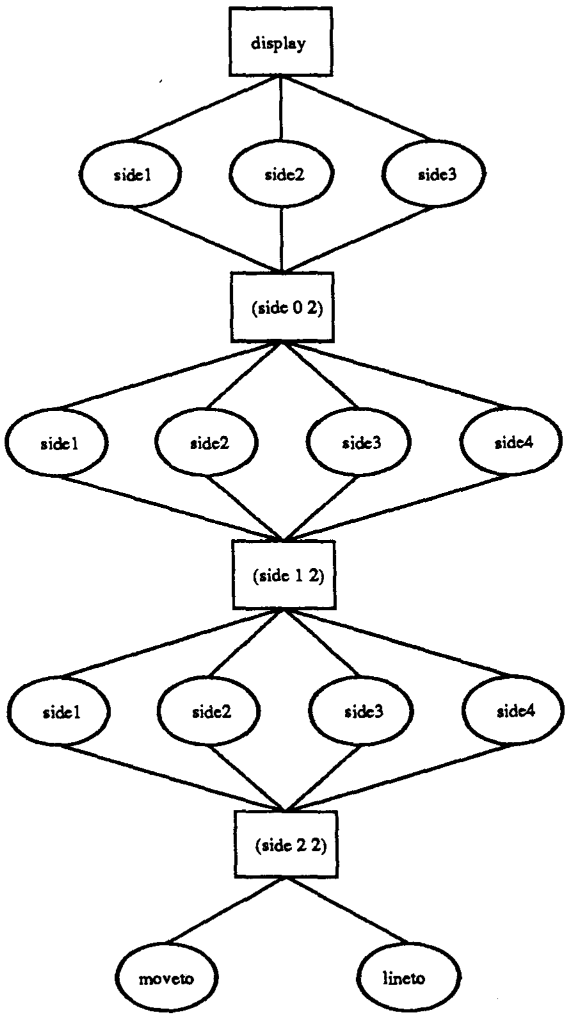


Figure 5-3: A small snowflake and its path structure

the stack for this object and any of its subobjects. Finding the creating object is made difficult because of the *new* function. Consider first a case where there is no funarg problem, that of an object A with one subobject B. A may be duplicated several times, so there can be multiple instances of A, but because these instances will all share the same path there is only one instance of B. The display module will encounter B once for each copy of A, and in each case it will calculate a different absolute transformation for B. This precludes avoiding the funarg problem completely by using stored absolute transformations. This also precludes the use of any funarg solution that involves maintaining and following a parent pointer to the creating object, since an object's parent is not unique.

What Dee does is maintain a pass count for each object. This count tells how many levels separate the current location of the object from its creator's frame. When an object is passed as a parameter, the count is incremented, and when the routine to which it was passed returns the count is decremented. The pass count is copied into the object descriptor when the object is drawn. This saved count tells the display module how many transformation stack entries it must skip before it finds the entry for the creating object.

The pass count is also used by the interpreter to calculate the value of control points. Recall that the value of a control point is the value assigned within the object definition, transformed by object's transformation, and then inversely transformed by the current transformation. The difficulty occurs when an object has been passed; in this case the calculation must invert the current transformation relative to the object that created the control point's object. An example may make this clearer. Consider the following objects:

```
(defineobject a
    (control p)
    (method
        (:= p [0 0])
    )
)

(defineobject b (args (object o))
    (method
        (with (translate [5 5])
            (print (getpoint o p)))
    )
)

(defineobject c
    (method
        (with (translate [10 10])
            (object A (a)))
        (with (translate [100 100])
            (object B (b A))
        )
    )
)
```

Here object `a` defines one control point, `p`, and gives it the value `[0 0]`. Object `b` takes an object `o` as an argument, and prints the value of its control point `p` under a translation of `[5 5]`. Object `c` instantiates an `a` translated by `[10 10]`, and then passes the result to `b` with a translation of `[100 100]`. The value of the control point `p` relative to `c` (`c` itself could be instantiated with any transformation) is `[10 10]`, so the value of the control point when it is printed is `[-95 -95]`. In order to calculate this the interpreter must take into account not only the current transformation in `b`, `(translate [5 5])`, but also the transformation of `b` in `c`, `(translate [100 100])`. It does this by keeping the same sort of transformation stack as the display module and using the pass count to determine how many transformations must be considered to find the current transformation.

5.8. The *using* statement

When an object is transformed, the interpreter must reexecute all *using* statements that depend upon the object's location. These consist of all *using* statements for the object being moved, as well as all *using* statements in the object for objects that were passed to it as parameters. These *usings* are found by following the two *using* chains stored in the object descriptor. There are several steps involved for each *using* statement; this section will call the object that is the subject of the *using* statement the *used* object, and the object whose definition contains the *using* statement the *containing* object.

The interpreter first frees the part of the execution tree below the *using* statement's node. This may delete other *using* statements; the interpreter must take care to remove these from their *using* chains. When the *using* was first executed it placed a *start* mark in the display tree before executing any subordinate statements and placed an *end* mark afterwards. By consulting pointers to these marks within the *using* node, the interpreter deletes any portion of the display tree created by statements within the *using*.

At this point all results of the original execution have been deleted. The interpreter now recreates the environment that was in effect when the *using* was first executed. The *using* node contains a copy of the current stack frame when the *using* was first executed, a pointer to the current path, and the current transformation. These all temporarily replace the values of the corresponding variables in the interpreter state. If the used object was passed to the containing object, the interpreter has to do some extra work. Any calculations of control point values require taking into consideration the transformations of ancestors of the containing object, so these transformations must be put onto the stack before the stored current transformation. In order to find these transformations the interpreter follows the parent pointer in the containing object's descriptor and uses the stored transformations in the descriptors found along the way; the pass count tells how far the parent chain must be followed. This parent pointer is not usually accurate, as described in the previous section, since calling *new* for an object creates multiple parents for all of the object's subobjects, but recall that *new* actually does a call when copying an object that was passed any objects as arguments. The parent pointer is correct in this one instance, and this is precisely when it is needed for *using*.

Once the environment has been reestablished, the interpreter reexecutes the code in the *using* statement. This reexecution may include new *using* statements; the interpreter makes sure these get put into the *using* chains ahead of the *using* currently being reexecuted to avoid needless reexecution.

5.9. Incremental parsing

When the user makes changes to the textual representation of the picture Dee must determine just what has been changed and alter the parse tree appropriately. Some window systems [23] provide the tools needed to do this easily; unfortunately X [12] does not. Building the proper tools would have been a time-consuming process clearly irrelevant to the research issues in Tweedle.

Dee runs a subprocess of Emacs [13] and communicates to it using Unix's interprocess communication mechanisms. When the user asks Dee to do the changes to the text, Dee has Emacs copy the program into a temporary file. Dee then parses this changed file and compares the new and the old parse trees to determine where the changes occur. This technique, clumsy as it is, works acceptably well in practice and has the advantage of basing the results upon changes to the parse tree rather than changes to the text of the program. The user can add or change comments or indentation, or can change a variable's name, and when the changes get executed the comparison module will report that no changes were made, causing no reexecution to take place.

5.10. Incremental execution

As discussed in Section 4.1, there are four different possibilities in incremental execution. Some objects may need reexecution, some objects may need extension, the main program may need extension, and the main program may need full reexecution. The final possibility is easy, the other three are more complicated.

If an object needs reexecution, the interpreter redoes each execution in the invocation chain. For each one, the statements in the execution and the components in the object's path are freed. The argument values stored in the object descriptor initialize the parameters, and the body of the object is executed. After this, the interpreter reexecutes all *using* statements for the object as described in the previous section.

When objects are extended, the stored final values of the stack frame are used to reestablish the state at the end of the object's execution, then the newly added code is executed. As in the previous case the interpreter reexecutes the appropriate *using* statements, and the new final values replace the previous ones.

Extending the main program is quite simple; the interpreter just maintains the main program's final stack frame between executions.

When an object with variants is changed the interpreter must also reexecute any invocations to the variant objects. A possible problem occurs if the changed original object definition has new variables added, since the original's variables' offsets now conflict with the offsets of the variant's variables. The most common case for this to occur is when the original object gets extended, and the problem solves itself then. The interpreter assigns offsets in the order that the variables occur in the program text, so the only conflicts that occur are between the new variables and the variables in the variant. If the variant definition is unchanged, it cannot refer to these new variables, and the original's variables and the variant's variables peacefully coexist in the stack frame since all stack frame entries are the same size. If the variant definition uses these variables, it must have changed too, so it will have been reparsed with new, nonconflicting offsets for its variables.

In the other case, the new variables were added internally to the original definition. This will cause some of the old variables to have larger offsets, and some of these will conflict with those in the variant. Moreover, the variant can use these variables, so it would have two variables available to it with the same offset. When this occurs, the interpreter forces all the variants to be reparsed and thereby gain new variable offsets.

5.11. Display and graphics editor

The display module calculates bounding boxes for objects as it traverses the tree. These bounding boxes are used by the editor to determine which object the user is pointing to when he attempts to a selection. The editor maintains a current path pointer into the display tree, and when the user makes a selection it looks through the components of the current path to find the appropriate object. If the user clicks the mouse multiple times without moving the mouse, the components are searched starting with the last object found, and if another object is found beneath the cursor it replaces the last object in the selection. This allows the selection of objects that are obscured by other objects in the display. If the user edits the selected objects, the editor's current path pointer is moved to the object's path.

Every element in the picture is not necessarily selectable; in particular output generated through the direct use of paths cannot be selected. There must also be some variable in the current routine that refers to the object at the end of the routine. This restriction is not normally a problem since the editor creates new object variables for each object it creates. The only problems can occur in user-written code; for example, object creations passed directly to *draw* statements, as in

```
    (draw (rectangle))
```

cannot be selected. The interpreter will find object references even if they are stored in arrays, so programs can create editable objects in loops by storing their references in an array.

A more severe restriction is that the user cannot select objects that were created within *using* statements. The problem with these objects is that they are defined within the program to have a particular relationship with other objects; if, for example, an arrow is drawn connecting two boxes the semantics of *getpoint* and *using* guarantee that the arrow is guaranteed to connect the correct points, no matter how the boxes move or change. If the user moves the arrow and then moves one of the boxes, the reexecution of the *using* statement would cause the change to the arrow to be undone. Just what the appropriate behavior here should be is rather unclear; this solution has the advantage of being at least consistent. In practice this requires the user to divide the elements of picture into two classes, editable objects and subordinate objects that connect them. For most pictures this division causes no problems, but for others it is rather contrived.

The editor generates new code in response to user input in the form of a text string, which is inserted into the program text at the correct place. The editor calls the preparser to translate the string into a linked list and then passes this list on to the parser. The parser inserts the new code into the parse tree at the appropriate place and then parses it, and finally editor invokes the incremental execution module on the changed routine definitions.

5.12. Display optimization

Whenever the display tree for a program changes, the editor must update the window containing the current picture. The current implementation always fully redraws the picture in response to these changes, but there are several possible optimizations not implemented because of time pressure. These are display coordinate caching, incremental bounding box calculations, and incremental redisplay.

5.12.1. Display coordinate caching

The editor display module always has to draw changed portions of a picture, but is sometimes must also redraw unchanged portions. This occurs very frequently in the current full redisplay scheme, but will also occur in optimized schemes when the window containing the picture is uncovered by the window system or when the display module has to patch up newly exposed parts of the drawing in response to a user change. Each redisplay transforms the relative coordinates stored in the display tree into the absolute display coordinates required by the window system. Caching these absolute coordinates can make this redisplay more efficient.

Any caching scheme is complicated by the fact that the display tree is not really a tree but rather a directed acyclic graph. If an object is copied with *new* its path appears only once in the tree even though it appears multiple times in the drawing. The following caching method only saves the display coordinates for one instance of the shared part of the tree; it could easily be extended to save any fixed number of instances by sacrificing storage in the non-shared case.

The tree traversal can tell which parts of the tree it has encountered before by tagging each tree entry as it encounters it. This tagging must uniquely identify each traversal; a simple two-state tag will not suffice since each traversal will not necessarily visit each node in the tree. Further, altering the display will cause some nodes to be marked as changed, and the cached information in these nodes will be out of date. There are thus four possible cases to consider for each node:

1. **Marked as changed, tag not equal to current tag:** The cached information is obsolete, and this is the first time the traversal has encountered this node. Recalculate the display coordinates, cache them, and tag this node with the current tag.
2. **Marked as changed, tag is equal to current tag:** This node has been encountered before, so its cached values do not apply to this visit. Calculate the display coordinates and use them.
3. **Not marked as changed, tag not equal to current tag:** The cached information is still valid and applies to this visit. Use the cached coordinates and tag this node with the current tag.
4. **Not marked as changed, tag is equal to current tag:** This node has been encountered before, so its cached values do not apply to this visit. Calculate the display coordinates and use them.

This caching will save some execution time, but it may not make the picture display more quickly. A moderately complicated picture like Figure 5-2 takes about 2 seconds of real time and 1 second of execution time to display. Profiling reveals that between 5 and 10 percent of the execution time is spent performing matrix multiplications and coordinate transformations, so the benefits of caching would be slight. Nonetheless, it requires very little extra storage and the software overhead for maintaining a cache is very small, so it would be a worthwhile addition.

5.12.2. Incremental bounding box calculations

Bounding boxes are used by the editor to resolve mouse hits and by the incremental redisplay algorithm described in the next section to determine what parts of the picture need to be redisplayed. Changing the picture will cause some of the bounding boxes to change.

An objects' bounding box is the smallest rectangle containing the bounding boxes of its subobjects and paths. When an object is moved, added, or deleted the bounding boxes of all its ancestor objects may change. These changes can be carried out by a two pass algorithm: first information about what boxes need recalculation propagates up the display tree, then a second pass downward performs all these calculations.

Because of path sharing with *new* and object connection with control points, a single editing operation can affect many different objects throughout the display tree. Were this not the case, a single pass up the tree would suffice, but when multiple changes occur this approach can result in calculating bounding boxes for some objects multiple times. By doing two passes this extra work is avoided. Here is the bounding box algorithm:

1. For each changed object, mark it and its ancestors as needing recalculation all the way up the tree to the root. If a node that is already marked is encountered, stop; all its ancestors will already be marked.
2. Traverse the tree. At each node, recompute the bounding boxes of all marked children by recursively applying this procedure; then set the current bounding box to include the boxes of all children.

During this bounding box calculation, the cached display coordinates can be used and updated.

5.12.3. Incremental redisplay

The biggest potential perfomance gain comes from incremental redisplay, since only the parts of the picture that need redrawing are sent to the window system. This algorithm requires bounding regions for both the old and the new locations of an object; if an object is added to the picture its old bounding region is null and if it is deleted from the picture the new bounding region is null.

The bounding regions used by this algorithm could be either simple bounding boxes or shapes that fit the object more closely. Closer approximations to the true shape of an object will require less patching up of the picture, but the union and intersection calculations on regions will become more complex. The optimum balance to achieve fastest redisplay will depend upon the relative speeds of calculation and drawing in a particular system.

This algorithm relies on the ordered organization of the display tree, with the leftmost children of a node being drawn first and being overlapped by the children to the right of it.

1. Set up two clipping regions on the picture window, OLD and OLD+NEW. OLD is the union of the previous bounding regions of all changed objects, and OLD+NEW is the union of the previous bounding regions and the new bounding regions.
2. Fill the OLD region with the background pattern. This erases the previous objects.
3. Construct a line of nodes through the tree through the leftmost chain of nodes from a changed object to the root. Continue this line to a leaf node, always following the leftmost child. This line divides the tree in two parts, those nodes lower in the stacking hierarchy than any changed objects and those nodes at least as high in this hierarchy as the lowest changed object.

4. Do a preorder traversal of the tree:
    - If a node is to the left of the dividing line, check if its bounding region intersects the OLD region.
        - If the node is a leaf and intersects OLD, draw it using OLD as a clipping region. If it is a leaf and does not intersect OLD, ignore it; it does not need drawing.
        - If the node is not a leaf and does not intersect OLD, ignore the node's children; they do not need drawing. If it does, apply the same criteria to each of the node's children.
    - If a node is on the dividing line or to the right of it, do the same except use OLD+NEW as the testing and clipping region. Any recursive applications should be tested against the appropriate region depending upon whether the child is to the left or the right of the dividing line.

Figure 5-4 shows this at work. Figure 5-4a shows the display tree for Figure 5-4b just before the central box is moved to the position shown by the hollow square. Each of the five children in the tree is shaded the same as the corresponding box in the picture. The OLD region is the medium shaded area, and the OLD+NEW region is that plus the area in the hollow box. Figure 5-4c shows the display after OLD is filled with the background pattern. The dividing line is constructed next, going from the center child node up through the root node.

The display tree now gets traversed. The root node is on the dividing line, so all of its children are examined. The leftmost child is to the left of the dividing line and intersects OLD, so the part of it in OLD is redrawn, yielding Figure 5-4d. The next node is also to the left of the line but it doesn't intersect OLD, so nothing happens. The third node is the moved object. It is on the line and intersects OLD+NEW, so it is redrawn in OLD+NEW giving Figure 5-4e. The last two nodes are each compared to OLD+NEW, each intersects it, and so they are redrawn clipped to OLD+NEW, Figures 5-4f and 5-4g.

The effect of this algorithm is to compare all objects in the tree against the OLD region; any intersecting it need redisplay because filling the background pattern will have erased them. Any objects in the tree to the right of the dividing line should overlap the redrawn object, so they are also compared to the NEW region by comparing them with OLD+NEW.

5.13. Relative transformations

When the user moves an object in the editor, the result is a transformation relative to the object's current location. The *transform* statement requires an absolute transformation; how should the relative transformation be converted to an absolute one? Four solutions come to mind.

The original transformation of the object is stored in the object descriptor; use

```
(concat <object's transform> <new transform>)
```

as the transformation in the *transform* statement. Unfortunately the object's transformation is just stored as an array; inserting this into the program text is unenlightening.

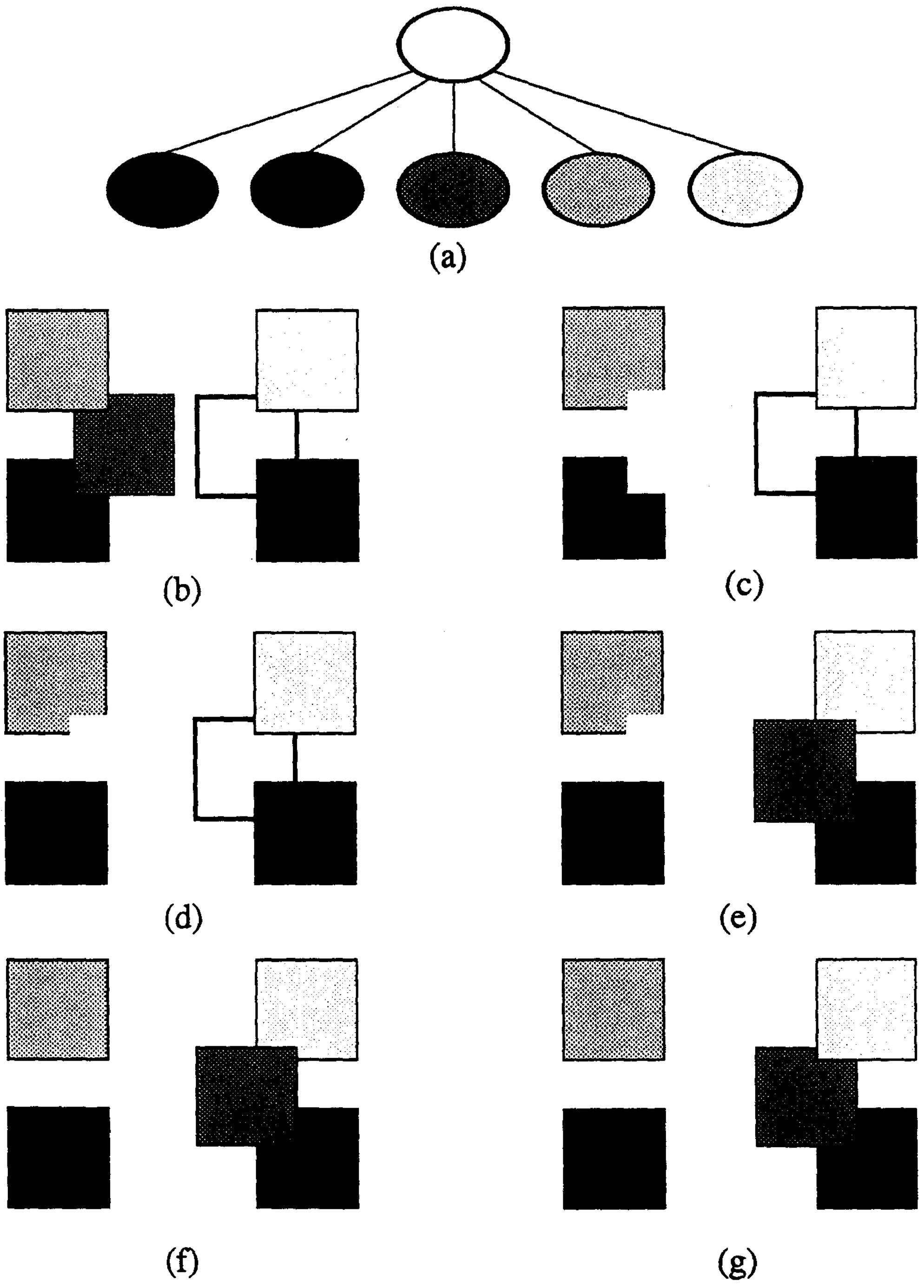


Figure 5-4: The stages of incremental redisplay

Another solution is to add a built-in function to the language that takes an object and returns its current transformation. The editor would use

```
    (concat (currtrans <object>) <new transform>)
```

in the *transform* statement. This has the problem that it makes an object's transformation an accessible part of the program state. All the benefits obtained by making this state invisible are lost.

The best solution would be to keep a symbolic representation of the current transformation, and use that as the old transformation in the *transform* statement. This solution works well but is quite a bit of bookkeeping.

The solution actually used in Dee solves the problem by avoiding it: a new statement *rtransform*, or relative transform, was added to Dum. *Rtransform* is defined so that the two statements

```
    (rtransform <object> <new transform>)
    (transform <object> (concat <object's transform> <new transform>))
```

have the same results. This solution, while not quite as elegant as the previous solution, was considerably easier to implement. The editor actually produces *rtransform* statements rather than *transform* statements in response to the user moving objects.

The same problem arises when the user copies an object: Dee must translate the displacement for the new object into an absolute position. This is solved in the same way, by adding an *rnew* function that creates a new copy of an object relative to where the old one is.

Something subtly unusual goes on with transformations when transforming things in a graphics editor. This is best explained by first giving an example: Assume the user has created a square at the point (50,50). The correct code to do this is

```
    (with (translate [50 50])
        (object a_square (square))
    )
```

If the user then rotates the square by 10°, the resulting code should have the same effect as

```
    (with (translate [50 50])
        (with (rotate 10)
            (object a_square (square))
        )
    )
```

In other words, the rotation should be performed upon the square before the translation (Recall that transformations are successively applied to the coordinate system from the outside in or successively applied to the object from the inside out. Either view yields the same results). It appears that subsequent transformations should be nested inside the extant ones. If, however, the rotation is then followed by a translation of (20,0) the user expects the rotated square to move twenty units to the right; that is, the result should have the effect of

```
    (with (translate [70 50])
        (with (rotate 10)
            (object a_square (square))
        )
    )
```

and not of

```
(with (translate [50 50])
    (with (rotate 10)
        (with (translate [20 0])
            (object a_square (square))
        )
    )
)
```

In the second code example the innermost translation would be along a line rotated 10° from the horizontal, not the same thing at all.

More generally, the object's current transformation C can be decomposed into a linear component C_L and a translation component C_T; C is the product $C_T C_L$. A new transformation, N, can similarly be decomposed into $N_T N_L$. If N is applied to the object after C the result should be, not NC as might be expected, but rather $N_T C_T N_L C_L$. The graphics editor must be careful to put the transformations together in the right order.

5.14. Source-code optimization

After being edited for a while with Dee, Dum programs tend to become littered with lots of *rtransform*, *raise*, *lower*, *delete* and *recall* statements, obscuring program flow and increasing execution time. A source code optimizer can improve the program considerably.[11]

This version of the optimization algorithm removes *rtransform*, *delete*, and *recall* statements but leaves *raise* and *lower* statements in the program. Removing these statements is slightly more complex since it involves reordering the statements in the program but would proceed along the same general scheme.

This is the optimization algorithm:

1. Traverse the execution tree of the program. For every object that is created, keep the following information:
    - A pointer into the parse tree to the invocation.
    - Whether or not the invocation is in a loop. If so, the invocation cannot be modified or deleted since doing so might change or delete the invocations of other objects.
    - Whether or not the invocation contains any calls to user-defined functions. If it does, it cannot be deleted since user-defined functions can have side effects in the picture.
    - Pointers to each object used in the invocation. As long as the current object exists, these objects cannot be removed.
    - A pointer into the parse tree to the *draw* statement that drew the object, if any.
    - Whether or not the *draw* statement is in a loop and also uses a subscript calculation to find the object. If so, it cannot be removed since doing so might delete the other objects from the picture

[11]Due to time pressure, Dee's source code optimizer was never completely implemented.

- A list of actions for the object: *recall*, *delete*, and *rtransform* statements, uses of the object or its control points in other object invocations, and uses of the object or its control points in other places. Each of these contains a pointer into the parse tree where the action occurs; the *recall*, *delete*, and *rtransform* statements also indicate whether or not the statement is safe to optimize away. A statement is unsafe if it uses user-defined functions, if it occurs in a loop and uses a subscript calculation to find the object, or if it occurs in a variant of the object originally defining the current object.

Put all records containing this information into a list of unoptimized objects.

2. Repeat until the list of unoptimized objects is empty:
   a. Pick an unoptimized object.

   b. Move it to a list of optimized objects.

   c. Go down the list of activities and, depending upon the type, do different things:

      - Recall: If the *recall* statement is unsafe to remove or the invocation is unsafe to modify, skip this activity. Otherwise, change the invocation into the result of the *recall* statement and remove the *recall* statement from the parse tree.

      - Delete: If either the *delete* statement or the object's *draw* statement is unsafe to remove, skip this activity. Otherwise, remove the *delete* statement and the *draw* statement from the parse tree. Be sure to fix the pointer to the *draw* statement in the optimization record.

      - Rtransform: If the *rtransform* statement is unsafe to remove, skip this activity. If not, there are two possibilities. If the invocation is safe to modify, remove the *rtransform* statement and add a new *with* statement around the invocation. Otherwise, if there is a previous *rtransform* statement that is safe to modify, remove the current *rtransform* and concatenate its transformation into that of the previous *rtransform*. This can only be done if the current *rtransform* is not contained in a variant of the object containing the previous *rtransform*.

      - Object and control point uses: skip these activities.

   d. After going through the activities, see if the invocation can be removed. This is possible if the activity list is now empty, the optimization record indicates there is no *draw* statement, and the invocation is safe to modify. If these all hold, remove the invocation of this object and go through the list of objects used in the invocation and, for each one, delete the activity record referring to the use. Move the object from the optimized list back to the unoptimized list if it has already been optimized, thereby allowing objects used only in other invocations to be removed if the other invocations all go away.

3. Now go through the parse tree and collapse any nested *with* statements into a single one. If consecutive transformations are of the same type, for example two translations, they can be combined into a single transformation; if not, they can be combined with the *concat* function. Also in this pass remove any statements that have

no subordinate statements; the previous steps will tend to create empty *with* and *using* statements in particular.

4. Regenerate the program text from the parse tree.

5.15. Libraries

The major goal of the implementation of libraries is to avoid recompiling them at each compilation while still allowing the program to use only the libraries it actually includes. This is done by keeping all entries for library routines in the symbol table between executions but marking inactive those entries for libraries not included in the current picture. When the parser encounters a library specification, it checks to see if the library is in a list of all libraries encountered so far. If it is, it activates all library entries for that library; if not, it parses the library. Several libraries of predefined objects are always implicitly included in each program.

5.16. Generating PostScript

At first glance it appears that Dee could generate PostScript [1] for hardcopy by doing a straightforward translation of the current program. This would work only if the program contained no statements like *translate*, *raise*, or *lower* since these have no PostScript counterparts. Dee instead generates hardcopy by traversing the display tree and issuing PostScript code. This is a relatively straightforward task with one notable exception: curve operations. Dum's curves are defined to go from the current point through a single specified point with the previous and next points on the curve providing control information. PostScript instead uses Bezier control points [11, 25] between the two points on the curve; the hardcopy routine must construct the appropriate control points from the given information. To make matters still more complex, the control point calculation for the first curve segment of a closed curve requires the value of the last point on the curve.

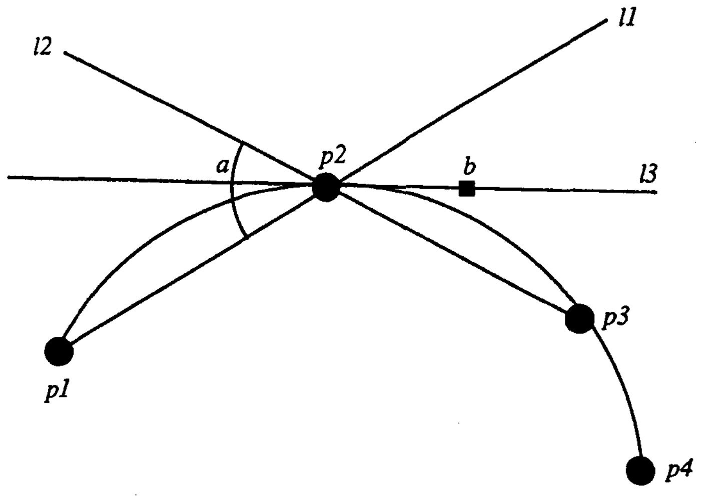


Figure 5-5: The calculation of a Bezier control point

Figure 5-5 shows part of the calculation used to find the control points. The curve is going between point *p2* and *p3* with *p1* as the preceding point and *p4* as the next point. Line *l1* is the line through *p1* and *p2* and *l2* the line through *p2* and *p3*. Line *l3* is constructed to bisect the angle *a* between *l1* and *l2*, and the Bezier control point *b* is found by going out along line *l3*. The distance between *p2* and *b* is depends upon the angle *a*; small angles mean the curvature is small near *p2*, so *b* is further out, while large angles mean the curvature is large near *p2* so *b* is closer in. The actual formula used is

$$d * \min(0.5, c * a/180)$$

where *d* is the distance between *p2* and *p3* and *c* is a constant scaling factor; experimentation showed that the most pleasing curves are produced with $c = 0.82$. This method is generally satisfactory but occasionally produce a strange curve.

6. Contributions and Future Work

6.1. Contributions

Tweedle fully integrates a procedural language and a graphics editor. Chapter 3 referred to the ''carefully cultivated illusion'' that the language serves a subsidiary function to the editor; one measure of the success of the marriage between language and editor is how well this illusion succeeds. How frequently does the user need to edit the program text directly? In my experience creating drawings for this thesis I have encountered four classes of situations requiring text editing:

1. Creating objects which require procedurality: these are the cases for which text editing was intended. Because of the nature of the illustrations they tended to come up more frequently than they might normally.
2. Providing exact values for point variables: this was also intended, but proved to be far commoner and far more tedious than originally expected. Gargoyle's snap-dragging technique [9] would drastically reduce the need for these types of interactions.
3. Deleting code for editing actions performed incorrectly or by mistake: Dee has no ''Undo'' function, so these had to be manually removed from the program. An ''Undo'' function would eliminate these interactions.
4. Hand-optimizing code: since the source code optimizer was never finished, any optimization had to be done manually. This only arose for examples where the code was to be shown in the text. Finishing the optimizer would eliminate this.

The editing process in general runs quite smoothly. I frequently would switch back and forth between making text changes and graphics changes in the same session; having both styles of interaction available at the same time is a valuable tool. Even if the graphics editor were unavailable the incremental execution facilities make Dee a good environment for writing and debugging graphics programs. The current implementation frequently sacrifices efficiency for simplicity and yet its response time is quite good; this shows that there is nothing inherently slow about the ideas embodied in Dee, and with some work Dee could be made to execute as quickly as any other graphics editor.

Tweedle's greatest contribution is in extending the realm of procedural representations to interactive programs. All procedural representations done previously have been rather batch oriented: the representation is created and them moved as a whole to its consumer, a document compiler or a printer. Tweedle is interactive; changes to a program take place incrementally. In order to make this work well the interpreter must understand the structure and execution of a program so that it can execute appropriate parts of a program as the representation changes. Static structure in the language allows the interpreter to gain the information it needs by static analysis of the program text.

Tweedle's drawing model combines segment and procedure based models by treating drawing procedures in an object-oriented fashion. Object definitions are as simple as drawing procedures, but having their result be manipulable by the program gives the advantages of segments. The variation hierarchy in Dum is analogous to the class hierarchy in object-oriented systems.

The moral of the story is that procedural representation languages are still programming languages, and their design can benefit from the same techniques used to design general purpose languages. Besides static structure and an object-oriented drawing model, Dum has subroutine libraries and typed subroutine parameters. Libraries allow multiple pictures to share common elements and allow people other than the picture creator to do the programming necessary for complicated objects. Typed parameters allow the editor to figure out what kinds of values to supply as arguments to newly instantiated objects and how it should supply them.

The object variation hierarchy is a new idea in editing facilitated by Dum's procedurality. Describing the change from original to variant as the series of editing operations that effect the change is natural, intuitive, and directly models the editing process. In Dum one can move a subobject around; in the procedural model having something be in different places at different points in the execution is perfectly reasonable. A declarative model would require either some sort of meta-syntax to describe the change process or a means of resolving conflicting descriptions such as the original claiming the subobject is in location A but the variant claiming it's in location B. The main benefit of variation over simply copying the definition and changing it is that the variant can follow later changes made to the original object. This benefit has shown up most in allowing slightly different objects that should remain consistent with each other; the various labeled ellipses and rectangles used in illustrations in this theses are an example of this.

The incremental execution facilities have worked out extremely well and should be applicable to other systems with rapidly changing representations.

6.2. Deficiencies & future work

Dee is far from being a production-quality editor. Besides small things like line join styles, generalized fill patterns, and color, the two major missing features are source-code optimization and grouping. Optimization was fully described in Section 5.14; grouping is the ability to perform actions in the graphics editor to more than one object at a time.

There are many places in Dee where it was easier to always recompute information than to keep state that would allow Dee to determine if the current information was still valid. Bounding boxes and redisplay are the two most notable examples of this; whenever the structure of the image changes at all Dee recomputes all the bounding boxes and redisplays the picture. The delay caused by this could easily be eliminated by the more clever algorithms described in Section 5.12.

The editor would benefit from a finer grade of incremental execution. The present scheme works well for nicely structured diagrams with many short object definitions; unfortunately, this characterizes only a subset of possible pictures. Many programs turn out to have a very flat structure consisting of a long main program calling library objects. Any change other than adding new code at the end of the program requires complete reexecution. The interpreter could improve its response for programs like these by checkpointing the state at frequent intervals through the main program.

When adding an object the editor always prompts for the parameters the same way; as far as it is concerned a line segment with one point parameter and a circle with one point parameter look the same. More sophisticated interaction techniques like rubber-banded lines, circles, or rectangles could be provided by allowing an object definition to designate some kind of interaction function that the editor would call for each parameter. These interaction functions, written in Dum and included in the same libraries as the objects they apply to, would provide the interactive feedback necessary to support the appropriate type of rubber banding for each type of object.

Object definitions act as mathematical functions since their action depends only upon the values of their variables. Object invocations are thus well suited to being executed in parallel; one invocation cannot affect the execution of another. The parallel execution of Dum programs is an interesting research area.

Dee's internal model has the editor creating new code and passing it to the interpreter, which adds it to the program and executes it to update the display. This has the advantage that it is immediately obvious if the editor is generating incorrect code. An interesting alternative structure would be for the editor to both modify the program and change the display directly. With this approach the incremental execution mechanism only needs to be invoked when the user changes the program with the text editor. Changes to the text should occur rarely enough that the extra time needed to fully reexecute in response to such a change shouldn't be too much of a bother, so incremental execution could be completely disposed of. Experimentation is needed to see if the extra time spent by Dee providing for incremental execution is recovered by the time saved by incrementally executing programs.

6.3. What I would do differently

The X Window System [12] proved to be simple and easy to use; it also proved to be critically lacking in high-level capabilities. Particularly missed was the ability to define editable sections of text on the screen, a feature present in Andrew [23]. This lack led to a baroque process structure for Dee: an editing session consists of the main Dee process, two copies of the terminal emulator program, and a copy of Emacs, all communicating through interprocess communication mechanisms. This turned out to work surprisingly well (I was rather surprised to get it to work at all!) but would have all been completely unnecessary in a more full-featured window system.

Dee uses X's curve mechanism; this was easy to implement but has been a source of difficulty ever since. X's curves go through specified points but frequently do very unintuitive things between these points. Duplicating these curves exactly in hard copy is neither easy nor in many cases particularly desirable. I originally believed simulating a more accurate curve mechanism like B-splines using straight line segments would be intolerably slow but recent work by other people has demonstrated otherwise.

An editing session in Dee consists of creating a complex interlinked data structure, the execution tree, and then repeatedly throwing pieces of it away and replacing them with new data. The memory management problems turned out to be immense; I estimate that a month of implementation time was spent on tasks that would have completely gone away if garbage collection had been available.

Paths need to become full-fledged datatypes. They were not so designed at first since PostScript seemed to get along quite well without them, but they have ended up in something of a state of limbo. The editor never creates paths and it cannot do anything useful with them if the user does. Paths end up getting hidden away in object definitions where the editor never needs to look at them. An even more serious deficiency is that variant objects cannot modify paths in the original object since it has no way to refer to them. The lack of a path datatype also makes it impossible to extend the various routines used to create different line styles in Figure 1-2 to work on arbitrary paths.

Acknowledgments

"You ought to return thanks in a neat speech," the Red Queen said, frowning at Alice as she spoke.

— Lewis Carroll

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I. Syntax of the Dum Language

In this description, SMALL CAPITALS denote nonterminals, **boldface** denotes terminals, and *italics* indicate explanatory information.

Conventional syntax is used: ''*'' indicates zero or more of the preceding item, square brackets enclose optional material, and ''|'' separates alternatives. Quotation marks and parentheses are always terminals; square brackets, asterisks and vertical bars are always meta-syntax except in the productions for LBRACKET, RBRACKET, STAR, and VBAR.

PROGRAM	→	LIBRARY-SPEC* ROUTINE*
LIBRARY-SPEC	→	**$library** TEXT-STRING NEWLINE
ROUTINE	→	FUNCTION-DEFINITION | OBJECT-DEFINITION
FUNCTION-DEFINITION	→	(**function** NAME [RETURNS-CLAUSE] [ARGS-CLAUSE] METHOD-CLAUSE)
OBJECT-DEFINITION	→	(**defineobject** NAME [VARIANT-CLAUSE] [ARGS-CLAUSE] [CONTROL-CLAUSE] METHOD-CLAUSE)
RETURNS-CLAUSE	→	(**returns** DATATYPE)
VARIANT-CLAUSE	→	(**variant** NAME)
ARGS-CLAUSE	→	(**args** ARG-SPEC*)
ARG-SPEC	→	(DATATYPE NAME*)
CONTROL-CLAUSE	→	(**control** NAME*)
METHOD-CLAUSE	→	(**method** STATEMENT-LIST)
STATEMENT-LIST	→	STATEMENT*
STATEMENT	→	NORMAL-STATEMENT | ROUTINE-CALL
NORMAL-STATEMENT	→	DATA-DEFINITION | WITH-STATEMENT | PATH-STATEMENT | IF-STATEMENT | FOR-STATEMENT | WHILE-STATEMENT | BEGIN-STATEMENT | ASSIGNMENT | TRANSFORM-STATEMENT | RTRANSFORM-STATEMENT | RECALL-STATEMENT | DELETE-STATEMENT | DRAW-STATEMENT | RAISE-STATEMENT | LOWER-STATEMENT | USING-STATEMENT | PATH-CONSTRUCTOR
DATA-DEFINITION	→	(DATATYPE NAME [*initial*-EXPRESSION])
WITH-STATEMENT	→	(**with** *transformation*-EXPRESSION STATEMENT-LIST)

PATH-STATEMENT	→	DRAWPATH-STATEMENT | FILLPATH-STATEMENT
DRAWPATH-STATEMENT	→	(**drawpath** [OPTIONS-CLAUSE] STATEMENT-LIST)
FILLPATH-STATEMENT	→	(**fillpath** [OPTIONS-CLAUSE] STATEMENT-LIST)
OPTIONS-CLAUSE	→	(**options** OPTION*)
OPTION	→	LINEWIDTH-OPTION | FILLPAINT-OPTION
LINEWIDTH-OPTION	→	(**linewidth** *number*-EXPRESSION)
FILLPAINT-OPTION	→	(**fill** *paint*-EXPRESSION)
IF-STATEMENT	→	(**if** *conditional*-EXPRESSION *if-true*-STATEMENT [*if-false*-STATEMENT])
FOR-STATEMENT	→	(**for** *initial*-EXPRESSION *increment*-EXPRESSION *final*-EXPRESSION STATEMENT-LIST)
WHILE-STATEMENT	→	(**while** *conditional*-EXPRESSION STATEMENT-LIST)
BEGIN-STATEMENT	→	(**begin** STATEMENT-LIST)
ASSIGNMENT	→	(**:=** LVALUE EXPRESSION)
RECALL-STATEMENT	→	(**recall** LVALUE ROUTINE-CALL)
LVALUE	→	NAME | SUBSCRIPT
TRANSFORM-STATEMENT	→	(**transform** *object*-EXPRESSION *transformation*-EXPRESSION)
RTRANSFORM-STATEMENT	→	(**rtransform** *object*-EXPRESSION *transformation*-EXPRESSION)
DELETE-STATEMENT	→	(**delete** *object*-EXPRESSION)
DRAW-STATEMENT	→	(**draw** *object*-EXPRESSION)
RAISE-STATEMENT	→	(**raise** *object*-EXPRESSION)
LOWER-STATEMENT	→	(**lower** *object*-EXPRESSION)
USING-STATEMENT	→	(**using** *transformation*-EXPRESSION STATEMENT-LIST)
PATH-CONSTRUCTOR	→	SEGMENT-CONSTRUCTOR | ARC-CONSTRUCTOR | CLOSE-CONSTRUCTOR

SEGMENT-CONSTRUCTOR	→ (SEGMENT-TYPE *point*-EXPRESSION)
SEGMENT-TYPE	→ **moveto** | **rmoveto** | **lineto** | **rlineto** | **curveto** | **rcurveto**
ARC-CONSTRUCTOR	→ (ARC-TYPE *centerpoint*-EXPRESSION *radius*-EXPRESSION *startangle*-EXPRESSION *endangle*-EXPRESSION)
ARC-TYPE	→ **arc** | **arcn**
CLOSE-CONSTRUCTOR	→ (CLOSE-TYPE)
CLOSE-TYPE	→ **closepath** | **closecurved**
DATATYPE	→ **number** | **point** | **object** | **paint** | **array** | **string**
EXPRESSION	→ ROUTINE-CALL | POINT | SUBSCRIPT | GETPOINT | NAME | NUMBER | TEXT-STRING
ROUTINE-CALL	→ (NAME *argument*-EXPRESSION*)
POINT	→ LBRACKET *x*-EXPRESSION *y*-EXPRESSION RBRACKET
SUBSCRIPT	→ (**sub** *array*-EXPRESSION *number*-EXPRESSION)
GETPOINT	→ (**getpoint** *object*-EXPRESSION *point*-NAME)
NAME	→ CHAR CHAR*
NUMBER	→ [SIGN] [DIGIT*] [. [DIGIT*]] [e [SIGN] DIGIT*]
SIGN	→ + | -
TEXT-STRING	→ " ANY-CHAR* "
TOKEN-SEPARATOR	→ SPACE*
SPACE	→ SPACE-CHAR | TAB | NEWLINE | COMMENT
COMMENT	→ # ANY-CHAR* NEWLINE
ANY-CHAR	→ " | # | $ | (|) | LBRACKET | RBRACKET | SPACE-CHAR | TAB | CHAR
CHAR	→ ! | % | & | ' | + | , | - | . | / | : | ; | < | = | > | ? | @ | \ | ^ | _ | ' | { | } | STAR | VBAR | DIGIT | CAPITAL-LETTER | LOWER-CASE-LETTER
DIGIT	→ **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9**

CAPITAL-LETTER	→	**A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z**
LOWER-CASE-LETTER	→	**a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z**
LBRACKET	→	**[**
RBRACKET	→	**]**
STAR	→	*****
VBAR	→	**|**

Notes:

1. A TOKEN-SEPARATOR may appear between any two consecutive tokens. Any two adjacent NAMES must be separated by a TOKEN-SEPARATOR.
2. At least one of the DIGIT strings in a NUMBER must be present.
3. NUMBERS are a subset of NAMES; any NAME that qualifies as a NUMBER is a NUMBER, not a NAME.
4. Quotation marks are included in STRINGS by doubling them.
5. SPACE-CHAR, TAB, and NEWLINE are ASCII characters octal 40, 11, and 12, respectively.

II. Predefined Functions

The type definition any in these descriptions indicates that the argument so qualified can be of any type. If an argument is followed by ellipses (...) it means that there may be any number of arguments of the same type.

II.1. Mathematical functions

`(function + (returns number) (args (number n1 n2))`
Returns the sum of n1 and n2.

`(function - (returns number) (args (number n1 n2))`
Returns the difference of n1 and n2.

`(function * (returns number) (args (number n1 n2))`
Returns the product of n1 and n2.

`(function / (returns number) (args (number n1 n2))`
Returns the quotient of n1 and n2.

`(function mod (returns number) (args (number n1 n2))`
Converts n1 and n2 to integers and returns the remainder when n1 is divided by n2.

`(function int (returns number) (args (number n))`
Converts n into an integer.

`(function neg (returns number) (args (number n))`
Returns the negative of n.

`(function sin (returns number) (args (number n))`
Returns the sine of n considered in degrees.

`(function cos (returns number) (args (number n))`
Returns the cosine of n considered in degrees.

`(function atan (returns number) (args (number n))`
Returns the arctangent in degrees of n.

`(function atanp (returns number) (args (point p))`
Returns the arctangent in degrees of p considered as a vector.

`(function sqrt (returns number) (args (number n))`
Returns the square root of n.

`(function rand (returns number)`
Returns a pseudo-random integer between 0 and 2^{31}-1, inclusive.

II.2. Comparison and logical functions

`(function < (returns number) (args (number n1 n2))`
Returns whether n1 is less than n2.

`(function <= (returns number) (args (number n1 n2))`
Returns whether n1 is less than or equal to n2.

`(function > (returns number) (args (number n1 n2))`
Returns whether n1 is greater than n2.

`(function >= (returns number) (args (number n1 n2))`
Returns whether n1 is greater than or equal to n2.

`(function = (returns number) (args (any v1 v2))`
Returns whether v1 and v2 are of the same type and have the same value.

`(function <> (returns number) (args (any v1 v2))`
Returns whether v1 and v2 are of different types or have different values.

`(function and (returns number) (args (number n1 n2))`
Returns whether both n1 and n2 are nonzero.

`(function or (returns number) (args (number n1 n2))`
Returns whether either of n1 or n2 are nonzero.

`(function not (returns number) (args (number n))`
Returns 1 if n is 0 and 0 otherwise.

`(function null (returns number) (args (object o))`
Returns whether o is equal to the null object.

II.3. Point manipulation functions

`(function makepoint (returns point) (args (number n1 n2))`
Returns a point with x coordinate n1 and y coordinate n2.

`(function px (returns number) (args (point p))`
Returns the x coordinate of p.

`(function py (returns number) (args (point p))`
Returns the y coordinate of p.

`(function p+ (returns point) (args (point p1 p2))`
Returns the sum of p1 and p2 considered as vectors.

`(function p- (returns point) (args (point p1 p2))`
Returns the difference of p1 and p2 considered as vectors.

`(function p* (returns point) (args (number n) (point p))`
Returns p considered as a vector scaled by n.

II.4. Transformation functions

`(function rotate (returns array) (args (number n))`
Returns an array representing a tranformation matrix for a rotation by n degrees.

`(function translate (returns array) (args (point p))`
Returns an array representing a tranformation matrix for a translation by p.

`(function scale (returns array) (args (point p))`
Returns an array representing a tranformation matrix for a scale by p.

`(function concat (returns array) (args (array a...))`
Returns an array representing the concatenation of all the array arguments.

II.5. Array manipulation functions

`(function arr (returns array) (args (any a...))`
Returns an array containing all the arguments, with subscripts starting at 0.

`(function lbound (returns number) (args (array a))`
Returns the lowest subscript in a.

`(function ubound (returns number) (args (array a))`
Returns the highest subscript in a.

`(function elements (returns number) (args (array a))`
Returns the number of elements in a.

`(function in (returns number) (args (array a) (number n)`
Returns whether a contains an element subscripted n.

II.6. String functions

`(function str (returns string) (args (any a...))`
Returns a string with the string values of all arguments concatenated together.

`(function print (args (any a...))`
Prints the same string as would be returned by `str` in the dialog window.

`(function getfont (returns number) (args (string s) (number n))`
Returns a number referring to a font named s in size n.

`(function strwidth (returns number) (args (string s) (number n))`
Returns the width of s in font n.

II.7. Paint functions

`(function grayscale (returns paint) (args (number n))`
Returns a gray paint. If n is 0 or less the paint is white, if n is 1 or more it is black, and if between it is the corresponding amount between.

II.8. Object functions

`(function new (returns object) (args (object o))`
See section 3.3.

`(function rnew (returns object) (args (object o))`
See section 5.13.

`(function text (returns object) (args (string s) (number n))`
Returns an object that represents s displayed in font n.

`(function nullobj (returns object)`
Returns a null object.

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