Methods for Sculpting Digital Topographic Surfaces

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Abstract

This investigation offers an argument and demonstration of how two seemingly different graphic representations of terrain are formally equivalent, and how when they are coupled with a data structure and computer algorithm for converting from one to the other new kinds of digital sculpting may be undertaken. The thesis defines a *generic digital topographic surface sculpting tool* which incorporates concepts native to the artistic endeavor, *sculpting*, and which offers unique advantages over other common approaches to digital surface manipulation. Implementation of the key components of this definition serves as a proof of concept for evaluating the merits of this approach.

The thesis makes three primary research contributions. The first is a formalism which starts with an interdisciplinary survey of relevant literature and methods of manipulating digital and non-digital surfaces. The traditional (non-digital) sculpting processes looked at are: *carving*, *modelling*, *construction of objects*, *casting and moulding*, and *kinetic sculpture and arrangements*. From this survey, a basic definition of the sculpting endeavor is devised; the constituent parts for which include the following four universal components: *tool*, *material*, *method*, and *simultaneous multiple degrees of freedom*. Each element of this basic definition of sculpting is then discussed individually in order to tailor a generic (and implementable) definition of a digital sculpting tool.

The second research contribution is the definition of the generic sculpting tool itself. The definition consists of four components: (1) a shape, (2) a path, (3) a relationship between shape and path characterized by orientation (angle and track point position) and static and dynamic mode, and (4) the effect, or result of the application of a shape to a path, which is ultimately an addition to and/or subtraction from the surface. Effect's parameters include its scope of action, which distinguishes between local, regional and global moves and passes, together with a formalism for corner, overlap and end options. Significant is that the definition is a simple and compact one. It encapsulates all of the necessary parameters necessary for defining *any surface geometry*, not only topographic surface geometry. It also offers *mathematical and geometric equivalence* – for every surface and path together with their relationships there exists exactly one surface geometry which may result. The definition also does not include the surface representation itself, i.e. its surface defining parameters are *decoupled* from the digital surface representation (raster, TIN, contour lines, etc.). The alternative internal representation of a surface that is instantiated by this definition is therefore a very compact and simple one.

The third research contribution is the demonstration of the ideas via an implementation of a raster-based prototype software, *Topographic Surface Sculptor (TSS).* Base class equivalents to the generic tool design's components are devised. They are: *CTool, CShape, CPath, CEffect,* and *CTarget*. The prototype implementation demonstrates the conceptual simplicity of how extrusion of two lines together may create geometrically very complex surfaces which are easy to change, and at the same time intuitively straightforward for a user to generate and control.

The fourth research contribution is a conceptual discussion of the implications of this approach on ways of thinking about traditional sculpting in general. The generic digital sculpting tool definition encapsulates traditional sculpting's requirement for a material and a tool into one internal digital representation. This coupling of tool and material suggests ways of sculpting which remain unexplored in any media, and merits further exploration in the digital domain.

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This thesis is dedicated to Wade Hokoda (1958-1997)

Chapter 1: Introduction

1.1 Motivation

Changing the topographic surface of the earth is a universally specified need across cultures and throughout history. Methods for regrading sites have a rich and early heritage overlapping several disciplines and scales. Sculpting is another fundamental human activity with established traditions and profound implications for how people generate three-dimensional forms. The motivation for this investigation arose out of a desire to make computing qualitatively better for users involved in surface grading tasks, and the belief that improved methods to do so may be realized through the translation and incorporation of traditional sculpting ideas into software tool design.

This thesis examines the components of traditional sculpting in order to define a *generic digital sculpting tool*. A software implementation embodying the concepts developed in this thesis is demonstrated with a *topographic surface sculptor (TSS)* software prototype, which serves as the basis for an evaluation of the merits of this approach.

1.2 The Problem

Many environmental effects, including humans, affect topographic geometry (figure 1.1). Environmental processes are those resulting from biological, weather, or other natural resource behavior, and occur directly on the earth's surface. Human induced changes often work through representations of topography before affecting actual earth movement; i.e. via indirect means. Such human changes ultimately may be built in the landscape via tools (e.g. shovels, bulldozers, explosives, etc.), or directly by way of bodily contact with the earth (e.g. via hands or feet). This thesis focuses on indirect human-induced topographic surface sculpting resulting from interaction with digital software tools working on a digital surface (e.g. DTM) representation – the highlighted grey region in figure 1.1.

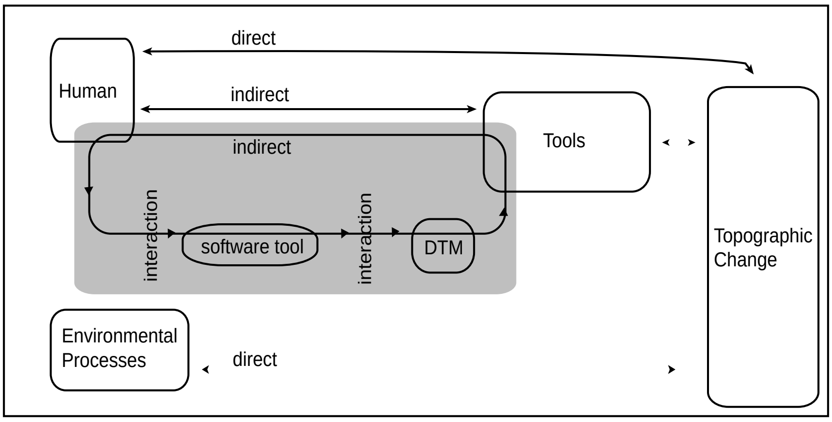

Figure 1.1: Topographic Manipulation; Context Diagram. This thesis focuses on indirect human-induced topographic change; i.e. the region highlighted in grey.

Designers of topography need to accomplish many tasks as they work. Typically they require a graphic representation, and tools and methods for editing and evaluating the different design scenarios which are graphically represented. A designer or artist would like to try out many designs quickly and easily. Iterations around the grey highlighted design loop area of figure 1.1 typically occur as many times as project resources allow. For topography, the standard representational options continue to be primarily contour line drawings, cardboard horizontal layer models, clay, plaster, or wood models, as well as digital terrain model (DTM)

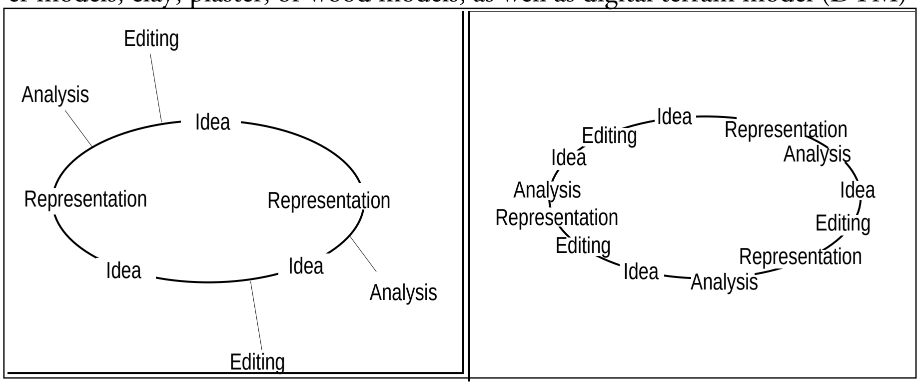

Figure 1.2: Iterative Design Loop. With existing representational options, the editing and analysis phases of design are typically quite removed from the iterative design loop; i.e. they are treated like satellite experiences.

representations. When it comes to manipulation of these topographic representations, the editing and analysis functions are often dealt with as satellite experiences in the design cycle (see figure 1.2). In other words, there is usually a temporal break in the continuity of the design cycle in order to perform the editing and analysis tasks; tasks which have proven cumbersome.

The objective is to place the landscape designer/user closer to the target concern – spatial characteristics of landform – rather than the characteristics of the model medium, much as a sculptor seeks to explore forms spatially. The quest is for surface sculpting methods which situate the designer as conductor rather than as a constructor of model or drawing. This emphasis lets the designer do what she does best: spatially design topography. Such methods would tighten the iterative design loop for landscape designers, i.e. bring the editing and analysis phases closer to the idea and representation cycle, thereby enhancing the exploration and evaluation of alternatives. Opportunities in the digital medium to address the short-comings of these representational options begin to present themselves.

Digital methods for changing the topographic geometry specifically have been variously referred to in the literature as DTM manipulation[1], dynamic terrain[2], editing[3], sculpting[4], modification[5], or deformation[6], transforming[7], among other terms, like modelling, grading, and constructing. While these cited references do involve geometric change to a topographic surface, more typically in application domains the terms refer to changes confined to colors, texture maps, placement, and other attributes besides DTM geometry itself, with the exception of constructing which implies model generation as opposed to editing. Moreover, the distinction between manipulating existing geometry and creation of models remains confused. The terms editing, modifying, deforming, grading and sometimes modelling often imply changes to an existing physical situation, while the other terms only sometimes imply an existing surface. Of all terms, *sculpting* suggests the expressive quality of geometric control universally sought after. Sculpting is also a term rarely used in the context of DTM geometry, making it opportune to establish a definition tailored to such a program here.

As part of Geographic Information Systems (GIS's), DTM-oriented software has evolved with the ability to handle the large datasets characteristic of landscape, but have heretofore focused on the display and analysis of elevation data, rather than on active tools for manipulating form. Most research efforts continue to focus directly on the implementation-specific issues: Data structures and/or alternative graphic representations for meeting specific efficiency or visualization requirements, i.e. computer graphics performance objectives, and/or greater representational realism, respectively. Geometry manipulation strategies in those few software systems which offer them, moreover usually allow only either *global* or *local* changes to a model: A local change is a change that happens to a single ver-

1. Weibel, R., and Heller, M. (1990).
2. Institute for Simulation and Training Website
3. Bär (1994)
4. Westort (1996)
5. Moshell (1992)
6. Foley et al. (1987)
7. McCullough (1986)

tex; a global change is one that affects the entire topographic dataset, e.g., scale changes, which exaggerate the Z value[8]. A common objective among users, however, is to achieve geometric control over *regional* model geometry, i.e. a user-specified regional scope of action – not the entire data set and not just one vertex.[9]

1.2.1 Previous relevant work

Approaches to modelling and manipulation of digital surfaces typically fit into one of the following categories:

(1) Construction of parameterized primitive forms; as with computer aided architectural and product design. (see Mitchell, 1990, 1991)

(2) Data-structure specific approaches; for example contour line manipulation methods (Breeden, 1997, LandCAD homepage), raster-based approaches (see Bär, 1994), or methods for triangulated irregular networks (see Bechmann, 1994; Commercial Terrain Visualization Software, 1998; De floriani & Puppo, 1992).

(3) Filters and Masks, which screen out or exaggerate a polygonal area of a model (see ArcInfo, ESRI).

(4) Real-time simulation / Physics-based modelling. These methods overlap with the previous three approaches and involve the mimicking or "simulating" of natural, or physic-based behavior of the landscape in the computer. (see Moshell, 1992; Li and Moshell, 1993)

While there are overlaps between categories, the most commonly found methods applied to topography belong to the second category. These include the "Sewing Machine" approach of LORAL Advanced Distributed Simulation[10] and the real-time earth moving approaches developed by Li and Moshell of the Institute for Simulation and Training. In both cases, the objective is to alter TIN surfaces in real time. Their priority the simulation of actual earth-moving equipment and tools that one is familiar with in real life (category 4 above). These constraints result in a tool and surface parametrization which requires a close coupling between the desired external representation and the geometric manipulation method. Ervin and Westort (1995) borrowed the simple raster array data structure common to GIS systems, but is not dependent on it, unlike most other approaches.

The challenge of this project has been to devise new ways of representing the three-dimensionality of terrain in a modular fashion in order to free the manipulation method from the granularity of the external representation. Data structure enters the picture later when one needs to convert to a TIN or grid or contour line, or whatever to operate between what is saved on disk and what is

8. Ervin(1991)

9. Ervin and Westort (1995)

10. LADS (Loral Advanced Distributed Simulation) (1995);

displayed. The manipulation may occur in an intermediate step. While in the future these intermediate steps may be developed to offer real-time performance, the focus here has been on the design of a sculpting system which emphasizes model fidelity and achievement of *any model geometry*. Conversion between the different terrain model output representations to achieve explicit performance objectives is a solvable issue that may follow from conclusions drawn from this study.

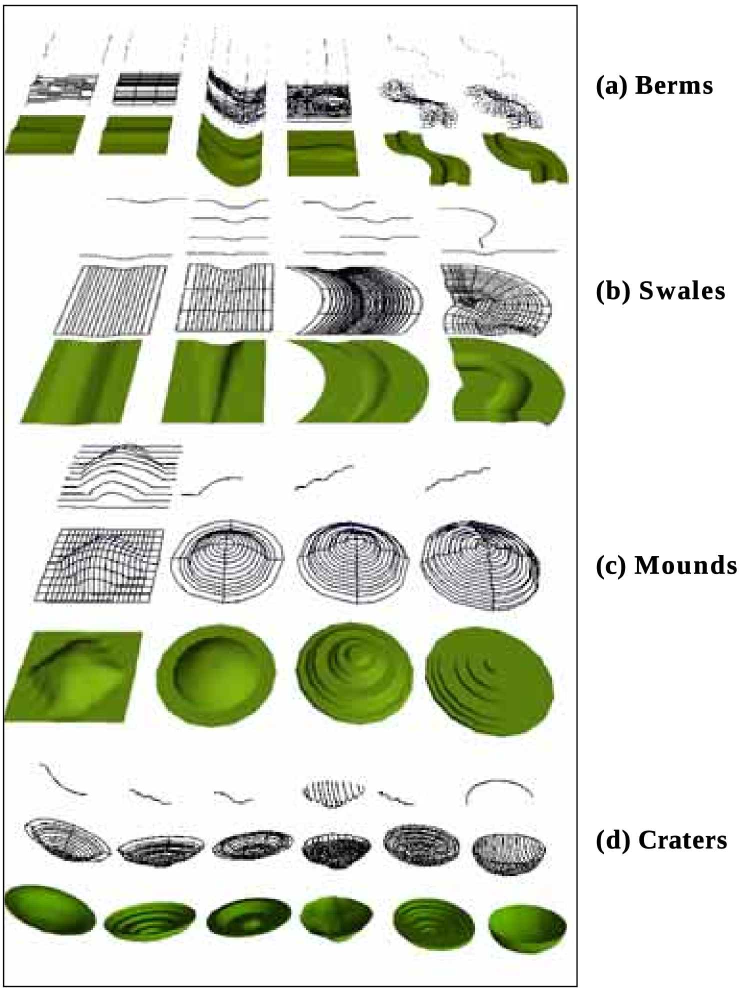

Figure 1.3: Preliminary Library of Topographic Primitive Forms. (a) Berms, created using the *Alias* functions patch, skin, extrude (fixed blade orientation), extrude (perpendicular blade orientation). (b) Swales, created using *Alias'* skin, extrude. (c) Mounds, created with skin and revolve functions. (d) Craters, generated from *Alias*' revolve and skin functions.

Previous work by the author has addressed the paucity of useful functionality at the user-defined regional scope of action specifically. Figure 1.3 shows the author's first attempt to model a vocabulary of digital topographic primitive forms for inclusion in a preliminary library. Using the CAD software package, *Alias*™, the component parts of the surface generation technique are shown directly above the resultant rendered surface objects. Combining these primitive forms also in *Alias*™ to design a topographic space, is less than satisfactory as figure 1.4 a and c. The continuity of the terrain is interrupted, leaving only discrete surface objects. What is called for are ways to instantiate specific topography so that they integrate within the continuity of the surface.

Figure 1.4: **Mill Creek Canyon Park**, designed by Herbert Bayer and built in Kentlands, Washington, USA. (a) wireframe model of site topographic primitives, (b) photograph of existing site, (c) shaded model of site topographic primitives. a and c modeled in *Alias* by the author.

The prototype landform design system of [Ervin and Westort 1995] also borrows the simple raster array data structure common to GIS systems. The CAD modeling strategies skin, sweep, and algebraic combinations of Constructive Solid Geometry modeling are adapted and called a *virtual bulldozer*, to consist of three main parts shown in figures 1.5 and 1.6:

1. An "extrude" tool, made of a "path" and a "blade"
2. A library of parameterized primitives
3. Boolean and algebraic combinations between primitives and extrusions.

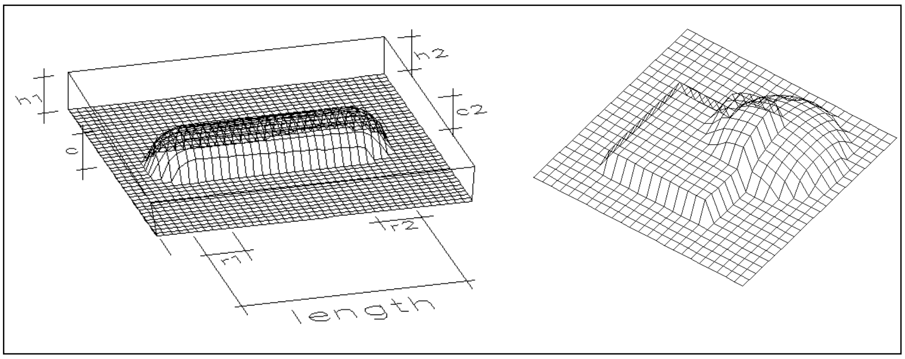

Figure 1.5: **Topographic Primitives in AutoCAD.** (a) a parametrized berm with its length, height and location specified; (b) a mound and box overlapping, with

Ervin and Westort (1995)'s system tries to develop just such capability via a library of topographic primitives including mound, berm (shown in figure 1.5-a), swale, torus, box, etc. each with their own geometric properties parameterized. Primitives can be combined into a single landform, using algebraic operators such as: +, -, max, min, average, etc. The max function is illustrated in figure 1.5-b.

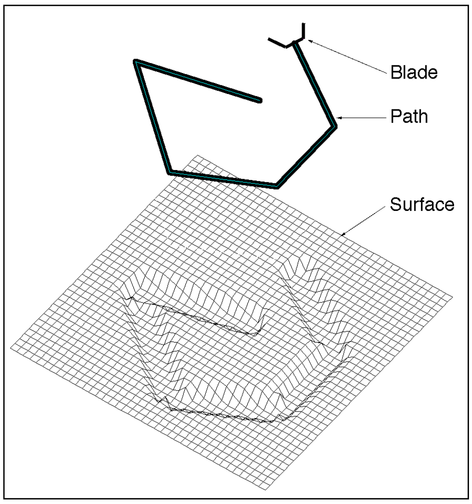

Figure 1.6: The *virtual bulldozer* prototype of Ervin and Westort (1995).

At the same regional scope of action the simple metaphor of a two-dimensional profile, or blade, is swept along a three-dimensional trajectory, or path, leaving behind a modeled digital topographic surface. This path and blade system takes a simple rectangular blade and moving it along a path constrained to straight lines and large radius curves. A blade is defined as a user-definable number of points that define a two-dimensional profile. A path is defined as a user-definable number of three-dimensional points, i.e. a three-dimensional polyline.

A real bulldozer always cuts relative to the existing surface, as its treads are confined to travelling over the surface. For this virtual bulldozer, the points of a path may have no z-coordinate specified, in which case the tool will cut relative to the existing terrain, taking its base Z value from the terrain data. If a Z-value is specified in the path, the blade cuts along the absolute path given. A single path may have both specified and unspecified Z-values, allowing a mixed path. By making the Z-coordinate optional along the path, the virtual bulldozer has the ability to either accommodate or ignore existing topographic conditions of a site; to both mimic and go beyond the abilities of a real bulldozer.

This approach to DTM sculpting suggests the potential for digital representations to compensate for some of the awkwardness of working with existing digital methods, traditional contour lines or horizontal models. Ervin and Westort (1995)'s description of the virtual bulldozer, however, relies only on "operators" and "primitives"; a dichotomy which calls for further resolution and development.

1.2.2 GUIs alone are not the answer

In computing, human participatory control is typically discussed in terms of graphical user interfaces (GUIs). Wake, 1991 describes the chronological progression of GUI techniques as consisting of the following four fundamental developments:

- User-computer dialogs - i.e, command line driven requesting and answering between computer and user, typically via command languages.
- Menu-based - either text-based or icon-based representations of command choices.
- Icon-based - pointing -based interaction based on combinations of keystrokes and icon-based images from which to specify user-tasks.
- Tool-based - direct manipulation of tools – things which look and work like real-world iconic equivalents of the icons being manipulated (e.g. calculator, pen)

While tool-based GUIs may be read as a simple derivative of the icon-based variety because of their continued reliance on icons, pointing, and keystrokes to achieve software tasks, the trend in GUIs towards "greater continuity of engagement" has been noted by McCullough 1996. GUI developments have expanded along the following progression, he points out, and promise extension to full body immersion:

- Command Languages
- Pointing, modified pointing, pointing in three-dimensions
- Spatial Action
- Ergonomics or Fit
- Touch
- Orchestration

This trend towards dematerialization of the tactile world – direction "virtual reality" – holds no promise to fulfill the desired complexity of expressive geometric control, however, since "doing with tactile forms makes mental topologies"[11], and this sensibility would be lost in ever more dematerialized environments. Indeed later GUI developments in this direction have not replaced the earlier GUI interaction techniques of pointing, clicking and dragging, McCullough accurately notes. Instead of *degree* of human-computer immersion, therefore, digital environments offer the more compelling opportunity for new *mental models* – or generative structures – of desired tasks, like DTM sculpting, for example, which would take advantage of native digital understandings. Evidence supporting that other technologies have followed a similar route – a route from being mere technologies to finding native generative structures which graduate them to creative *medium* status.

For example, in the early days of cinema, the only way cinematographers found to tell a story on film was to place a camera in front of a theatre stage and

11. McCullough, p.129

leave it for the duration of the performance. Eventually, however, cinematography evolved as a technology to develop its own uniquely cinematic or *native*, narrative forms.[12] I.e. it evolved as a narrative medium. These developments include panning and sophisticated camera motion, clipping of scenes, close up and panorama shots – all devices which have come to be regarded as native to cinematic communication. A similar trajectory is unfolding for digital technology, and the challenge that topographic sculpting tasks present are ripe for such extrapolation. The objective in this case is not to mimic sculpting and modelling as we experience them in the real world (e.g. simulation), or to automate known manual methods, e.g., contour line drafting, but rather to develop a *system of symbols* and *actions* that afford new ways of representing sculpting surfaces that only the digital environment may host.

1.3 The Approach

The term sculpture is derived from the Latin *sculptura*, from the verb *sculpere*, *to carve or cut out of stone*[13]. While in common usage today carving remains one of the five main sculpting processes, the other four have evolved to be *modeling*, *casting or molding*, *construction of objects*, and *kinetic sculpture and arrangements*[14]. Discussions of these sculpting process categories are typically conducted either to:
(1) instruct art students in the techniques of these main sculptural areas: Modeling[15], carving[16], casting/moulding[17], construction of objects[18], or kinetic sculpting and arrangements[19]; or to
(2) enhance a viewer's appreciation of sculptural works, i.e. *sculpture*, or statuary, via art historical, theoretical, or biographical inquiry and discussion[20].
Rarely are processes of making in one medium considered to arrive at new methods in another – the interdisciplinary approach taken here. Although these sculpting process categories are reasonably identifiable, it is difficult to pin down the general notion of sculpting because it appears in so many guises and contexts. Indeed the overlap between examples seem so disparate and at odds, that anything unifying seems doomed to miss something fundamental.

12. example given by Prof. William Mitchell, lecture GSD, 1992.
13. Rich, 1965
14. Humphreys, 1984
15. see for example, Rich, Tiranti, Clarke, Midgeley, Jagger
16. see for example, Meilach, Jagger, Clarke, Miller, Hendrick, Forman, Batten, Vasari
17. see for example, Rich, Beecroft, Tiranti, Midgeley, Perry, Clarke
18. see for example, Schodek, Midgley, Clarke, Rich (and Taylor, Wickham, Reed, Moore for model -making specifically)
19. see for example: Schodek, Miller, Midgley, Clarke, Beecroft.
20. see Humphreys, Read, Elsen, Butler, Penny, Krauss, Battcock, as well as many monographs on individual sculptors and their oevre.

This has already been indicated by the variety of words that are commonly used to suggest the activity. One of the problems in dealing with a concept as general and inclusive as that of sculpting is that no single example can suggest more than a fragment of the full concept, so any good example is in danger of being perceived as more representative than it possibly can be. There is accordingly not much hope for stating in a few lines a precise and complete definition.

On the other hand, there is an alternative approach to problems of this kind, more common in the humanities than in the sciences, that emphasizes an extended discussion of the subject rather than a formal treatment. In the present case, it involves the formulation of an admittedly imprecise approximate definition, which is then elaborated and made increasingly more complete through examples and explanations of its associated categories, processes and components. At the same time, the concept suggested by the definition, perhaps rather vague and limited at the outset, becomes progressively sharper and more explicit as the discussion proceeds. To formulate a starting definition for sculpting, we consider the above-listed commonly understood sculpting categories and processes, and for each examine a simple case that everyone will no doubt accept as an example.

This is in fact a common approach to abstraction. It consists in taking a description of a "typical" concrete example and systematically suppressing the concreteness by substituting general terminology for the concrete. The idea seems to be that the "abstract" formulation so obtained will capture the "essence" of the system. In addition to equipping this investigation with a vocabulary and set of starting concepts, this approach to the topic helps us formalize what constitutes a *sculpting system.* And as our ultimate interest is to invent new *sculpting methods* situated as part of a comprehensive sculpting system, we shall understand such methods as structures, or explicit instantiations of that system. Rickart defines the relationship between system and structure as follows:

> "A *structure* is any set of objects (also called elements) along with certain relations among those objects.... A structure may involve an infinity of both objects and relations. "[21] [emphasis added]
>
> "A *system* is any collection of interrelated objects along with all of the potential structures that might be identified within it.... Every structure, along with its substructures is obviously a system, but a system is only "potentially" structured. It will exhibit structure as soon as any of its potential structures are made explicit"[22] [emphasis added]

Working then from a gradually inclusive qualitative definition, we aim to arrive at explicit "generic" definition tailored to extrapolation into objects for implementable objects.

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21. Rickart (1995) p. 17

22. Ibid. p. 19

1.4 Research Objectives & Organization of this Thesis

The research of this thesis therefore falls into three general categories: First, an interdisciplinary inventory of notions of sculpting is presented. Chapter 2 focuses on landform as an expressive medium. Chapters 3 and 4 clarify the term, *sculpting*; with chapter 3 developing a first basic definition, and chapter 4 clarifying the definition's individual components: *tool*, *material*, and *method*.

The second research category translates these components of our sculpting definitions into conceptual requirements for a generic sculpting tool for the digital environment. Chapter 5 defines the tool, chapter 6 translates the definition into an object-oriented class hierarchy. Up through until the end of chapter 6 an "ideal" sculpting system is described; not until chapter 7 when we first deal with topography do we narrow our focus to topography specifically.

The third research category is a technical demonstration of the ideas manifested in the ideal description. A subset of the class library description is taken for a prototype implementation to topography, in the form of the *and conceptual Surface Sculptor (TSS)* software, and this minimal set is described in chapter 7. Chapter 8 applies the implementation to some interesting examples to demonstrate its utility and the merits of the definition supplied by this thesis. Chapter 9 discusses the implications of our definition, both in terms of sculpting as a creative enterprise in general, and what our technical implementation here suggests for future research efforts in this area.

In summary, the following are the intended scientific contributions of this thesis:

(1) An interdisciplinary categorization of digital and non-digital surface manipulation methods (inventory phase).
Chapters 2-4

(2) A working definition of sculpting and conceptual design of an ideal generic sculpting tool.
Chapters 5 & 6

(3) A proof of concept software implementation for the key sculpting functionality for topography, in the form of an extendable *Topographic Surface Sculpting (TSS)* prototype software system.
Chapters 7 & 8

(4) Demonstration and evaluation of the results.
Chapters 8 & 9.

Chapter 2: Landform as Expressive Medium

Grading may be mostly or entirely a problem of disposing of surplus fill to the best advantage. At other times it will consist of arranging for proper drainage, removing objectionable humps or filling gullies; disposing of stone walls or boulders; reshaping to obtain a desirable view or to avoid an undesirable one, or rearranging contours for better appearance.

Nichols

2.1 Introduction

Landform has served as an expressive medium for centuries. This chapter gives a broad survey of some characteristics of topography as a material. The traditional tools and methods with which topographic material is typically manipulated in the field are presented in the first section 2.2. How representations (drawings and models) are used to represent changes are also reviewed starting with section 2.3.5, Topographic Manipulation in Professional Practice. Attempts at parameterizing discrete landform shape i.e. specific geomorphology, are presented in the chapter's last section.

2.2 Landform Construction Tools

In common usage the term, *landform* generally refers to a natural or constructed feature made out of earth or soil; with special emphasis on its formal or geometric characteristics. The word differs from *landscape* and *terrain*, and resembles more closely *topography*, because of its focus on the ground plane itself, and the general exclusion from its usage of vegetation, water and cultural features like buildings and roads and infrastructure. Rocks or soil, i.e.the loose upper layer of the earth where plants grow, is what landform is made of. Paving or groundcover vegetation like grass, all of generally low relief, often cover it. Due to its course structure in the field, mechanically moving the earth at a large scale calls for employment of earth moving equipment; known for being some of the largest and most rugged machines in existence.[1]

There are two basic levels with which to consider the direct construction of

1. see Orlemann (1995)

landform via excavation equipment of tools: (1) the individual marks made by a machine, or a part of a machine, and (2) the overall intended surface impression of a set of marks by a particular machine, for which standard parameters and forms exist. For example, a bulldozer makes individual passes or cuts (level 1), the set of which taken together may be used to create cellars, ponds, roads, etc. (level 2).

2.2.1 Excavation Tools and Machines

The standard textbook for training excavation engineers on the mechanics, behavior and appropriate use and application of excavation machinery is by all accounts Nichols' *Moving the Earth,* now in its 9th edition. Its table of contents is divided both by task and by machine, with no clear distinction maintained along the lines of level one and level two described above. It reads as follows:

- Land Clearing
- Surveys and Measurements
- Cellars
- Ditching and Dewatering
- Ponds
- Roads
- Blasting and Tunneling
- Pit Operation
- Costs
- Basic Information
- Revolving Shovels
- Conveyor Machinery
- Tractors & Bulldozers
- Tractor Loaders
- Scrapers
- Dump Trucks
- Grading and Compaction Machinery
- Compressors and Drills
- Miscellaneous Equipment

Level one, or the individual marks a particular machines makes is taken up either during description of a particular machine's member part, and/or in descriptions of individual jobs, tasks, i.e. level two, for which an array of tools may be mentioned. The 1:1 scale relationship with the excavation equipment and the earth is regarded in this text as an opportunity to focus both on the machine *shapes*, and the corresponding *paths* possible for the various machine's application to the surface. We take up level one first. Nichols outlines the following types of excavation machines, classified here according to shape of the machine's component which shifts dirt:

a) Tractor

Industrial crawler tractors are made up of a center sector or chassis that contains the engine, transmission, and steering units; and two track frames that supply traction and support.

b) Bulldozers

Bulldozers are tractors equipped with a front pusher blade, which can be raised or lowered by hydraulic or cable control and which is used for digging and pushing. The shovels (or blades) of these machines are all rectangular with a rectangular back. Angling dozers are bulldozers which have blades that may be set at angles to cast dirt to either side while the tractor moves forward. When their blades are set straight, they do the same work as straight dozers. The primary variant among them are their range of motion, or paths, which Nichols describes as either linear in two or three-dimensional space, and the fate of the scraped or dug earth material (not depicted here). The before and after surface effects are basically the same. A deepened or flatter area left behind the wake of the shovel or blade.

The blade is a massive structure that has a rectangular base and back. The leading edge of the base is a flat blade or knife of tough, hard steel which projects ahead of and below the rest of the blade. The front of the blade is called the moldboard and is convex and sloped back. As this blade is pushed into the ground, the knife normally cuts and breaks up the direct that is pushed up the curve of the moldboard until it falls forward. Material being pushed ahead of the blade is thus kept more or less in rotary movement, which tends to even up the load and offer less friction and a larger load than would be obtained with a flat vertical molboard.

The blade on a 25 ton bulldozer might be 13 ft. wide and 4.5 high. The profile of the theoretical load would be a right triangle 4.5 x 4.5, with an area of 10.25 square feet. Multiplying this by the 12 foot blade width, we have 123 cubic feet. Adding 20 per cent for center bulges, this would be 148 cubic feet or 5.5 loose cubic yards. Different manufacturers rate blades of this size at 5 to 7.5 loose yards.

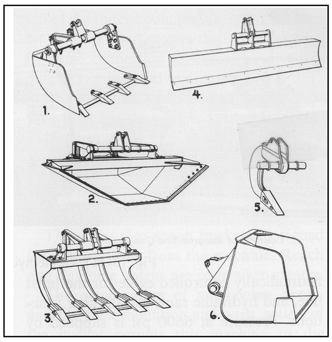

Figure 2.1: Example dozer blade shapes. (Nichols, 1971, p.13-101)

The capacity of a bulldozer blade cannot be computed exactly, i.e. its *load*. The blade forms only one of the 6 sides of a shapeless pay load. Since the load must slide or roll along the ground, friction is a very important limiting factor on load size. Materials with low internal friction or light weight, and downhill pushing favor big loads. Pushing through a slot or between windrows, or with the blade almost touching that of another dozer, increase load by reducing side spillage. A good average load may be said to be 20% more than would be measured by the full width and height of the blade, with a forward slope of 1:1. The actual load would be higher in the center and skimped in at the corners, averaging out as above. Under very good conditions the load might average 6 inches higher than the blade top, and extend forward on a 1.5 to 1 slope. Then the profile would be 5 ft. x 7.5 ft. or 19 square feet. Multiplying by 12 ft. width, we get 230 cubic feet or about 8.5 yards loose.

Capacity of blade is greatly affected by grade. Downhill the load tends to slide along with minimum pressure, uphill its friction rises and it spills more off the sides. Possible load, both from standpoint of power to push it and ability to keep it in front of the blade, increases about 4 per cent for each per cent of down slope. That is, a dozer might push double its normal load down a 25% grade. Uphill the load falls off at first almost as rapidly, but the decline slows with steeper grades. A half load might be pushed up a 20% grade, and a quarter load up 100%. When a job is in progress dozer blade capacity can be checked by counting the number of full passes required to dig a known yardage of a bank, or by counting loads pushed into a pile, and measuring the pile. The first result is in bank yards, the second in loose yards.

c) Scrapers

Scrapers are the standard tool for alternating cuts and fills. They can dig, haul and spread in a single normal working cycle. It is not only an excellent machine for bulk earth-moving, but a precision finishing tool as well. They are usually rated for heaps with 1:1 slopes. Scrapers are digging, grading and hauling machines with a centrally mounted bowl that carries or drags loads. A very wide range of types and sizes exists. They may be towed or self-driven.

d) Compressors, and Compacting machinery

Compaction is the art of artificially increasing the density of the soil typically by expelling air or water from spaces between soil particles. It is measured in volume-weight. The purpose is to stabilize soil, particularly in built up fills, embankments, and dams for minimum change in volume or shape under influences of weather and time, and under the weight of structures, pavement, and traffic.
In nature this process occurs via: wetting, drying, freezing, thawing, ground water movement, and weight of higher soil layers, i.e. settlement.

Soil may be compacted by pressure, kneading, vibration, impact or by combinations. The following are a list of compacting machinery with the corresponding mechanical means for achieving compaction:

- steel wheel- pressure
- sheepsfoot rollers- pressure
- pneumatic tired roller- pressure with some kneading
- wobble-wheel rollers- kneading and pressure
- vibratory rollers- pressure & vibration

- pneumatic or gasoline powered hammers
- jump rammers
- vibrators
- Puddling is the method of adding water until the soil is semi-liquid, and allowing it to dry and settle. It is a compression-based technique.

e) Revolving Shovels

This class of equipment includes *backhoes, cable-driven draglines,* and *conveyor machinery* (or cable excavators), or ***cable loaders***. A *cable excavator* is a general term which includes any cable operated machine using an excavator bucket working between a head structure and a tail anchor spaced hundreds of feet apart. The head structure usually is a guyed mast but may be moved by a self-supporting tower. The tail anchor usually is designed to move along an arc, the radius of which is determined by the length of the operating cables.

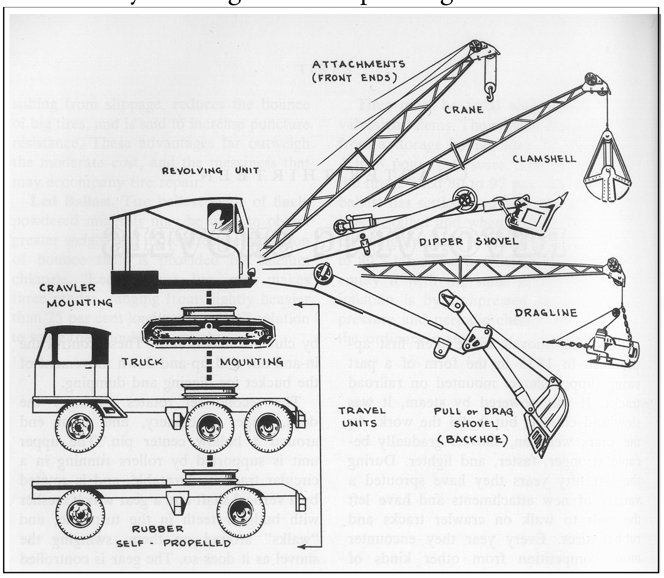

Figure 2.2: Diagram of rotating shovels. (Nichols, 1971, p.13-2)

The components to the basic standard revolving shovel are the following:

- **Deck-mounted drums** which are fitted with spools for cable or with sprockets for chain, which are rotated and stopped by clutches and brakes to control the in and out and up and down movements of the bucket for digging and dumping.
- The second set rotates (swings) the deck, upper machinery and front end around a hollow center pin. This mechanism is an important factor in the efficiency and adaptability of the shovel. It enables it to face in any direction for digging and dumping, and to move loads quickly anywhere within its reach.
- The third power train provides means to walk or propel the shovel. The shov-

els themselves vary greatly in size and weight. (see figure 2.2)

The measurements of the container, i.e. most buckets and container bodies are rated by the manufacturer as to carrying capacity in loose yards. The smallest model has a bucket capacity of one quarter cubic yard and weighs about 7 tons; the largest have buckets over 40 yards, and weights of hundreds of tons. The smaller sizes tend to be faster and jerkier than their big brothers, and are of course much weaker. Shovels may be classified as full revolving and part revolving types. The part revolving was the original construction but has now been superseded by the more convenient and flexible full swing.

The shovels mounted by front end attachments to a Revolving Unit, which in turn is mounted upon a truck.

- Crane Bucket
- Clamshell
- Dipper Shovel
- Dragline
- Pull or Drag Shovel (Backhoe)
- Pulltype buckets are available in widths from 15” to 72”, and push buckets, whose digging action resembles
- Crescent Buckets

f) Blasting and Tunnelling / Explosives

Explosives are usually used for cutting through rock and underground to depths unreachable by other mechanical means. The primary purposes of rock excavation include:

- Stripping – the removal and wasting of any type of rock or dirt in order to uncover valuable layers.
- Cutting – the removal primarily to lower the surface. In road and airport construction.

The spoil is generally used for fill elsewhere in the project. In ditching it is often used for backfill after installation of pipes.

- Quarrying or mining – excavation of rock which has value itself, either before or after processing. Quarries are ordinarily concerned with the physical characteristics of stone, and mines with its chemical compositions.

One excavation can involve all three classifications. Blasting may be divided into a primary operation in which a rock is loosened from its original position in bulk and secondary work which consists of reducing oversize fragments, and breaking back ridges and purs. Only explosives resulting in cratering or other kinds of surface grading operations will be considered here. Its geometric effect, in other words.

g) Drills & Compressors

Rotating drills are usually powered by air supplied by portable compressors that are driven by standard types of industrial engines. They draw in atmospheric air, compress it, and deliver it through a hose to the tools. The compressed air provides a power medium similar to steam in performance, with the important difference it can be used cold.

In terms of their shape, the primary variation among drills is the shape of their rotating head or table, an endless array depending on type of material being drilled or compressed. Their primary geometrical effect is a round columnar hole, with a characteristic bottom, and a top edge determined by the surface of drill entry orientation.

h) Pumps and Dredging

Pumps and dredging equipment are mostly used for water removal, or for scraping the floors of water bodies for landscape reclamation and environmental remediation work.

i) Wheel Excavator

Wheel excavators are primarily used for coal mining and consists of a self propelled crawler mounted unit that carries a cutting wheel on the end of a long boom that can be raised, lowered, and swung; it also has a stacker-like conveyor belt for discharging the spoil, that may or may not be separately controlled.

2.2.2 Level Two; Specific Landform built by Excavation Equipment

The end elements of excavation are surveyed according to their geometric effect/ form classification categories. In some cases the individual shapes and paths are described, but mostly we focus on the result of a set of shapes and paths and the individual machines or machine components used to make them.

a) Cellar

The three standard machines for digging small cellars are the bulldozer, the shovel dozer, and the hoe shovel. There are three primary methods for constructing a cellar. The first is done by dragging a large dipper shovel which piles the spoil on both sides. Materials for foundations are tucked and piled on the floor of the trench. After the foundations are up, the piles are bulldozed around and between them, and the surplus used to build up the grade throughout the area. Another method of line digging is to use a dipper or tractor shovel, load all spoil into trucks, sell or dispose of part of it, and use as much as is necessary for backfilling spaces between other houses in the same development. The third method requires at least partial backfilling as soon as the foundations are up, to provide access to building material.

b) Terrace

Three principal types of terraces are normally used. Each is constructed along level or contour lines.

- Ridge terrace - a ridge built of soil obtained from both sides
- Channel terrace - a ridge constructed of dirt from the upper side only
- Bench terrace - a stair structure with steep risers separating relatively flat cultivated areas.

c) Gully (including Ditches and Swales)

A gully is a drainage channel that has become so deepened or enlarged that its banks are unstable and tend to extend destructively into surrounding land.

d) Land-leveling

Slope patterns
land leveling may be divided into six classes, according to the result obtained.
1) Spot grading
2) General downward slope away from water supply – for sprinklers
3) Uniform grade in direction of irrigation
4) Uniform grade in direction of irrigation and at right angles to it.
5) Uniform grade in direction of irrigation and exact level at right angles to it
6) Exact level
Other special cases for earth manipulation at the second level which require unique techniques and equipment include the following categories: Ponds and Reservoirs, Canals, Banks, Irrigation systems and drainage, Berms, Roads, and mining and quarrying. Please see Nichols (1971) for more in depth descriptions of these days.

2.2.3 Gardening Equipment

Manual tools, which are not machines, but also working on a 1:1 scale with the earth. Mail order catalogs for such items are a useful place too look for categorization schemes. The Cleform Tool Company[2] offers the following distinctions: Hoes, shovels, rakes, water hoses and irrigation equipment, trowels, brushes, hammers, forks, picks, and others which we will not cover here, like buckets and special clothing. Their catalog also has categories for short-handled tools, and long-handled tools, and for some articular jobs, like interior and exterior tasks. Overlap exists between these categories, but this thesis inventories gardening and outdoor tools only. A distinguishing characteristic of all of them is that they are manually operated or held.

a) Shovel

A shovel is a tool for scooping up earth or snow, here manually, but it may also be attached to a large machine. Blades for bulldozers are often called shovels as well.

2. http://www.ccp.com/

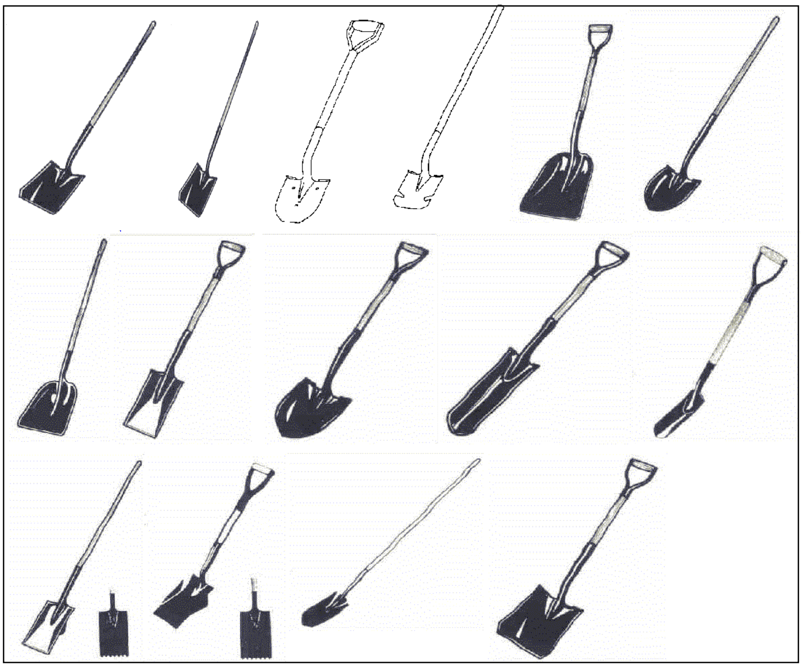

Figure 2.3: Example shovel shapes. (Cleform Tool Company)

b) Hoe

A hoe is a tool with a blade and a long handle used for weeding or otherwise loosening the soil.

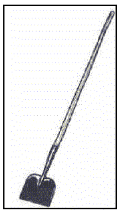

Figure 2.4: Example Hoe. (Cleform Tool Company)

c) Rake

A rake is a long-handled tool with prongs used for drawing together hay or fallen leaves, etc. or for smoothing loose soil or gravel.

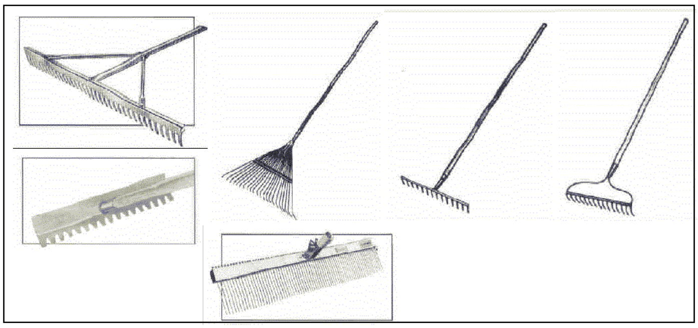

Figure 2.5: Example Rake shapes. (Cleform Tool Company)

d) Trowel

A trowel is a small tool with a flat blade for spreading mortar, etc. It may also have a curved blade for lifting or digging up plants, earth, or for scooping things.

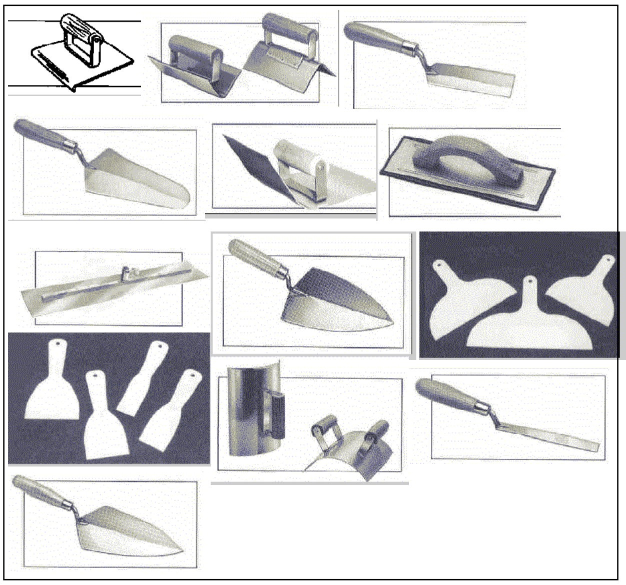

Figure 2.6: Example Trowels. (Cleform Tool Company)

e) Brushes & Brooms

A brush is an implement with bristles of hair, wire, or nylon etc. set in a solid base. It is usually passed over a surface to clear, or smooth it, or to gather up dust, dirt, or debris. It may also be used to paint or apply a typically liquid material over a surface. They may have short handles or long ones.

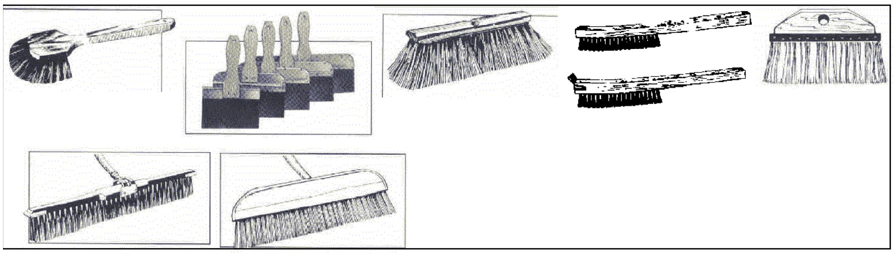

Figure 2.7: Example Brushes and Brooms. (Cleform Tool Company)

f) Hammers

A hammer is a tool with a heavy metal, stone head used for breaking things, driving nails in, to shape something, or to make a sound by hitting against something. Heads made out of wood or softer material are usually called mallets, and are used for tenderizing food, and by judges or auctioneers to make an official sound.

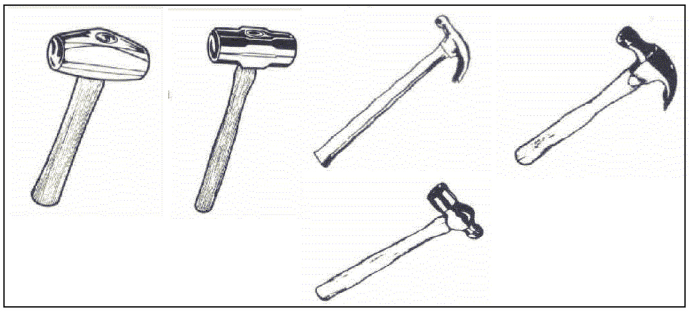

Figure 2.8: Example Hammers. (Cleform Tool Company)

g) Forks

A fork is a pronged tool or instrument used for digging or lifting things, like dirt or hay. They typically have long handles.

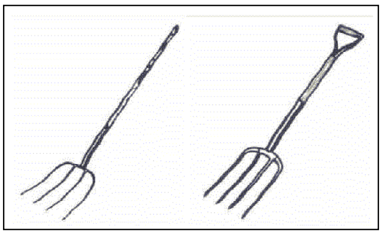

Figure 2.9: Agricultural forks. (Cleform Tool Company)

h) Picks

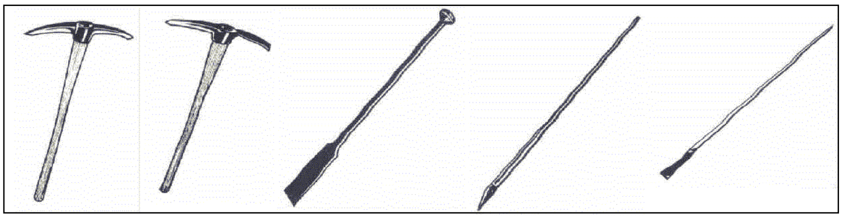

Figure 2.10: Example Picks

2.2.4 Agricultural Equipment

Equipment used for agricultural purposes, but not covered among the excavation machinery above includes the following:

a) Plows

A plow is an implement for cutting furrows in soil, drawn by a tractor or by draft animals. The shape of a blade, which is typically pushed or dragged has the shape of a coil which is turned by the material being plowed, ultimately out of the path of the plow. A snowplow resembles a plow, but is used to clear away snow.

b) Spreaders

A spreader is a machine for spreading soil or seed around at a particular thickness over a specific area.

2.2.5 Topographic Manipulation in Professional Practice

The topographic condition of a site is regarded by professional landscape architects and engineers as an essentially plastic one. Unlike the methods and tools employed on site, their way of working is an essentially indirect one, through representations. Through three-dimensional modelling, rendering and visualization, designers are able to try out an assortment of design approaches on a topographic surface. Design alternatives are seen, changed, and analyzed a scale smaller at scales smaller than 1:1 before actually constructing them. For environmental designers, visualization works in close concert with manipulation and quantitative and qualitative analysis.

The process of landscape design has been characterized as consisting of three phases[3]: Phase One is the inventory and analysis phase where inventories of existing physical and cultural conditions of the site and its surroundings are recorded. Conflicts, constraints, and opportunities which will guide the design development are identified. Phase Two is design development which involves synthesis of observations and evaluations of Phase One into a design concept which generates one or more design solutions. Phase Three is design implementation, involving the translation of design intentions into construction drawings and specifications. The following sections describe how contour lines and models

3. Strom

are used as part of these three phases in traditional practice.

a) Contour Lines

Contour lines are a two-dimensional graphic technique used to represent three-dimensional landform on a planar surface, typically paper. They are lines which represent the same elevation along their entire length and commonly have regular vertical separations, otherwise called *iso-lines*. They are the most popular and widely used method of representing landform on paper because they allow both the display of other information on the same map, and the designer to approximate the elevations of other points with relative accuracy [Landphair, et al'88]. Topographic manipulation via contour lines is typically a manual process which simply:

1) sets some preliminary elevations and lines of slope, including fixed floor elevations, main drainage pattern, and critical spot elevations (figure 2.1a), and then
2) draws connections between zones of major importance, staying within functional, environmental, and legal constraints (Landphair, et al'88).

Regional changes to the landform via contour lines require a re-working of the elevations in the area of interest, followed by a reconfiguration of all major connections and lines relative to the change (figure 2.1b). Most regional changes require a subsequent global re-working of the line representations, making geometric modifications via this method labor-intensive, and therefore often inflexible and cumbersome.

Despite that contours are essentially a fictitious representation – they neither reflect how elevations are measured, nor true elevation values along the lines –the primary reasons for their subsequent standardization and persistent dominance in the landscape design professions are that they fulfill the following six needs:

- to include a high density of quantitatively precise topographic elevation data
- to include other geographic information that one cannot see on land or in a section profile at high densities.
- to be portable and durable
- to be reproducible
- to allow this information to be editable and changeable
- to provide straightforward means for calculation of cut and fill, slope, and visibility analyses.[4]

b) Model-Making

The same lag time involved with manually manipulating contour lines holds true for use of other analog models during the manipulation process, many of which start out with contour line drawings (e.g. clay, cardboard). Employed in architecture, engineering, and landscape design offices and studios at every stage, during the inventory phase they are a means to record the “before design” site circumstances. During the design development phase they are used at various levels of detail, from very rough sketch models, to very detailed accurate ones to test out

4. Westort, Caroline (1993)

and present specific design scenarios. Choice of the modelling media varies according to the model's intended purpose, phase in the design process, resources available, and ease of generation and manipulation criteria.

Use of analog models in the landscape process is both an essential, and resource-intensive endeavor. A simple chipboard model often requires several hours to cut and assemble. Making changes to models in non-digital media often requires the designer to return to a contour representation on paper and through another cutting and assembly routine. Layered models are constructed by cutting individual layers are cut out along contour lines superimposed on a piece of cardboard of a thickness that is to scale. The layers are then piled up and glued together. Geometric changes to these models involve first revision of the contour map, and then re-cutting and re-compilation of the individual layers accordingly. Because this method works via contour line abstraction, it too is a relatively inflexible means for regional geometric modifications. This choice of which modelling material to use in which phase of a design process is a judgement we will encounter again with other sculpting processes.

2.3 Descriptions of Landform

Attempts to define discrete geometry of landform ranges from the purely semantic and qualitative to highly explicit mathematical descriptions.[5] Attempts at parameterizing topography have been largely qualitative and subjective, and the prevailing nomenclature is verbal and non-unique. Such adjectives as *hilly, steep, gentle, rough,* and *flat* mean different things to different observers, depending on their experience and the scale of the landscape under scrutiny. The common nouns, *mountain, plateau, hill,* and *plane* are equally imprecise.

This section reviews strategies for describing landform in quantitative and qualitative terms. These methods complement the objectives of professional practice by offering ways in which the topography may be variously represented in its before and after states.

2.3.1 Contour signatures

An inventory of a library of contour line signatures recommended for instruction to landscape architecture construction students is presented by Landphair (1988). The advise is for students to memorize these contour line configurations Valleys, types of hills and ridge lines, and landscape features that occur as points or as complete landscape units are the three categories dividing the types of landscape features, according to Landphair (1988).

5. Pike,1993 p. 6.

> [He says the] list is by no means all-inclusive, nor is it meant to be, however, it can be most beneficial to beginning students to have a basic vocabulary of landform that helps associate contour signature with a mental image.[6]

a) Valleys

- Glen or Dale - A small narrow valley usually bounded by gently sloped concave sides (figure 2.11-a)
- Ravine - A deep valley bounded by steep slopes with little flat land at the base, usually only a stream bed (figure 2.11-b)
- Flood Plain - Abroad, flat to gently rolling land area bounded by distant distinct ridge lines (figure 2.11-c, d)

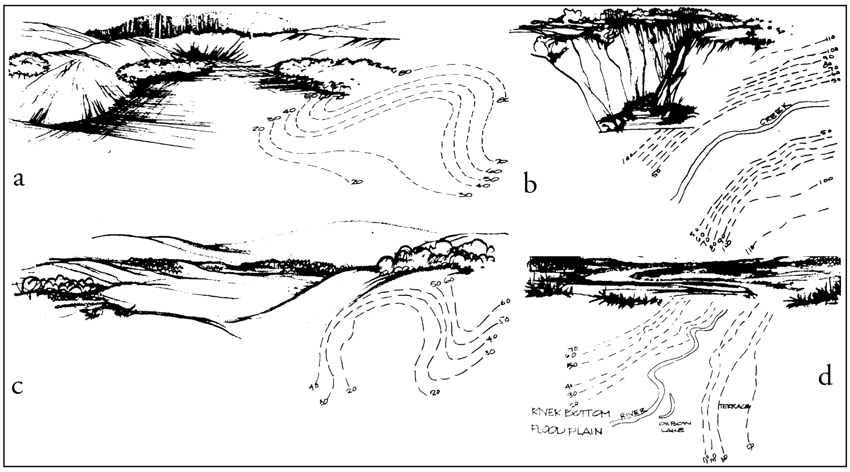

Figure 2.11: Landphair (1988)'s Contour Line Signatures for Valleys. *a* is a Glen or dale, *b* a ravine, *c* a flood plain, and *d* ariver bottom.

b) Types of Hills and Ridge Lines

- Hogs Back - A long distinct ridge line, characterized by concave slopes at the sides. (figure 2.12-a)
- Knoll - A hill usually round to oval-shaped with convex slopes (figure 2.12-b)
- Knob - An abrupt hill with concave slopes and a rounded top (figure 2.12-c)
- Camel Back Ridge - Paired knolls of near equal size that occur along a ridge line. (figure 2.12-d)
- Butte - A steep-sided formation with a nearly flat top. These are usually igneous rock intrusions that have been exposed by the forces of erosion. (figure 2.12-e)

6. Landphair (1988) p. 32-35

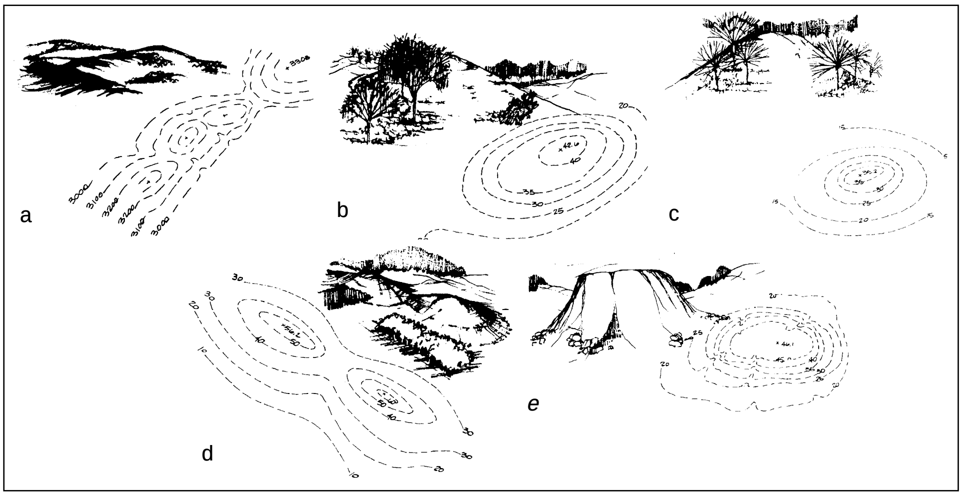

Figure 2.12: Landphair (1998)'s Contour Line Signatures for Hills and Ridge Lines. *a* is a hogs back, *b* is a knoll, *c* is a knob, *d* is a camel back ridge, and *e* a butte.

c) Landphair (1998)'s general terms for point-based or complete landscape units

- Bay and Promontory, or Headland - A bay is shaped by a ridge line, and the promontory is the dominant upland feature that shapes the bay (figure 2.13-a)
- Meadow or Terrace - A flat to gently rolling plain that occurs on a hillside or along a ridge line (figure 2.13-b)
- Swale - A shallow lineal depression with a parabolic cross section and gently sloped sides (figure 2.13-c)
- Fan (Alluvial Fan) - A nearly flat deposition of water-transported soil at the base of a watershed. The fan will usually be dissected by several water courses rather than a single stream as shown (figure 2.13-d).
- Toe (of the slope) - The toe is the point where the slope of a hill changes from its steep downward face to more gently sloped terrain. Where a structure is involved, it may refer to the base of the cut or fill (figure 2.13-e)
- Saddle - The low point between two domes or knolls along a ridge line. This feature is sometimes referred to as a pass as well (figure 2.14-a)
- Crest - The point of highest elevation on a hill. This point is usually marked on a topographic map by a spot elevation. (figure 2.14-b)
- Military Crest - The point on the slope of a hill that will not allow any person or object to be silhouetted against the horizon and also allows full view of the slope below (figure 2.14-c).

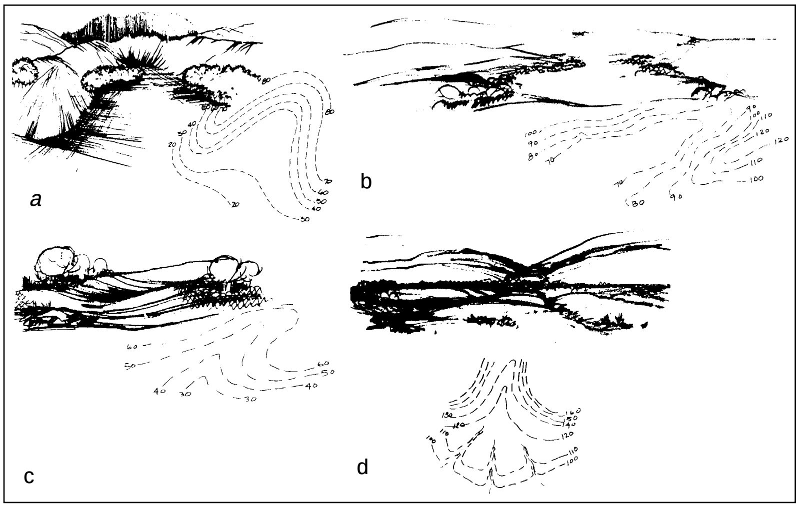

Figure 2.13: Landphair (1998)'s Point-based or Complete Landscape Units. *a* is a bay or promontory, *b* is a meadow or terrace, *c* is a swale, *d* a fan.

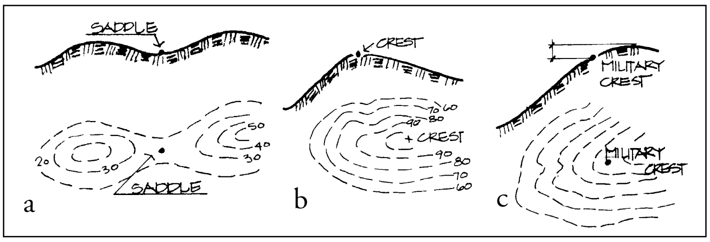

Figure 2.14: Further point-based examples from Landphair (1998). *a* is a saddle, *b* is a crest, *c* is a military crest.

This collection of contour line signatures demonstrates how they can be basically categorized as concave, convex, linear, or point-based.

2.3.2 Drainage patterns

Another scheme for classifying formal approaches to landform includes an approach to constructing drainage patterns. Harris and Dines offer the following summary chart of drainage sheet types (figure 2.15).

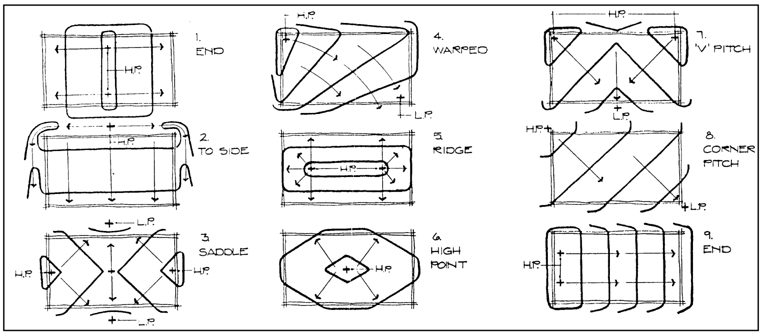

Figure 2.15: Drainage Pattern Construction. Landphair, 1988

2.3.3 Geomorphology / Geomorphometry

Among the physical geographers and geomorphologists who have also sought classification schemes to describe discrete landforms of the earth's surface, a sub-science known as *geomorphometry* has emerged. Geomorphometrists closely couple their interest in topographic form with analysis of the underlying natural processes and effects behind earth surface genesis, like synoptic meteorology and global climate. Thus their parameterization objectives are either for feature-extraction, or automating the reconstruction of existing topographic features (Strahler 1992 and 1994). It is not generally of interest to geomorphologists to sculpt or construct hypothetical landform; the target concern here. We nevertheless include geomorphometric approaches to landform in this survey as potential entries to a library of tool shapes as suggested in chapter one.

Two basic approaches to the geomorphometric description of landform may be distinguished (Evans, 1972): *specific geomorphometry* which offers some equations for Euclidean geometric approximations of discrete forms found in nature, like drumlin, swale, esker, for example; and *general geomorphometry*, which offers parameters for assessing the continuity of the landscape, like gradient, curvature, and aspect (see Evans 1972 and 1986, Pike 1988, Dikau 1989, BrÄndli 1995), and particularly those related to hydrological surface drainage features, such as channels, ridge lines, and watersheds (Brändli, 1995).

While our primary interest here is the former category, it may generally be said that due to their emphasis on shape extraction for analytical purposes, strategies at quantifying specific geomorphological form overshoots the parameterization task (excessive numbers of parameters) for constructive objectives. Three general approaches may be distinguished[7]:
(1) Lists of indices or parameters,
(2) fitting equations to landform, and
(3) distribution approaches.

Although historically, option two, fitting equations to landform, has been

[7] Evans (1986)

discouraged in the literature by Beckinsale 1991, Jarvis 1981, and Evans 1972, it offers the most promise for populating a library with a finite set of generic topographic primitive forms. Most of the primitive equations useful to constructive purposes were born out of attempts to classify topographic form, and are based on semantic descriptions and definitions. We will discuss these classification strategies first, and then review the landform equation approach.

Classification efforts early in the 19th Century confronted the classic conflict between a genetic basis for categorization, favored by the influential English geomorphologist Davis and a generic formal classification scheme, favored at the time by German geomorphologists. Beckinsale et al 1991 distinguish between the following six classification strategies bourn out of this original distinction, differing mostly in their spatial scales of generalization:

a) Encyclopedic

This classification scheme was pioneered by the German geomorphologist Albert Penck 1894, in his book, *The Morphology and Terminology of Landforms.* He claimed that all forms of the surface could be assigned to six fundamental types which were themselves arrived at by a systematic grouping of element form, or assemblages, resulting from *true erosion* (the linear action of rivers), *denudation* (by distributed weathering and mass movements), and *accumulation*:

- the **plain** - virtually horizontal
- the **escarpment** - a steeply sloping surface
- the **valley** - two more or less steeply sloping surfaces facing each other across a narrow strip of even surface, which usually declines in the direction of its downhill slope.
- the **mountain** - which slopes away in every direction
- the cup-shaped **hollow** - surface falls in a circle towards a fixed point.
- the **cavern** - almost enclosed by land surface

And the six fundamental forms, or categories of units, in ascending order of magnitude are:
(1) Form element,
(2) Fundamental form,
(3) Groups of forms or landscape
(4) Extended area of equal elevation,
(5) A system, or grouping of such areas,
(6) Continental block and abyssal deep.

If fundamental forms have the same outward appearance they may be called *homeoplastic*, and if the same original, *homogenetic*, according to Penck.

Geicke in his *Textbook of Geology* distinguishes between two kinds of action which generate topographic forms which we only list here because no formal parameters are given:

(1) **Hypogene Action** -- which includes the following causal effects:
Volcanic
Earthquake

Secular Upheaval and Subsidence
Other Crustal Changes
(2) **Epigene Action**
Atmospheric
Water
(Rain (chemical, mechanical), underground water (chemical, mechanical), brooks & rivers (c&M) (transport, excavating, reproductive),
Terrestrial Ice
(Frost (destructive), Snow (Conservative, Destructive), Ice-Sheets and Glaciers (transport, erosion, deposition)
Oceanic Waters
(Erosion, Transport, Reproduction)
Life (Organisms)
(Destructive, Conservative, Reproductive)

Passarge, 1912 in his textbook, *Physiologische Morphologie* classified form elements in groups also according to their genetic bases, which may be monodynamic (one dominant force) or polydynamic. He sets up two great types of surface forms, landforms and coastal forms or landscape and coastscapes, and then, using a classification of *forces* in agreement with it, groups of landforms representing classes, order, families, genera, and species or special forms:

Surface classifications based on the petrological character and structural arrangement of the underlying rocks, such as igneous or sedimentary or metamorphic do, according to Falconer, usefully emphasize the dependence of surface form upon the natural structure of the local geology, but they appeal more to geologists than to geomorphologists.

A.J. Henderson (1911:25-26) based his morphological classification upon certain *elementary forms*:

- the ridge
- the mount
- the table
- the furrow
- the hollow
- the depression
- the col
- the plain
- the cavern

These forms might then be subdivided according to the variation of shape and size. For example, a mount may be conical and either peaked, truncated, or rounded; dome-shaped and either symmetrical, elliptical or crested; columnar and either angular or rounded, peaked or truncated; pyramidal and either triangular or polygonal, truncated or stepped. Henderson's approach drew heavily on Supan's *Grundzüge der Physischen Erdkunde* (1884, 1899), which was recognized as having, in common with other purely morphological schemes, the obvious weakness that its various groups include forms which differed widely in origin and that it emphasized superficial form to the exclusion of genetic aspects.It was an approach criticized, however, for being too purely morphological, void of causality, and irrelevant except tot hegeomrphologists. And from a finite set of objects, the shape and geometric parameters may then be “transformed ”much as CAD objects are as described in Appendix A. Henderson’s approach therefore suits our topographic primitive approach here because the genetic origins of form are of secondary importance.

b) Subdivision

Unstead (1933) used a so-called *synthetic method* to combine *stows*, small regions exhibiting a unity of relief – into the successively higher order of *tracts* and *regions*. Bourne (1931) identified the soil site as a basic morphological unit, groups or which combined into distinctive spatial assemblages or patterns.

Linton (1951-217) deals with the regional classifications based on the amalgamation of supposedly basic spatial units. Scales between site and continent are converted, recognizing the characteristic groupings of one and the characteristic subdivisions of the other, carrying both processes to the point where their results converge.

- site
- stow
- tract
- section
- province
- continental subdivision

Dikau, 1989 derives a landform classification system where approximate age is plotted against size of geomorphological objects. From a DTM, he describes landforms through a hierarchical subdivision of the land surface into relief units. These units are defined by the logical combination of derivatives of the DTM and can then be combined semi-automatically to simulate the complex relief features seen in nature. One method to classify the high variety of relief forms discussed above is based on their hierarchical subdivision into relief units which can be described with geometrical and topological attributes. The model kernel is defined by mesoform elements and facets. These are the units for form synthesis. Their typology is strictly based on the concept of homogeneity of geometrical attributes. The can be described as surface units in three-dimensional space, making a complete description of the surface possible. Some definitions:

- **Form facets** - are relief units with homogeneous gradient, aspect and curvature. They represent the lowest hierarchical level of every size type.
- **Form elements** - are relief units of homogeneous plan and profile curvature. They can be subdivided into form facets.

Both units may be superimposed by microforms or microform associations. Further possibilities to classify main types and types of them are shown in Dikau, 1989. The attributes he shows are the basis for our current investigations of the modelling process discussed below. Relief forms are relief units of homogeneous shape. The attributes are derived from plan and profile shape which can be described by different relief form indices.

The situation here relates to the two hierarchical arrangements of time and space. The hierarchy of space can be defined by different levels of types of relief, ranging from the pico- to the mega-relief. Landforms of different sizes, from impact craters of raindrops to extensive shields, are associated with defined levels. The primary hierarchical level of our experiments comprises the micro- and meso- relief. The spatial scale of this types ranges from approximately some meters to one kilometer. He provides a more detailed explanation of the different size types of objects in relation to width, area and height.

c) Others

Other descriptions covered by geomorphologists which are not reviewed here include, drainage basin hierarchies, classifications based on practical considerations, and more complex regionalizations. Please see Brändli, 1997 for more discussion on these.

d) Equations for Landform - Summary

Although Jarvis, 1981 and Evans, 1972 argue against it, mathematical descriptions such as ellipsoids have been used to approximate specific geomorphological objects. Combinations of single parameters or rations are typically used to describe karst depressions, cirques, drumlins, and so on. The surface form of karst depressions has been measured by the ration of the mean depth and diameter. Cirque form has been quantified by height length rations and some additional parameters. [8]

Hypsometric curve or hypsographic curve is a shape descriptor often used for drainage basins. It is the monotonically decreasing function giving the proportion of the land above a given value that is represented by the horizontal axis. Usually it is applied as a descriptor to a single drainage basin.

2.3.4 Organic vs. Chrystalline forms

Other more qualitative descriptions of landform are inventoried here from the domains landscape architecture and planning. Often a distinction is drawn between organic or curvilinear forms and chrystalline, or prismatic forms to describe the constructed landscape. Strom, et. al. () instruct in their book *Site Engineering for Landscape Architects* that the visual form of grading may be broadly categorized into three types: *geomorphic*, *architectonic*, and *naturalistic*.

- **geomorphic**- the proposed grading blends ecologically and visually with the character of the existing natural landscape. It reflects the geologic forces and natural patterns that shape the landscape by repeating similar landforms and physiographic structure. Generally, the intent of this category is to minimize

8. Van Kreveld (1996)

the amount of regrading necessary in order to preserve the existing landscape character.

- **architectonic** - The proposed grading creates uniform slopes and forms, which usually are crisply defined geometric shapes. The line along which the planes intersect is clearly articulated, rather than softened by rounded edges. This type of grading is appropriate where the overall impact is human dominated or where a strong contrast is desired between the built and natural landscape.
- **naturalistic** - The last category is perhaps the most common type of grading particularly in suburban and rural settings. It is a stylized approach in which abstract (or organic) landforms are used to represent or imitate the natural landscape.

This thesis recognizes no formal distinction between Strom's geomorphic and naturalistic landscapes, rather they describe different ideological approaches to designing landform.

Higuchi describes seven classical types of landscape spaces, for which he tries to analyze the compositional features and spatial elements[9]. While these are composites of discrete landscape elements, they offer some potential for combinations or composites of discrete forms to be offered as a set for selection in a digital system:

a) The Akizushima-Yamato type

A valley enclosed on all sides by green mountains rising in layers. In the valley is a broad, fertile meadow, watered by a clear stream "a beautiful land, surrounded on all four sides by green mountains". An image of this type is not available.

b) 8-petal lotus blossom type

highland valleys, which together with surrounding peaks, suggest the lotus blossom configuration. secluded plain surrounded by high peaks.

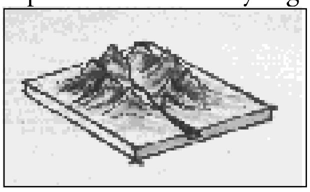

Figure 2.16: Higuchi's type landscape type 2. (Higuchi, 1988)

c) Mikumari Shrine type

A river or rivulet flows down through the mountains. At which point where water is first drawn off for use in the wet rice fields below, which normally coincides with the point where the steep slope of the mountains gives way to the gentler

9. Higuchi (1984) p. 94

slope. The river divides the fields from the sacred ground occupied by the shrine.

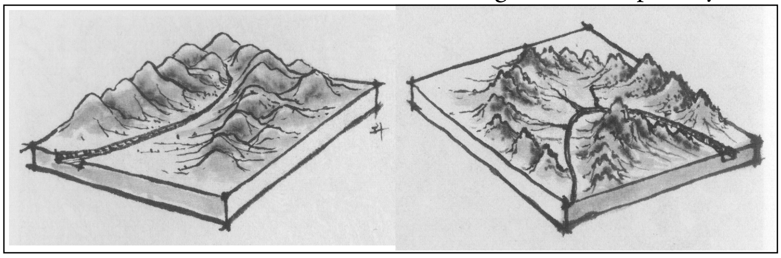

Figure 2.17: Higuchi, Type2a, 2b. (Higuchi, 1988)

d) Secluded Valley Type

A river flows down through a narrow valley with relatively high mountains on either sides. The inner recesses form a secluded space, which is apt to have a mysterious, other worldly atmosphere about it.

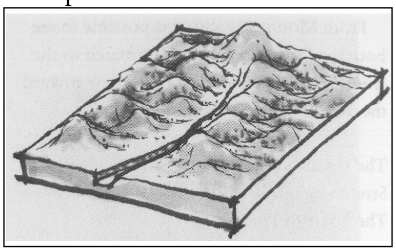

Figure 2.18: Higuchi Type 4. (Higuchi, 1988)

e) The Zofu-Tokusui Type

A site where the vital energy that flows throughout the earth is confined by water and not scattered by wind. i.e. a plain w mountains on the north, hills to the east and west, and open land to the south, w rivers flowing down from NE and NW and converging south of the plain

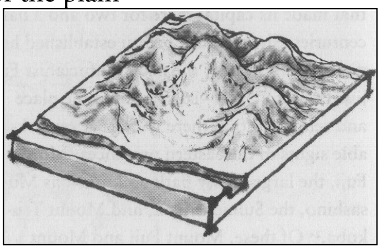

Figure 2.19: Higuchi Type 5. (Higuchi, 1988)

f) Sacred mountain type.

A small mountain rising from a plain or projecting into it from a more distant mountain range. Provides focus and order for the surrounding space.

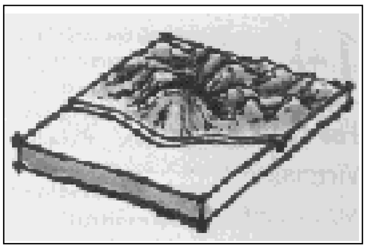

Figure 2.20: Higuchi Type 6.

g) Domain-viewing mountain type.

A small mountain situated near a plain or juts out into it from other mountains. The difference is that the sacred mountain type is looked up to as an object of worship, whereas the domain-viewing mountain serves as advantage point from which to look down on the surroundings.

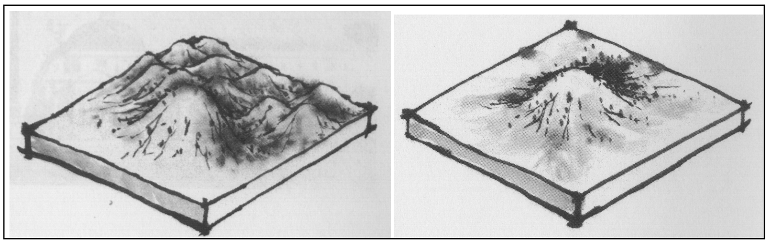

Figure 2.21: Higuchi Type 7. (Higuchi, 1988)

Morrish, 1996 investigates “historical roots and contemporary expression that the role of the earth and sacred mountain play in the formation of urban space to illustrate some basic notions of the origins of integrating land and built form together into a comprehensible urban terrain.”. He does this to provide some alternatives to the simply leveling of sites to produce a generic “pad” for the building of generic buildings. His approach is to provide a comprehensive listing of landscape-specific terms and a definition for it. Some of these purely semantic descriptions include graphic sketches along with them. Several of the sketches and definitions offer opportunities for definition of useful constituents to a topographic primitive library. For example:

- **mountain**: ME montaine<OFr montaigne<VL *montanea for Lmontana<montanus, mountainous<mons 1. a natural raised part of the earth’s surface, usually rising more or less abruptly and larger than a hill 2. a chain or group of such elevations 3. a large heap, pile or mount 4. a very large

amount.

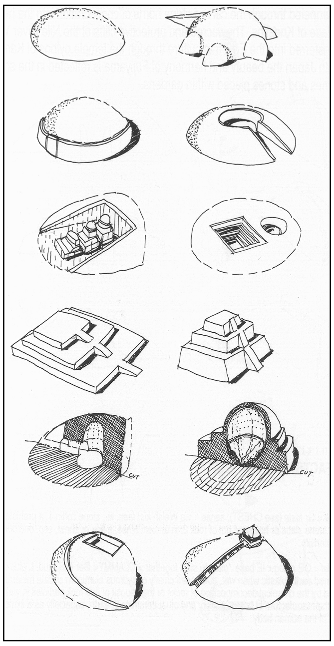

Figure 2.22: Mound Primitives from Morrish, 1996.

Morrish offers the following definitions of some terms used for landforms, among others:

- **ridge**:. ME rigge < OE hrycg, akin tooONhrygr, backbone, Ger Rücken, back<IE *(s)krreuk-, a hump, mound< base *(s)ker-, to bend> curvus, bent circus, a ring. 1. orig., an animal's spine or back. 2. the long, narrow top or crest of something, as of a wave, a mountain, etc. 3. a long narrow elevation of land or a similar range of hills or mountains. 4. the horizontal line formed by the meeting of two sloping surfaces.
- **mound** - prb. <MDu mond, protection, akin to On mund, hand (mound n. Fr monde<Imundus, the world). vt. Archaic 1. to enclose or fortify with a mount. 1. a heap or bank of earth, sand, etc. built over a grave, in a fortification, etc. 2. a natural elevation like this, small hill 3. any heap or pile 4. Baseball. the slightly raised area on which the pitcher must stand when pitching

2.4 Conclusions

This chapter reviewed the ways landform functions as an expressive medium; how it is manipulated both on site and via representations. In summary, earth moving is done on site with large earth-moving equipment and tools. When the scale is 1:1 the tools are either manual (e.g. shovels and axes and rakes), or mechanical (e.g. bulldozers, plows, backhoes, steam rollers, etc.). Sometimes explosives are used. In professional practice, representations of topography are manipulated via other tools (e.g. pencil, paper, computers, rulers, compass, etc.). The point is that landform is plastic. Its geometry is changed, measured, and parameterized by humans. The products of earthform construction are as varied as the intentions for constructing them. There are therefore many ways to achieve a desired surface geometry. And different tools used in different combinations may achieve the same, or different, end geometric result. The universality of tools for determining surface geometry makes it necessary to clarify what a tool is for abstraction into the digital realm. The next chapter investigates the role of tools in the broader context of traditional notions of sculpting. Chapter 4 defines the term tool more explicitly for sculpting surfaces.

Chapter 3: Towards a Definition of Sculpting

3.1 Introduction

This chapter is dedicated to clarification of the term, *sculpting*, to arrive at a working definition for dynamic topography. We start with a discussion of the distinction between *relief sculpting* (including *intaglio*), and *sculpting in the round.*[1]. These categories classify sculpture by their "degree of three-dimensionality" and therefore pertain to sculpting topography. Section 3.3 discusses the implications of the sculpture vs. sculpting distinction in terms of parts speech and how focusing on the verb-like qualities suit the research objectives of this thesis. Description of individual sculpting processes and their general characteristics are presented next. The traditional sculpting processes c*arving, modelling, casting/moulding,* and *kinetic sculpture and arrangements* have been devised chiefly to cater to the viewer of art objects, and not for furthering sculpting processes per se. For convenience, we retain the distinctions here; allowing them to help highlight those general characteristics of sculpting uniquely useful to handling relief digitally. Sections 3.4-3.8 offer descriptions of these commonly understood traditional processes, together with brief examples of each. Section 3.9 gives a summary while 3.10 offers the first basic definition of sculpting.

3.2 Relief Sculpture vs. Sculpture in the Round

Establishment of the surface is a primary move, since the parting from and clinging to a surface is the essence of the relief. Then that space between the surface and the highest point becomes a sphere of play and conflict between opposites, representing the desire to break away and the inability to leave the norm.

- Kenneth Martin

Relief sculpting consists of two basic divisions distinguishable by the degree of projection of form from the background surface or plane (figure 3.1). *Intaglio relief*, where the design is sunk below the surface, and *Bas-Relief*, where the forms are above the background surface. Completed works of intaglio relief, also referred to as *inverse bas-relief*, 'Egyptian Relief', or *sunken relief* has its highest points on a level with the original surface plane. Bas-relief, or 'basso-*relievo*' fre-

1. Pickard, (1996)

quently used to include all types of raised reliefs, including *Flat, Low, Medium, and Full relief.*

Flat relief, also known as '*stiacciato-relievo*', is the lowest possible true relief. In this form, the effects are achieved by means of contour outlines and finely incised lines on a surface. The projection is very slight and there are no undercuts in this type of relief. An undercut is a situation where for an (x, y) location in Cartesian space, there exists more than one corresponding z-elevation value for that location. This is thought of as a true three-dimensional situation A "no undercut" situation, on the other hand, possesses only one z elevation value per x, y location, i.e. there are no vertical cliffs, overhangs, or tunnels. It is usually referred to as a 2.5-dimension situation[2].

In Low relief the forms have relatively little projection from the background and have no undercuts, but the modelling is developed higher than it is in flat relief. Medium relief is also known as '*mezzo-relievo*' or *half relief.* The modelling is fuller than in the flat or low relief. Undercuts are occasionally present and the modelling may reach a height of approximately half the thickness of a head or body. Full relief is also known as *high relief* or '*alto-relievo'.* This is the highest type of relief. The forms are often in the full round, but remain attached to the background, although some portions, may be entirely free from the surface plane.

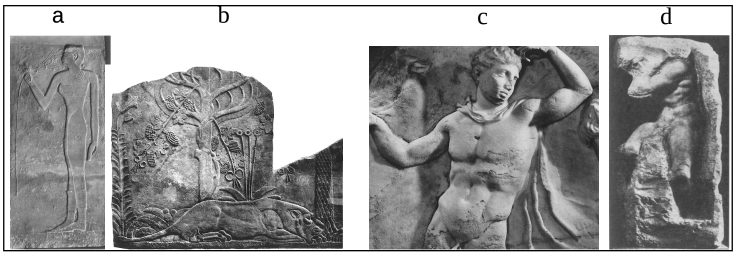

Figure 3.1: Examples of sunken, low, medium, and high reliefs. (a)Sunken Relief.*Young woman with a lotus blossom,* Egypt, limestone (Read, 1956, pl 65), (b)Low Relief. *Lioness from e palace of As-sur-bani-pal.* Assyria, alabaster (Read, 1956,p.64), (c) Medium Relief. *Fragment from the Parthenon frieze representing the Panathenaic procession,* Athens, marble (Read, 1956, pl 182), (d) *Apollo* High Relief. marble (Michelangelo).

A sharp line of demarcation is difficult to establish between relief sculpting and *sculpture-in-the-round*, since one form or degree of relief can, and often does, merge subtly into another, and occasionally several degrees or types may be incorporated into a single work.[3] A continuous progression can however be traced from the intaglio or sunken relief form through the true bas-reliefs to the full round. In sculpture in the full round, the figures or forms are free-standing and

2. Weibel, Heller (1990)

3. Read (1954)

can, in almost every instance, be seen from all sides and angles (figure 3.2).[4]

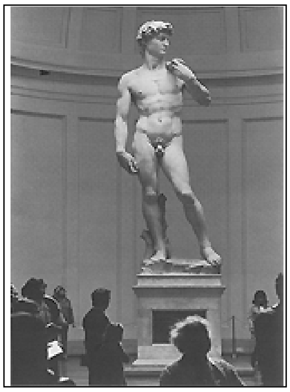

Figure 3.2: **Sculpture in the Round**. *David*, marble, Michelangelo. (Read, 1956).

There is usually no distinction made between the types of sculpting processes used for relief and those for in the round sculpture. All processes are found to be employed for all degrees of three-dimensionality.

3.3 Sculpture vs. Sculpting

In addition to classification of sculpture by its degree of three-dimensionality, an equally common way of discussing sculpture is via the processes and materials which lead to its creation. Before outlining these categories, a clearer distinction needs to be drawn between *sculpture* the object, or noun, and *sculpting*, the process, or verb, and this section seeks to clarify their differences.

By the 1930's in the United States and Europe, a sense of natural opposition between a "sculpture of space" and a "sculpture of time" was being laid out by the modern era. Sculpture of space is art concerned with "the deployment of bodies in space; where the relationships formed between the separate parts of a visual object are *simultaneously* given to its viewer". Whereas a sculpture of time holds that "all bodies exist not only in space, but also in time". They *continue*, and any momentary appearance is the center of a present viewing action[5]. Therefore,

> "sculpture is a medium particularly located at the juncture between stillness and motion, time arrested and time passing. From this tension... comes its enormous expressive power".[6]

Krauss offers the above definition to set up her influential theoretical treatise on meanings of 20th C. sculpture. And like most other discussions on the

4. Humphreys (1984)

5. Lessing, Gotthold (1957); Laocoön, tr. Ellen Frothingham, New York; Noonday.

6. Kraus, Rosalind E.; Passages in Modern Sculpture; The Viking Press, New York; 1977, p.3.

topic, her focus is almost exclusively on the sculptural works themselves, as objects, as opposed to the process of their making, i.e. *sculpting*.

Krauss's above definition in fact mixes the notion of sculpture as *noun* with sculpture as *verb*. "Sculpture is a medium", she purports above, implying that "it", i.e. the sculptural object (noun), is generated through working a material, i.e. through action, via a process (verb). Yet clearly the expressive power of the direct object "it", and its associated significance, is of primary interest. This mixing of parts of speech to refer to her subject is even more noteworthy given Krauss' citation of *structural linguistics* as one of the two primary cultural forces to have given rise to the spatio-temporal tension described above; the other being *phenomenology*.[7] Despite Krauss's almost exclusive interest in interpreting the sculptural object, her presentation of the temporal-spatial dialectic, together with her designation of structural linguistics as the explanation for its existence, offer useful departure points from which to consider notions of *sculpting*, the verb.

3.3.1 Sculpting as Verb

In her definition of sculpture above, Krauss mentions "action" and "motion" as part of "viewing action", or action performed by the viewer. The sculptor of course also functions as viewer and as the *subject* of the transitive verb phrase involving the verb "to sculpt", as in *He is sculpting the statue*, where *he* is the sculptor subject, *is sculpting* is the passively constructed transitive verb, and *the statue* is the direct object. A transitive verb takes an expressed or understood direct object from which a passive participle can be formed[8], as in the following phrases, respectively: *she sculpts the clay*, or *he is sculpting the earth.* Transitive verbs are moreover characterized by or involve transition, or a *state change,* to the direct object.[9]

Viewing action differs from the kinetic action, dynamism, or motion exhibited by the sculptural work itself, here called *material action.* Two kinds of material action may be distinguished: *end kinetic action*, or movement exhibited by a *finished* sculptural work or its parts, and *process kinetic action*, or transformations a sculpting material undergoes while *being sculpted.* Examples of material action belong to the *kinetics and arrangements* sculpting category listed above, and include the mobiles of Alexander Calder, the moving reliefs of Bury, and works by Jean Tingueley (see figure3.3). Some would argue that all sculpture is kinetic by virtue of its inherent structural properties[10]; that all exhibit the force of gravity, dynamism of tension, compression and bending, balance, whether or not these are visible. This thesis will not take on these latter kinds of dynamics directly.

7. Morris was first to discuss these two causes in terms of modern sculpture, however, in: Morris, Robert, "Some Notes on the Phenomenology of Making: The Search for the Motivated", *Art Forum*, VIII (April, 1970) pp. 62-66.

8. Oxford American Dictionary; Oxford University Press; © 1980.

9. Websters Dictionary

10. see for example, Schodek(1993)

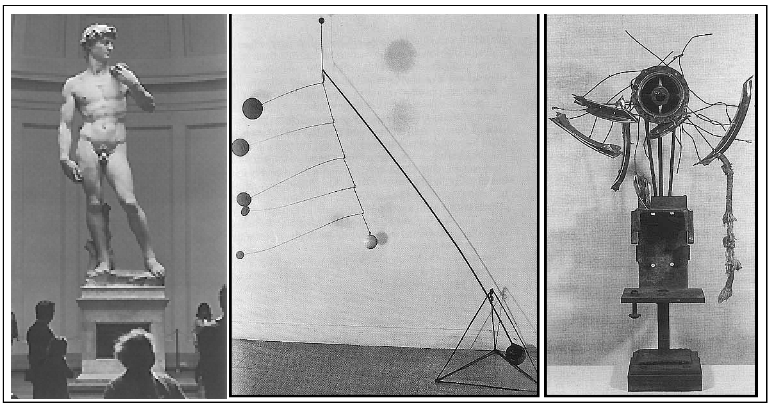

Figure 3.3: Examples of kinds of sculpting actions. Viewing action *David*, Michelangelo; End Kinetic Action. left, Calderberry *Bush*, 1932 Alexander Calder; and right, *Monstranz* 1960 Jean Tingueley.

Process kinetic action consists of any formal, chemical, or property change to a sculptural material in progress, including bending, hardening, softening, denting, scattering, color changes, etc. In this latter form of kinetic action the movement of the sculptor's tools with respect to the material, or *tool action*, is involved. In all three cases, the sculptural material, or the work itself, remains the direct object of the transitive verb. To summarize, sculpting verbs used transitively always involve the following three kinds of actions (see figure 3.4):

(1) User Action

(a) **viewing action** - visual behavior of the sculptor,

(b) **hand action** - actions performed by the hand on either the tool or the material itself.

(2) Tool action - actions of the sculptor's tools with respect to the indirect object.

(4) **Material action** - the geometric or formal transformation of the direct object, i.e. the sculptural material, which is either

(a) **process kinetic action** - occurring during the sculpting activity, or

(b) **end kinetic action -** which is the intended end behavior of the finished work.

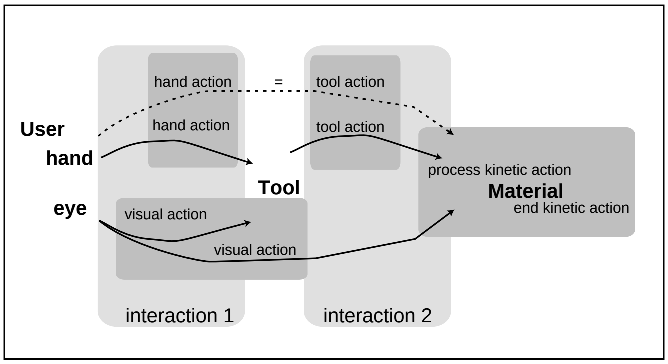

Figure 3.4: Diagram of four kinds of sculpting action: Hand, visual, tool, and kinetic. The dotted line between hand action and process kinetic action represents how sometimes the hand itself is used directly as a tool on the material.

In the case of dance, and performance sculpture, end and process kinetic action may be regarded as user action as well. This thesis does not engage this exception further.

The breakdown of sculpting into user, tool and material actions, all of which (for this thesis) act upon the direct object sculpting material. And sculpting *methods* in this context are comprised of the interaction of a tool with a material – or *process kinetic action.* The goal of this thesis is to organize a sculpting system whereby the different verb actions may be coherently coordinated, so that the user's mental model of a sculpting task may enjoy expressive control. This may occur by mapping user, tool, and material actions accessibly to a user.

The challenge for translating these different kinds of actions to a digital environment may be described as a mapping of: (1) hand with tool action, (2) tool with process kinetic action, and (3) visual with process kinetic action. Successful fostering of these relationships may be evaluated for whether the user feels expressive geometric control resulting from them. And parallels between these kinds of action and user-computer action may be made in such a way to complement our qualitative objectives. Namely, relationships one and two, i.e. hand with tool action, and visual with process kinetic, respectively, may be said to occur through GUI interaction. Relationship two, tool with process kinetic action may occur through definition of a generic DTM tool which allows for this type of interaction. Important to note at this point is that based on this categorization of sculpting actions, whether an interaction is real-time or batch-processed does not govern whether sculpting occurs or is possible.

3.3.2 Truth to Materials and Working Direct; The Onset of Modernism.

The level of tactile involvement of a sculptor with a material is an issue with developed precedents in the history of sculpting. In the 1920's and 30's in the US.

and Europe sculpture was embarking upon the modern era as laid out by the legacy of Auguste Rodin (1840-1917). A debate was being raged at this time about the making of sculpture as an enterprise. The argument had two sides: The first dealt with the issue of "truth to materials and authorship"; arguing against the notion of changing materials – between clay and bronze, particularly. The second argument dealt with whether the artist's direct manual interaction with the material led to a more authentic "exploration" and consequent "discovery" of forms during the making process.

The first argument was primarily against modelling and the discovery of forms in one medium only to be finally realized in another. This truth to materials stance involved the issue of the artist's role in the sculpture making process. If an artist did not hammer her own stone, the argument went, then she was not the "authentic author" of the work. This "authenticity to materials and authorship" issue was taken up in the work of artists like Henry Moore, Barbara Hepworth and Hans Arp in reaction against the well-known and controversial fact that Rodin realized most of his works through heavy reliance on technicians and assistants who performed the more difficult production tasks for his major works. Rodin made clear his priority for the artistic "idea" and asserted it as an end justifiable by whatever or whoever's means of production, so long as the authenticity of the idea remained with him and the production occurred under his tutelage and careful instruction. [11]

This argument had at its core the notion of craftsmanship. Whether the work expresses manual authorship via its materiality, and where or with whom the "idea" resides with respect to the work remain fertile points of debate in both digital and non-digital realms. With respect to topography, as figure 1.1 illustrates, indirect topographic design via digital media (software and hardware), calls for a direct "change in media" – from digital model representation to construction out of earth. This translation typically also involves changes in scale, personnel, and tools. The scale change goes from some larger scale to 1:1. A change of hands also occurs; the bulldozer driver, (or "excavation engineer") is typically not the designer generating the proposed design. And tools change – from modeling tools to excavation equipment. The tactile experience of the designer is thus only available in the model representation, and rarely does the end material itself (i.e. soil) enter the palette. For digital sculpting tools to satisfy this side of the sculpture debate, then, the challenge is to preserve the manual material authenticity – or an equivalent – in the modeling medium itself. This thesis argues in concert with the essential assertion of Rodin, therefore– that if the essence of craftsmanship and authorship are retained in the form-making process at the level of idea realization, then the design idea behind the work may justifiably reside with the form's originator – *in whatever material.* This frees the designer to explore forms in any material or scale deemed comfortable or appropriate, and digital tools offer potential as a potent addition to this sculpting palette.

11. Elsen, Albert (1974)

The second line of argument in the sculptural debate dealt with the issue of media responsiveness and whether one "discovers" forms from "hands on" making. In the case of the successors to Rodin, like Arp and Hepworth in particular, the "exploring" and "finding" of forms from personally and manually working away at stone and other materials indeed informed the artist and led to the final shape of their work, they claimed. The process itself generated ideas and therefore shaped the content of the end work. i.e. the form of the idea did not have a final shape before it was "built", rather it was during the building of the final form that the idea "emerged". This thesis regards this argument as the more legitimate of the two, and it is indeed the one further exploited in modernism since that point.

3.3.3 Sculpting as Subject of Sculpture

The history of modern sculpture may credit its onset to a shift from a sculpture which is object or "noun-based" to one transitive "verb-based". In other words, once processes of sculpting themselves emerged as legitimate subject matter for sculpture to express in material form, this self-reflexivity on process marked a new era in sculptural development; henceforth called modern sculpture.

Most credit Auguste Rodin, with "rescuing" sculpture from following a purely representational route, so that modelling of clay and marks left "unfinished" remain visible on the sculpture's finished cast surfaces. Minimal art in the 1960's took this up and dealt very directly with process, as taken up by the influential minimal artist, Serra. In modernism, the exploration of sculptural form for discovery, together with the independent art theorists' claim that individualizing of sculpting technique constituted the way sketching brought on originality in art, was extended by abstract minimalist art. In this form of sculpting, which emerged in the 1950's and 1960's by sculptors such as systems of artistic or sketch-like technique became themselves topics for sculptural works. Ways of making of sculpture became subject in sculpture.

This trend is exemplified by no clearer example than the list of transitive verbs replacing formal sketches in the working sketchbook of the minimalist artist, Serra.[12] It is a long list he made for himself in 1967-68 – a working notation, the beginning of which reads:

to roll
to crease
to fold
to tear
to bend
to shorten
to twist
to twine
to dapple

12. Krauss (1979)

to crumple
to shave
to tear
to chip
to split
to cut
to sever
to drop[13]

This chain of transitive verbs, each one specifying a particular action to be performed on an unspecified material, one senses the conceptual distance that separates this from what one would normally expect to find in a sculptor's notebook. Instead of an inventory of forms, Serra has substituted a list of behavioral attitudes. Yet one realizes that those verbs are themselves the generators of art-forms: they are machines which, set into motion, are capable of constructing a work. So, the notion of automating the production of a representation brings us closer to our target concern with representations of topography produced digitally, i.e. by a machine.

The following sections describe traditional sculpting processes individually and in greater detail.

3.4 Carving

"Of all activities carving is the most rhythmical; the left hand does all the thinking, holding the chisel, and the right is merely a motor."

-Barbara Hepworth
(sculptor, 1903-1975)

Carving is a *subtractive* process by which a hard material is worked on with tools which cut away areas and superfluous material until a desired shape or forms remain exposed. Because the original latin meaning of the term *sculpting* means carving, and because carving moves are left permanently to bear on a hard material surface, carving throughout history has often been regarded as the "mother of all sculpting processes". The process moves from 'roughing in' to detailing and then finishing (see figure 3.5), often with different tools associated with each phase. Various stones and woods, along with plaster and cement and wax are typically used for carving, and often individual materials have their own tools and processes associated with them. These three stages roughly parallel the three phases in topographic design discussed in the previous chapter.For stone carving, dif-

13. Serra, Richard as quoted in Krauss (1979)

ferent tools characterize the roughing in, detailing, and finishing stages of a work:

Figure 3.5: Example of a carved portrait low relief.(a) roughing in, (b) the beginnings of detailing, (c) further detailing, (c) the finished piece. (*Robert Browning*, by Watts, limestone, in Miller)[14]

a) Roughing In Tools

Roughing in tools are used to extract bulk material from the original stone. Typically, they include pitchers, hammers, electric drills, and saws. (figures 3.6 - 3.8).

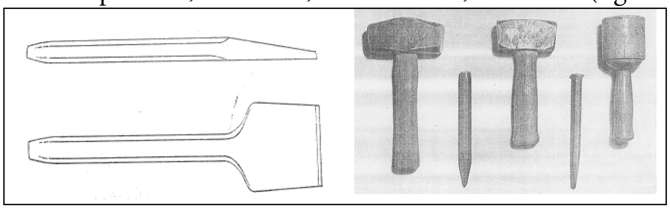

Figure 3.6: Roughing In Tools; (a) Pitchers, (b) Hammers.

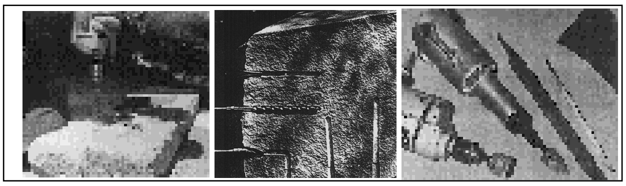

Figure 3.7: Electric Drills.

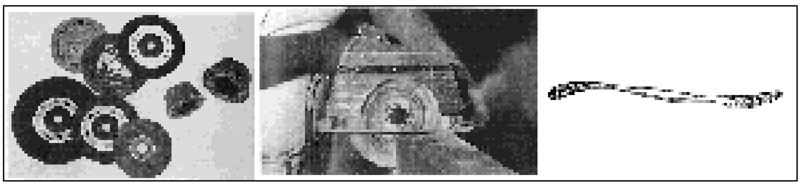

Figure 3.8: Saws, and a riffler.

A *pointing machine* is used to make an exact or near replica of a model, in any scale. The basic idea is a stand with various adjustable arms are set to particular parts of the model. The machine is transferred to a block of stone which is then

14. Miller (1948), p. 59-68.

roughed out with carving tools until the arms can be pushed back to their original settings. From the resulting basic shape the sculptor proceeds to detailing and finishing.

b) Detailing Tools

A series of chisels, boasters, and wide-toothed claws give finer detail. These may be completely manually operated or powered electrically (figures 3.9, 3.10). As for the marks made, flat chisels leave a patchwork of rectangular marks over the surface, while claws leave a striated effect. Round-ended chisels (i.e. gouges), and 'scribes' are used for channelling and incising linear detail. Wooden mallets are normally used with chisels for these later, more delicate stages. Obviously the different angles at which the tools are offered to the stone, i.e. its orientation, make for different results and effects and can only be fully understood by practice and a close study of finished works (figures 3.11, 3.12).

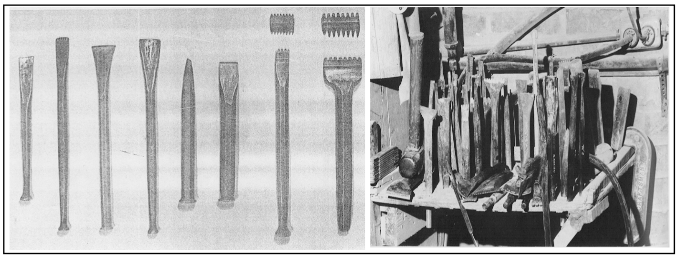

Figure 3.9: An assortment of manual chisels, varying by shape, width and number of teeth. Chisels with curved ends are known as *gouges*.

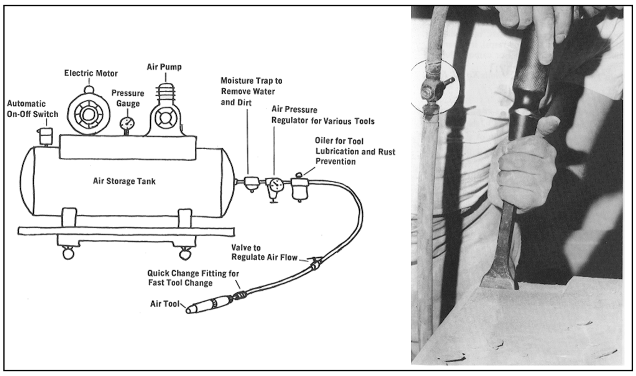

Figure 3.10: Electric Air Compressor with broad, flat chisel in action.

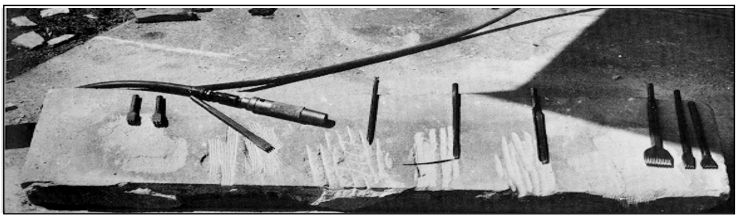

Figure 3.11: Marks made by square bush chisel, straight-toothed chisel, point, straight chisel, curved gouge, and gouges of different widths. (Meilach, 1970)

Figure 3.12: Marks made by electric air compressor-powered chisels and gouges. (Meilach, 1970)

3.4.1 Finishing Tools

After the shaping work has been done, finishing is often necessary. Fine chisels, rasps, files and rifflers are used to smooth away surface marks (figure 3.13).

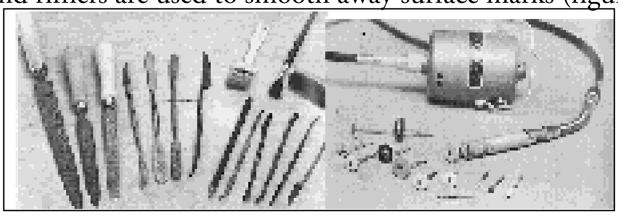

Figure 3.13: Finishing Tools. (a) an assortment of files and rifflers (Meilach), (b) miniature power tools for grinding, sanding, drilling, marking, cutting, carving, etc. (Meilach).

Polishing is done with different kinds of abrasive tools and carborundum papers – either by hand or with the assistance of electric tools which many sculptors use today for a variety of tasks (figure 3.14).

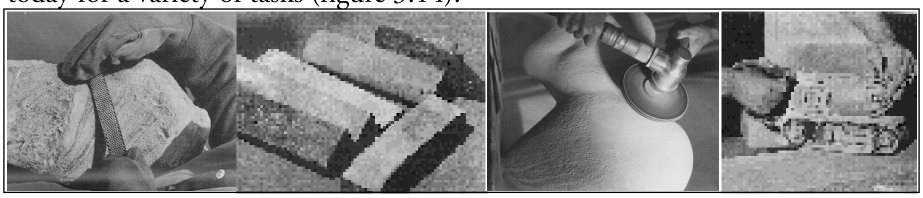

Figure 3.14: Finishing Tools in action. (a) Manual rasp in use, (b) carborundum papers, (c) electric polisher, (d) hand powered sander (Meilach, 1970).

3.4.2 Other Subtractive Techniques

Although typically not associated with direct carving, included and worthy of mention in this process category because they are subtractive are *milling*, *etching*, *lithography* and *engraving*. Tools and processes for these methods involve a lathe or milling machine, chemical acids and buffers, and a set of engraving knives and chisels, respectively. *Sand blasting* is another technique, often used to clean or smooth surfaces, where sand is projected at a typically stone surface to remove its top layer.

Like with the conventional DTM modelling practices discussed above, the carving process involves different phases, three as presented here. Significantly, different tools are associated with the different phases. Unlike with conventional practices, however, carving tools are usually applied to the same work, the same material, usually to produce a single work. Typically the materials used are hard, so there is no material change (lithography being an important exception), and besides the pointing process, no scale change either. Sketched out preliminary versions are usually modeled, but rarely carved. The representation is the final object.

Digital topographic carving typically is neither the final material, nor the same scale. The notion of a tools which act on different stages of the completion of a work is also an idea which any digital DTM sculpting tool would need to accommodate.

3.5 Modelling

"Modellierung ist setzen."
-Alberto Giacommetti (sculptor 1901-1966)
"Intelligence designs but the heart does the modelling."
-Auguste Rodin (sculptor 1840-1917)

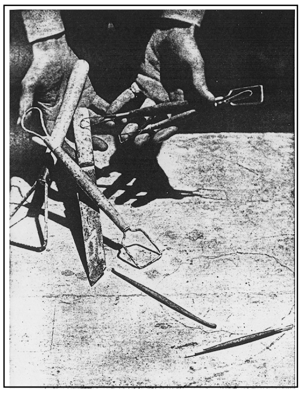

Figure 3.15: Clay modelling tools. Hands, wire with handles, knife, wire scrapers of various shapes and sizes. (Jagger, 1970)

Modelling is the opposite of carving in the sense that it is usually described as an *additive* method. Forms are synthesized, or “built up” out of a soft malleable or otherwise plastic material. They are easily altered in shape by being either carved directly, beaten, folded, or otherwise formed.

A rapidity of execution is associated with modelling, and it is very often utilized for three-dimensional sketches and for capturing and recording fleeting impressions. Unlike stone and harder materials used for carving, modelling materials permit corrections as the work is brought forward. Open and free designs are possible, since the process is often practiced as a transitory phase, for preliminary preparation often for the ultimate casting or firing of a piece. In the traditional sense, a modeled work is usually rendered permanent by casting or from heat, for example with terra-cotta sculpture. Classic modelling materials include clay and wax and plaster of paris.[15]

To model a relief sculpture out of clay, for example, a general form is usually roughed in by pushing, pounding and pressing chunks of clay together and against a flat surface with one’s hands or with a wooden mallet or tools which function similarly. The result is a level slab of clay ready for use. The desired basic form is “roughed out” and gradually built up so that eventually smaller and smaller pieces of clay are set into, or removed from, the target surface. The added pieces of clay are often squeezed or pulled or pounded first before being attached. The detailing and finishing stages of a modelling task vary considerably depending on the intended finished state of the work, i.e. if it is to be moulded or fired in kiln, or not. And while it’s often referred to as an additive method, most of the detailing tools shown in figure 3.15, ironically behave in a subtractive fashion – i.e. for cutting, carving, or gouging. Yet unique among these tools, as opposed to those from carving, is that they are definitely meant for a soft or plastic material. The same tools would not perform well on hard materials.

If the model is ultimately to be cast or fired, later modelling stages typically involve smoothing the surface; also performed manually by stroking with a damp sponge, tool, or directly with the palm of one’s hand. Textured patterns are also often pressed or stamped upon the surface using screens, bark, found objects, etc. at this stage. Glazing or treating the surface of the clay is characteristic of finishing for both routes as well. A modelled work which is not to be cast either reaches a finishing phase by being left to dry on its own, or it retains its full plastic qualities remaining in a state of flux, like with clay, sand, or puddy (figure 3.16). In any case, modelling efforts in general usually are for *quick and dirty* and *trial and error* explorations; the three-dimensional equivalent of the sketch pad. Because of this, assigning phases to the process seems more arbitrary. Its escape from easy categorization also applies to where and when modelling is employed. There are few tools attributable to individual phases.

Perhaps easier to generalize, however, are the parameters a sculptor requires

15. Humphreys, (1984)

to feel expressive when modelling. Let it be said that the geometric control a sculptor enjoys when modelling has to do both with the plasticity of the material, its "forgiving" and "obedient" qualities, i.e. its fluid end kinetic action. User action engages these material qualities via *simultaneous manipulation of multiple degrees of freedom.* For example, when a hand pushes clay around, during this movement the thumb may press harder at one point, while further along, based on the tactile and visible feedback to the modeler, she may shift the course of the push into another direction, while letting up on the pressure of the thumb, giving way to more pressure from the individual fingers. The result is a very complex form from what may be a very quick but multi-faceted action. It is this simultaneity which engages all verb actions together in coordinated concert/orchestration which allows a sculptor to feel "expressive", and "in control" of the geometry. This feeling results therefore from both user action and plastic end kinetic action which a material allows. These qualities also allow quicker and more rapid exploration of design alternatives, so that the "discovery while doing" aspect of creativity is honored. The relationships between the constituent parts of the process are therefore primary contributors to the quality of a sculptor's experience, and therefore need to be embodied in any generic sculpting tool definition.

Figure 3.16: Sand for permanently plastic modelling; i.e. not for casting or firing. (Ammann)

3.6 Casting / Moulding

Casting or moulding is a means whereby the form of a modeled work may be imitated (i.e. reproduced) and rendered rigid and durable by mechanical transformation or reproduction in another more substantial and permanent material, which is temporarily plastic (more viscous) at the moment of pouring or filling of the mold. The process of casting consists of two fundamental stages or phases[16]:

1) first fashioning an impression or negative mold from the original. The *negative*

16. Humphreys.

is the term applied to the hollow containing form or mold into which the positive, temporarily plastic casting material is poured.

2) securing a positive cast or reproduction of the original object from the negative impression.

These steps are to reproduce an object in form, texture and often color, identical in appearance with the original form which the copy or reproduction is made.[17] It is also a means of reproducing a work of art fairly economically, accurately, and in quantity. Casting/moulding is not merely a replication of form and feature, however, rather a translation from one material to another. Matisse was famous for not performing any scale changes in his translation from clay to bronze, for example.[18] The most common materials for casting are bronze, plaster, cement and plastic.[19]

There is considerable debate as to where to place moulding and casting processes in the broader sculpting enterprise. Does one explore and discover form when moulding or casting a piece? Or is it merely production? Is it just facilitating a state change (e.g. from a malleable to a permanent material state), or a material change (e.g. from clay to bronze)? Is it indeed a "true sculpting process" or merely the production of an object? If the former, does it mean that every statuette produced via casting and moulding is a sculpted work of art? And are all casts from the original mould, even when poured after the death of the original author "true", "original", or "authentic" sculptures? Who is the author in such cases? And what about those works which are cast and then altered after the cast takes place? At what point does sculpting begin and end?

Where moulding and casting resides in the sculpting process is the central debate which has emerged from modernism in reaction to Auguste Rodin's heavy reliance on the use of apprentices and technicians to transform his clay model maquettes into their bronze final form. It has been contested that if the sculptor is "in active attendance" during the casting and moulding process, and "participates" by making suggestions and providing guidance resulting in "formal changes" to the work, then the process may legitimately be said to be *sculpting*, otherwise it may be relegated to mere production or reproduction. There is evidence to suggest, for example, that during the final casting of *The Gates of Hell* (figure 3.17), Rodin was explicit to his apprentices, i.e. his *patinière*, as to what concentration of copper to include in the pour to achieve a desired patina surface effect. Because these instructions alluded to mere surface coloration or surface quality changes, rather than to true "formal" or "geometric" changes to the work, the debate with respect to his authorship continues to rage between those who say he was actively producing art during this phase, i.e. sculpting, and those who claim he was not[20].

17. Clarke (1938)

18. Parigoris (1997)

19. Woods, p. 298.

20. see Parigoris, p. 131 for more discussion of this example.

The theoretical implications of these issues for digital sculpting – how material change in a work influences the conception of sculpting in general– is broached more fully in the section on Materials of this chapter. Let it suffice for our purposes here, however, to say that casting and moulding is a process universally associated with the enterprise of traditional sculpting, but when and how it occurs remains critical to its precise role. Aspects of moulding and casting which require translation for digital sculpting include the following:

- state changes
- scale changes
- authorship and its legibility on the surface of a finished work
- reproducibility and its role in a sculptural piece.

Figure 3.17: *Gates of Hell*, Auguste Rodin. Bronze cast.

3.7 Constructing Combinations of Objects

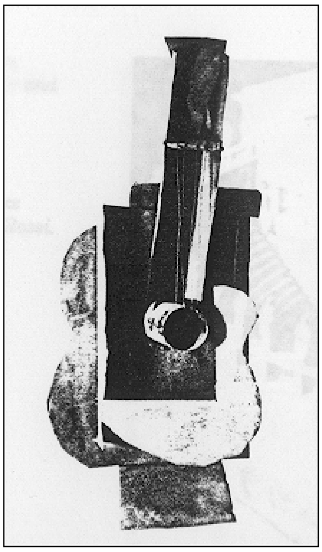

Figure 3.18: *Guitar*. Pablo Picasso (Read, 1956).

This set of processes allows for the bringing together of a wide assortment of materials with techniques like bolting, screwing, welding, taping, and roping, gluing in order to assemble and otherwise adhere different materials together – like stone, metal, wood, plastic, and other less conventional materials. Construction-based sculpture is virtually a 20th C. invention and reflects the influence of industrial processes on artists' imaginations and methods. Pablo Picasso and Julio Gonzalez are widely credited with bringing constructing into the sculpting domain[21]. Collage and dioramas are other terms used for this sculpting method which due to the overall properties of adherence may be regarded as another additive method, although the tasks and materials usually differ from those of modelling.

The activity *model-making* as noted in the above section refers to the making of a three-dimensional reproduction of something on a smaller scale. Buildings, cars, machines, boats, trains all have traditions and model-making cultures associated with them; firmly placing them in this 'construction of objects' sculpting category. Model-making for landscape, for example, involves the making of vegetation and cars and cultural features like power lines, roads, bridges, and also buildings. Landscape base models may be horizontal layered models constructed out of layered sheets cut-out along contour lines and pasted together to resemble "terraces", or "pancakes". The more pliable and plastic materials clay and plaster are also sometimes found for this representational purpose, typically to make

21. Humphreys (1984)

base-models, onto which other cultural features are either placed, or painted. [22]

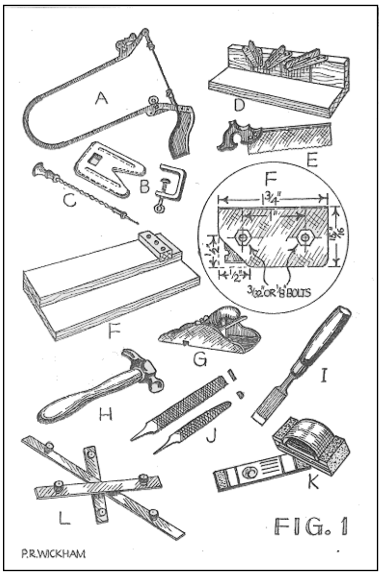

Figure 3.19: Model-making Tools. (Wickham)

Figure 3.19 displays the collection of tools required of a professional model-maker.[23] Model-making in this non-digital sense, involves a scale change and a construction process. The products of the activity are typically representational.

The construction of objects approach to sculpting in the digital medium is the single most widely exploited digital sculpting process so far computationally. The discrete parameters of individual pure shapes, together with the relatively simple Boolean algebra available for their combination offers an extensive array of combination strategies for generating and editing form. Mentioned in chapter 1, CAD is founded on principles of object construction. Kurmann (1995) is one example CAD implementation called "sculptor", for example.

Due to their fuzzy edges, curved surfaces, and often extensive continuity, topographic surfaces find exclusively combination of objects strategies quite limited, both for representation and visualization reasons, but also as strategies for achieving desired geometry. Options for the latter typically include mere placement of discrete terrain features on top of an existing DTM, or painting them on. As figure 1.4 illustrates, embedding of features, together with merging of different models address the need for continuity, but availing methods to the user for accomplishing typically do so at the expense of geometric control over seams and edges and therefore geometric control and expressive power. A robust generic DTM sculpting tool would have to incorporate these disparate concerns while taking advantage of currently existing methods.

22. Reed (1912)

23. Wickham (1970)

3.8 Kinetic Sculpture and Arrangements

A form does not yield its full effect instantly. We have to 'follow' it. Time intervenes in art of sight as in music, dance, literature.

Ozenfant

For me, the machine is above all an instrument that permits me to be poetic.

Jean Tingueley (sculptor 1988)

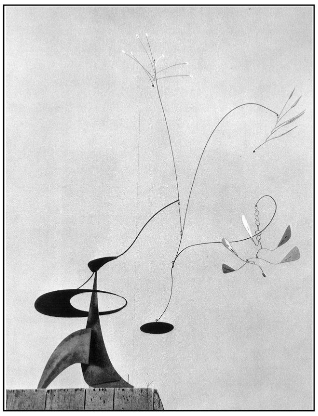

Figure 3.20: Mobile. *Bougainvillea*, Alexander Calder. (Read, 1956, pl 211)

Artists have been interested in moving or kinetic sculpture since the Futurists proposed the idea before W.W.I.[24] "Kinetic art has been a gradual attempt throughout this century to produce non-representational art using the parameters of real time and motion resulting from forces directly connected to physical systems."[25] Many of the works were interested in the aesthetics of dynamic situations rather than in the far more complicated task of making moving art. The artists pivotal in determining the practical aesthetic of kinetic art were few in number – Duchamp, Gabo, Calder, Moholy-Nagy.[26] Gabo fixed an electric motor to a metal rod which vibrated rapidly. Tingueley constructed motorized sculptures using a broad range of materials. Bury used thin plastic threads and electrically driven so they seemed to wave like grass. Andre and Long made constructions of loose objects.[27]

Aside from the kinetic behavior of finished works of sculpture, because our

24. Krauss

25. Burnham. p.218.

26. Ibid. p.226

27. Krauss,

target concern here is with the process of their making, theoretical questions immediately posit themselves. On one hand a kinetic sculpture is one that is continuously being sculpted because it was intended to act out its form as a performance. In this way, the sculpting act is on-going and does not cease. On the other hand, one may argue that sculpting ceases the moment the sculptor declares the work "done", i.e. ready to do its "kinetic thing", and the work proceeds without a sculptor's intervention. Yet there are works of sculpture in the making where the sculptor's involvement does not cease. Dance, for example, is often referred to as sculpting. Further, sculpting from such works have been claimed to persist in the minds of those who experience the work itself well beyond its physical occurrence. Again, where does sculpting and the sculptural work begin and/ or end? These are indeed rich and inexhaustible areas of sculpting to consider, and rather than engage the full theoretical underpinnings of them, we defer to the distinctions between different verb actions to clarify the objectives for digital sculpting. Kinetic sculpture and arrangements may be said to exhibit "end kinetic action". Such automation of movement, or animation, is clearly possible in the digital environment as well, via software devices like scripting, etc. A digital sculpting tool which embraces such opportunities would therefore automatically be responsive to this sculpting category.

3.9 Summary

This section offers a summary of the advantages and disadvantages of traditional sculpting processes.

3.9.1 Professional practice sculpting methods

a) Advantages:

- includes a high density of quantitatively precise topographic elevation data
- includes other geographic information that one cannot see on land or in a section profile at high densities.
- portable and durable
- reproducible
- information is editable and changeable
- provides straightforward means for calculation of cut and fill, slope, and visibility analyses.

b) Disadvantages:

- essentially fictitious
- do not represent measured information
- rarely is regional geometric control possible without a reworking of all lines
- resource intensive to change (time, skill)

3.9.2 Traditional sculpting: Carving

a) Advantages:

- geometric control
- tactile sensation
- permanent
- legible authorship

b) Disadvantages:

- not accurate
- non-repeatable actions
- difficult to reproduce
- only possible to modify in a subtractive fashion

3.9.3 Traditional sculpting: Modelling

a) Advantages:

- geometric control
- quick and dirty, quick response time
- tactile sensation
- additive and subtractive move possible
- legible authorship

b) Disadvantages:

- not accurate
- non-repeatable actions
- difficult to reproduce
- unless molded and cast, not permanent

3.9.4 Traditional sculpting: Moulding & Casting

a) Advantages

- scale change
- reproducible in quantity
- often a material change

b) Disadvantages

- no authorship

3.9.5 Traditional sculpting: Construction of Objects

a) Advantages

- accurate means for representing reality at a smaller scale
- wide assortment of materials and methods.
- topographic surface representation may be very realistic looking
- may be quick and dirty or very exact

b) Disadvantages

- often resource intensive (time, material, money, skill)
- depending on the scale, cumbersome to move or transport
- difficult to reproduce
- once constructed, difficult to edit or modify

3.9.6 Traditional sculpting: Kinetic Sculpture & Arrangements

a) Advantages

- dynamic behavior incorporated into the final work
- sculpting synonymized with performance

b) Disadvantages

- no easy distinction between user, tool and kinetic action

3.10 Sculpting – A Basic Definition

In light of the diversity of sculpting processes presented so far, we offer the following first basic definition of sculpting:

> The act of applying *tools* to *materials* via *methods* to enable the realization of three-dimensional forms. A sculpting method involves a feeling of *expressive geometric control* over a material from s*imultaneous, multiple degrees of freedom* of movement resulting in a visible state change to the material.

Except for some forms of kinetic sculpture and arrangements, sculpting results in either an additive or a subtractive geometric result to a surface.

3.11 Conclusion

Traditional and commonly understood notions of sculpting as presented in this chapter have associated tools and toolsets often specific to a material, together with unique ways of applying them. Whether one distinguishes sculptural categories by their degree of three-dimensionality, for example from relief to the full-round, or discusses it in terms of its traditional processes: carving, modelling, construction of objects, kinetic sculpture and arrangements, each category has its associated materials, tools, methods and way of working that offers the artist an expressive feeling of geometric control. All of these essential elements must be present for a sculpting "system" to be worthy of the name. What is called for next is a clarification of the individual components of the sculpting endeavor. The next chapter seeks to clarify these individual elements; *tool*, *material*, *method,* and *simultaneous multiple degrees of freedom.*

Chapter 4: Components of Sculpting

It is claimed that each art has its proper virtues, determined by the nature of its tools and materials, and that the faculties engaged by these tools and materials are so distinct that the products cannot be usefully compared.

[Read, 1956, p.4)

4.1 Introduction

This chapter describes the components of the sculpting definition presented in the previous chapter: Tool, material, method, and simultaneous, multiple degrees of freedom. The universal attributes of each of these are defined and provided as a segueway to the conceptual design for a generic sculpting tool presented in chapter 5.

4.2 Tool

Figure 1.1 mentions tool twice – “software tool” and” tools used indirectly by humans” to act directly on the target topographic surface, e.g., shovels, bulldozers, etc. Some would argue that the human body, especially hands, may be regarded as a tool as well. This section tries to clarify some of this confusion.

Wake, 1992 highlights several key characteristics of a tool; first, its role as an extension of the mind and body. Tools provide

> the mass, hardness and volumetric enclosure that combines with
> the pressure, tension and torque we transfer from our own bodies
> as power to perform useful work.

This prosthetic role of tool is two-way; sensory information is conveyed to the body as well as from it, he points out. Tools also “intrinsically involve planning and consideration of *process*, rather than merely consideration of the *task.”* This leads to the conclusion that tools may “signify those processes”. I.e., pictures of wood carving tools signify the process of wood-carving, rather than individual wood carving tasks, or moves.

Wake extends these general characteristics of tool to offer three categories of requirements for computer graphic entities to conform to a definition of tool:

- **Form**: To be a tool, the procedures must take form, in at least a visual sense if not a tactile one.

- **Function**: Tools must function either through their direct operation or indirectly through operation of their controls. Direct operation may be exemplified by the swinging of a hammer to strike a nail, or the wiping of a brush across a surface to leave a trail of paint. Indirect operation is exemplified by turning on the power switch on a table saw, or adjusting the focus on a camera.
- **Action**: The adjustment of the controls of a tool causes a visible state change. For example, the power switch causes the saw blade to visibly spin, and the focus adjustment changes the image within a camera's viewfinder.[1]

Wake goes on to say how tools are more significant as a means of achieving objectives than as objects themselves – they serve as a conduit for human intentions: maintaining a visual and often kinesthetic relationship to the work. And "people tend to define a problem according to the tools that they have available to deal with it." "If one is carrying a hammer, everything looks like a nail".[2]

Wake mentions four other classes of tools: Instruments, Machines, Technology, and the class of hand-held tools called widgets, gizmos, and gadgets. An *instrument* is a tool typically used for descriptive (measuring), extending the senses in the sense telescopes and microscopes extend visions, he says. *Machines*, on the other hand, generally imply a greater complexity than a tool via the presence of motors. They are a class of tools characterized by "external power and operation by controls, including buttons, dials and switches". These tools are operated indirectly.

> "The tool is manipulated by its controls rather than by handling the tools itself, and the user controls light, electricity, heat, and externally produced mechanical forces in order to perform work".

This separation of the control of the tool from the need to physically handle it allows us to consider tools in the computer graphics environment, where tools of this level of complexity may be represented on computer screens. He goes on to argue that some of the complexity, and therefore "lost richness" of tools may be re-captured with tool metaphors via strategies for assembly of complex tools through a set of simpler tools.

> "Through the structure and operation of these assemblages, the full range of operators, parameters, and modifiers necessary within a complex system may be embodied, visibly and accessibly."

So assemblages of tools may be realized through assemblages of their iconic metaphors. This adds a new level of meaning to our constructions of objects notion of sculpting, for here the symbols of tools together with their functionality are being constructed together and combined in predictable ways for a user.

In an effort to include the computer itself as a tool, McCullough, 1996 makes a clear distinction between a mechanism and a machine.

---

1. Wake, p.14
2. An old saying.

> "A *mechanism* is a device with multiple moving parts for the transfer of motion. A machine is a mechanism for the transfer of power. Power may be the force of the hand or the body, or it may come from outside sources. For example, an engine is a machine powered by combustion. Motive power may assist or replace human guidance, and this is an important distinction."[3] [emphasis added]

A computer belongs to the category *mechanism*, therefore, and he generalizes the definition of tool to include it as follows:

> "A tool is a moving entity whose use is initiated and actively guided by a human being, for whom it acts as an extension, toward a specific purpose."[4]

While this definition primarily refers to the relationships between a user and features of a tool (i.e. its controls which govern state change properties, like spinning, or blinking), and therefore emphasizes user interaction, "through their direct operation or... through operation of their controls", the generality of the definition is useful to our definition of sculpting. First of all, its describes the use of a tool as being "initiated" and "actively guided" by a user. Since our definition of sculpting calls for a method with which to combine tool with material, tool use as described by McCullough appears to be a description of method. A sculpting method must be initiated and actively guided by a user.

The definition of tool for sculpting underscores the difference between user action and tool action even further than McCullough. Figure 4.14.1 diagrams the parallels between the different tool definitions:

Wake	McCullough
Form	"entity"
Action	"moving entity"
	"actively guided"
Function	"acts as an extension"
State Change	

Figure 4.1: Tool definitions diagram comparing the tool definitions of Wake and McCullough.

Krishnan defines a tool as consisting of a *handle*, *task*, and *target*; a definition which conveniently distinguishes the user-tool interaction from the tool-material interaction, the latter embodying the task. Most tool definitions place an over-emphasis on the *shape* or form of the tool itself, and less on the actions, or verb-attributes which it performs. As mentioned in chapter 4, this priority has precedents in the history of relief modelling, e.g. with Auguste Rodin's modelled works, where legible marks indicating action on a plastic surface were regarded as indication of genius, skill.

A tool has a visible geometric form which may consist of the part that is

3. McCullough (1996) p. 64-65
4. Ibid. p. 68

held or operated by a user, or it may consist of that part which interacts with the target material, in this case a DTM.

4.2.1 Summary of Tool for sculpting

The priority for sculpting is to have control over the target geometry for the primary characteristic of a tool is its role as a *conduit between different geometric representations.* A tool and its use mediates between a before case and an after case. This governing characteristic is universal to any of the landform manipulation technologies we reviewed in chapter 2, and it holds true for the tools associated with the traditional sculpting processes covered in chapter 3. This notion of a tool also holds true for the digital tools – both hardware and software.

The challenge, therefore, is to design a tool which may perform this function – mediating between different geometric representations of a surface – so than any shape, any geometry, is possible. Just such a conceptual design is offered in the next chapter, but first we clarify what is meant by "geometric representation of a surface" in the next section which discusses the second component of sculpting, material.

4.3 Material

4.3.1 Introduction

Material is the second of the three primary constituents of sculpting. You sculpt some*thing* after all, some stuff, or material is manipulated. We've already seen how different sculpting processes have associated typical materials, each with particular properties; e.g. hard, malleable, viscous, depending on the process. Soil, earth, dirt, stone, rock, sand, gravel groundcover, grass, and paving are obvious end target materials of topographic design. The hard materials, such as stone, wood, bone and ivory, and plastics, are cut or chiseled until the desired forms are achieved. In some cases the shaping of a hard material is approached indirectly, and preliminary models are first constructed in a plastic material such as clay or wax, and these are used for guidance in working the hard stone or wood into final form.

Indirect topographic manipulation of a representation of topography, i.e. the manipulation of a digital topographic surface, as highlighted in figure 1.1 begs the following question: If material is one of the primary components of any basic definition of sculpting, how can a digital representation of a topographic surface fulfill sculpting's material requirement? The answer to this question is approached with three basic arguments: A discussion of the role of material in the sculpting process, a distinction between material and medium, and how digital topographic representation may function in this process.

4.3.2 Material vs. Medium

This inclusion of action as it is expressed in material qualities calls for a clearer distinction between *material* and *medium* is helpful. There are two ways of looking at material, one is its tactile qualities as a component of a sculpting medium, the other is what it is representing, e.g. marble or bronze for flesh, DTM's for topography, soil, or rock. McCullough defines *medium* as "a class of tools and raw materials, i.e. metalworking is a medium", where "a sense of medium emerges from skilled practice and transparent tool use."[5] He further cites the term, "affordances" to refer to "what a medium can do... a finite budget of opportunities – i.e. constraint – discovered,", so that "affordances + constraints shape expression while giving form". And the difference between an engineer and artist in terms of the affordances of a medium, are that the former engages in "practical exploiting of affordances and constraints", while an artist peruses, "non-practical exploiting of affordances and constraints of a material" Craftsmanship is in between, he claims, reliant on workmanship.[6]

In summary, the following general characteristics of a sculpting material are noted. It is a tactile, passive, locus for skilled tool use, provides structure as a physical constraint to the range of possibilities. It has physical permanence, and traces and marks may be left on it. Among these, the idea of being *tactile* and *physically permanent* seem the most challenging characteristics of material to overcome in a digital environment. A keyboard does not feel like landform to the touch.

> "For a medium to be engaging it must be dense... it must surround us in possibilities... such immersion is more sensory... a continuum of possibilities...with states in between other states, and through variety... impossible to exploit all of the possibilities."

McCullough tries to link the key characteristics of user and tool action with a digital "material" here; with the whole set constituting a "medium". This notion of a continuity of state possibilities via motion of tools with material, clarifies the distinction between material and medium, and suggests how verb-action may be achieved in a digital environment. Four basic ideas for the unification of material and digital notational artifacts are suggested by McCullough:

> (1) microstructure: bits vs. atoms – bits do not degrade like atoms, their microstructure may be reconstructed – reversible, replicated, recalled
>
> (2) format is determined after content in electronic media – artifacts in many different formats may emerge fro a single database
>
> (3) Increased notational density supports quasi-continuous operations formerly only available from physical materials. Modify notations nearly continuously. The fundamental condition of density is met – between any 2 practical possibilities, there exists a third.
>
> (4) better human-computer interfaces based on dense notations, provide increasing engagement in structural manipulations. they engage the hand in the modification of notation.

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5. Ibid., p. 193
6. Ibid., p. 196

The digital medium, may therefore compensate for the absence of tactile and permanence via a continuity of engagement with digital notation. This continuity of engagement characteristic of medium is in fact the activity-based component of the sculpting task. Mixing activity (the verb) with the object (the noun) has further precedents in art history, art theory, and the history of sculpting.

4.3.3 Representation

Even though we navigate daily through a perceptual world of three spatial dimensions and reason occasionally about higher dimensional arenas with mathematical ease, the world portrayed on our information displays is caught up in the two-dimensionality of the endless flatlands of paper and video screen. All communication between readers of an image and the makers of an image must now take place on a two-dimensional surface. Escaping this flatland is the essential task of envisioning information -- for all the interesting worlds (physical, biological, imaginary, human) that we seek to understand are inevitably and happily multivariate in nature. Not flatlands.

Edward R. Tufte

In habitual common usage, *representation* is often linked to *resemblance* and to the more general question of *imitation*. Typically there are three factors: a thing, its actual image, and a *mental* image[7]. Precisely because they are images, mental images are not *substitutes* or *doubles*, rather they are the product of a mediation with the world via our senses, typically visual and tactile senses, and our judgement and reason. Aristotle called immediate sensation a *trace* or *mark*, and called its likeness in the mind a *picture*[8]. In these terms, to make an image means not to make an impossible double, but to fashion a *fullest equivalent presence*. Rather than pursuing "photo-realistic" simulations for such equivalence, we are interested in how abstractions and representational conventions can be used to gauge visual and environmental impacts in a dynamic, interactive digital design environment.[9]

> "[Digital] visualizations... are attempts to answer the question 'What might it look like?', rather than 'What will it look like?'... the equivalent of a designer's quick thumbnail sketch, cross-section or doodle."[10]

As McCullough tells us in the previous section, the actual image one sees on the screen is only one manifestation of an infinite number of *visualizations* of the same underlying data. So there is data, or an *internal* representation, and a visualization of that data, i.e. an *external* representation, or image, and a mental mod-

7. Summers, David; Representation, chapter One, in Critical Terms for Art History, eds. Nelson, Robert S. and Shiff, Richard; The University of Chicago Press, Chicago and London; © 1992; p. 3.
8. Aristotle, 1978 Poetics, translated by W Hamilton Fyfe. Cambridge: Harvard University Press.
9. Ervin, 1992
10. Ervin, 1992

el or mediation between the two – Aristotle's picture. Conversely, any given image may have a plurality of corresponding internal representations associated with it. This leads to an expansion on Summers' triptych (thing, image, mental image) to the quattro: thing, internal representation, external representation, and mental image, which, when taken together with tools constitute a medium (see figure below).

material = mental Image + external representation medium = internal Image (i.e., data, algorithms,e tc.) + external representation (representation on screen) + mental image

Figure 4.2: Summary chart of medium vs. material.

a) The Role of the Mental Image.

As McCullough and Rickart both note, digital craftspeople (read sculptors) exhibit their skill maneuvering in their digital medium from within their *mental model* of the internal and external representations of their medium. It is the richness and fluidity of movement of such mental models which hold the potential for digital sculpting to realize its expressive quality and the user's desired geometric control.

The imagination may therefore be lead to a sense of equivalent presence, much as a description of words may induce the same sensation. And through such equivalence we may implicitly grasp 'higher' meanings from a work, as opposed to only the 'lower' visual ones. Representation therefore takes on a 'vertical dimension'; it may *signify* something 'invisible', yet be metaphorically present nevertheless as a notation. Representation may function therefore as a *sign*, and again not unlike a word. Representations may lie, as words can, via their implied truths and significance. This subjective task of the mental image to foster an acceptable equivalence between internal and external representations of a thing allow one to overcome both the tactile and the sense of permanence that are intrinsic to traditional notions of material.

Returning to the notion of sculpting, works of sculpture, regardless of how figurative or abstract, have always been appreciated particularly for their physical permanence through time, and their authentic uniqueness, i.e. their external expression of tactile marks. Walter Benjamin in his prophetic treatise on the postmodern relationship between art and technology would say that these characteristics make up a work of art's "aura" [11]. He explains how mechanical means of reproducing art, like photography, "wither" and "decay" a work of art's "authenticity":

> ...the technique of reproduction detaches the reproduced object from the domain of tradition. By making many reproductions it substitutes a plurality of copies for a unique existence.[12]

While this widely cited argument accurately foresaw the conversion of a cul-

11. Benjamin (1934)

12. Ibid.

ture formerly defined by "works of art" into one dominated by the photographic, cinematic, and digital image, it does not distinguish between mechanical means of reproduction of an art object and mechanical means of an art object's production, i.e. a sculpture's generation via mechanical means of exploration. Indeed the terms *aura* and *reproducible* both as Benjamin used them and how they have been understood since, have been widely debated and differently interpreted.[13]

Loss of aura in the material sense, as in permanent uniqueness, has been addressed by McCullough, 1996 to pertain to the digital medium. He introduces the notion of "a digital artifact".

> "Think of a digital artifact, shaped by software operations, made up of data assemblies. Although lacking in physical substance, it is a thing with an appearance, spatiality, structure, workable properties, and a history. Although it does not bear the mark of someone's hands as a clay pot does, neither is it the product of a standardized industrial process like an aluminum skillet. It is individual, and reveals authorship at the level of its internal organization. It is unique, for although flawless copies can be made, nobody is going to make another just like it unless by copying. It is abstract: a symbolic structure, a workable construction, in a digital medium, showing the effects of manipulation by software tools".

Such digital artifacts (read "sculptures") are individual, unique, and with a sense of history. They seek to re-invest the digital data assembly with that threatened loss of "aura". He reinforces this idea with the assertion "one file may take many forms", further debunking the aura-deteriorating notion of noun-hood by legitimating a synthesis between external and internal representations. Aura is not lost, therefore, but expressed differently in an infinitely large number of possible external forms. And the mental image mediates between the two.

4.3.4 Digital Topography as Sculpting Material

Tools are dependent on a data surface. A digital surface possesses both internal and external representations. A mental bridge between the two may be aided by metaphors for tools and their associated actions. This dual character of a digital surface representation is embodied in the idea of a *data model* described by Goodchild, 1992.

> A DTM is a digital description of a portion of the earth's surface. A terrain T can be described by a mathematical model, expressed as pair $T = (D,f)$, where $z = f(x,y)$ is a function with suitable continuity properties defined over an area D.[14]

The digital description may be internal or external. As mentioned in our discussion of relief sculpting in section 3.2, a surface may or may not experience undercuts, or places on the surface where there is more than one z-elevation value. This means that $z=f(x,y)$ may result in a single z in the 2.5-dimensional surface case, or a set of z's for real three-dimensionality where vertical cliffs, overhangs, and

13. See Parigoris 1996, Benjamin, 1986, Bass, 1987, and Lambert, 1987 for discussion along these lines.

14. DeFloriani, L., and Puppo, E. (1992); pp. 236-251.

tunnels are possible. Regardless of how many z-elevation values are involved at any one location, an internal representation is necessary for storing them. For digital topography to adequately fulfill sculpting's material requirement, the conceptual tool design must allow for any three-dimensional geometry, i.e. the multiple-z elevation case. Only for implementation purposes may one wish to limit the number of z elevation values stored in order to simplify the complexity of all of these possibilities.

While we briefly review the individual internal and external representations of topography in sections a and b below, the internal representations of digital topographic surfaces are discussed in greater detail by Goodchild 1992, Weibel 1990, and Schneider 1998.

a) Internal Representations

Often referred to with the ambiguous term, *data structures*, internal representation of topography may take several forms.

- **Points**

A digital surface is often represented internally in computer memory as Cartesian coordinate points, (x,y,z).

- **Raster**

Raster representations are sometimes alternatively referred to as *grid*, or *lattice* data structures. Points for vertices at regular intervals may be stored as an array. The individual z elevation values for such raster arrangements may be accessed via the indices to the two-dimensional array.

- **Contour lines**

Contour line internal representations are usually stored as functions for planar lines.

- **TIN**

Irregular triangulated networks are when triangles are stored. The individual triangles may be defined by their edges and constraints with respect to their angles.

b) External Representations

Once stored, the z-elevation values may be displayed in many different ways. There does not necessarily need to be a correspondence between the internal and the external representations of the data surface. Information depicted on screen may be created on the fly or otherwise interpolated for output, and/or the internal representation may be intentionally or unintentionally ignored or illegible on the output device. An external display of contour lines, for example, may originally have taken the form of functions for lines, or they may have been interpolated from triangulated, or point internal surface data.

In the case of a raster internal representation, lines may be connected and drawn between the points to appear as a regular lattice. Of course, the dimensions of the raster cells need not be drawn at the same size in the x and y transverse dimensions, but may take a rectangular shape if either direction is altered to a different size. Also, every vertex need not be connected, but perhaps every second, or every sixth may be to create a coarser output representation. The external representation may also be depicted as a densified version of the underlying data, with individual points interpolated and drawn at a finer resolution than the underlying data points. The individual cells may alternatively have diagonal bisecting lines drawn, resulting in two triangles per cell. Each of these triangles may be a facet, or planar surface; an object which is convenient for shade rendering. Alternatively, a combination of diagonal and rectilinear lines may connect vertices so that a surface appears as a lattice of hexagonal units. Another example display of the points would be to select an irregular assortment of vertices and connect them so that an irregular, triangulated network is displayed from the original internal raster representation. It is clear that a wide variety of external output representations are possible from a raster internal representation, and no correspondence between the two has to be present.

Visualization of data may take different points of view. In addition to plan view, often the three-dimensionality of a surface is best assessed in axonometric or perspectival view. Fly-throughs are a common display technique for showcasing a surface from differing points of view in real-time. External representations need not show the entire extent of the surface area either. Cross sectional profiles may be calculated from internal z-elevation values, or interpolated from them. These cross sections may take the form of the lines in the raster array drawn in the transverse x and transverse y directions only. Alternatively, the cross section may be cut diagonally across the surface, so that the section profile interpolates its height values from the given internal values. One or several sectional profiles may be displayed at one time.

Rendered external representation of digital topographic surfaces may also take several forms. For example, texture mapping of surfaces is commonly used to represent grass or paving or geological surface features. See Foley 1997 for more in depth discussion of alternative surface rendering strategies.

Indeed an output representation may even be expressed in the real landscape. The individual vertices of a raster internal representation, for example, could be externally take the form of stakes on the ground. A bulldozer may then be driven between them, and plow the soil to the desired grade.

In conclusion, the internal and external representations of a digital topographic surface need not correspond at all. And in fact, the external representation may take an infinite variety of forms subject to one's visualization objectives, output device available, etc. Just like in traditional sculpting, there are in fact many means to achieve one geometric end. Our already established definition of tool specified its role as a *conduit* between different geometric representations. There is usually a formal equivalence between the form of a tool and the resulting external representation.

Successful design of a digital DTM sculpting tool must be able to convert between different representations of surface geometry, including between internal and external ones, in such a way that any true three-dimensional geometry is possible. Most design approaches to software DTM manipulation do not maintain a clear distinction between the conceptual design for the method and the internal and external representations. The blurring of these distinctions often has the disadvantage of confining the manipulation method to a specific desired output representation. One often finds a “raster-specific” manipulation method, for example, or “contour-line” or “TIN” specific approaches. This thesis seeks to define an “external representation independent” conceptual design for a surface sculpting tool, thereby freeing the external from the internal representational constraints, and exploiting representations that only a digital environment may allow. Such alternative representations we shall see possess the potential to address more of the full three-dimensionality of sculpting. The tool design is presented in chapters 5 and 6, but first we define what is meant by “method” in our definition of sculpting.

4.4 Method

The third sculpting component, *method*, requires clarification because it is frequently used interchangeably with the terms *technique, process, procedure* and *strategy*. At its most general, method may be understood to be an order, system or planned way of doing something[15]. Method here refers to the means by which a user action gains access to a tool action resulting in an end kinetic action. It is therefore the external representation of the internal mechanization of action. Sculptural *technique*, on the other hand involves the notion the *skill* of the sculptor and the means employed in achieving desired forms in the material that has been selected for the work. Method, therefore, excludes skill in this context of sculpting. An external method may be regarded as what Rickart, 1995 refers to as a *structure*, or an explicit instantiation of a system, where the system in this case is a *set* of processes by which a tool is applied to a material.

Method therefore involves the orchestration of the three relationships which comprise the sculpting activity: (1) user action with tool action, (2) tool action with process kinetic action, and (3) user action with end kinetic action. These relationships must incorporate simultaneous, multiple degrees of freedom, and discussed in the next section.

4.5 Simultaneous, Multiple Degrees of Freedom

The notion of simultaneous, multiple degrees of freedom has direct links to the *finding* school of sculptural thinking, where the priority is discovery, exploring, and searching when making sculpture. Each of the relationships described as part of method above, is responsible for different degrees of freedom. The simultaneity of these relationships gives the user his/her sense of expressive geometric con-

15. Oxford American Dictionary.

trol. This concern implies that the "during" state of sculpting is the most important in determining success in the sculpting process. This section discusses this priority via the individual relationships individually, to uncover opportunities where these tradeoffs might best occur.

4.5.1 User Action with Tool Action Relationship

This relationship involves adjustments made by a user to cause behavioral changes to a tool. For manual tool usage, this relationship is closely coupled; the responsiveness of the tool action to the user is direct and immediate. For non-manually held or operated tools, there may be a delay between the setting of controls, dials or other buttons before a machine will "run", or act on a material. Exploration of forms depends less on the direct or immediate responsiveness of tool to user, and more on the behavior of the tool's settings set by a user to guide the tool.

4.5.2 Tool Action with Material Action Relationship

The relationship of a tool and the movement of the material as the tool acts upon it is heavily reliant on simultaneous, multiple degrees of freedom to be effective. Because perception of process kinetic action, visual or tactile, informs a user of direct effects, it is necessarily very closely coupled. The multidimensionality of it is a lesser concern, however.

4.5.3 User Action with Material Action Relationship (Visual, Tactile)

This relationship describes the user's actions and the behavior of material when it is done being sculpted by the sculptor. End Kinetic Action is static in most cases. Aristotle's "trace" or "mark" left on the material surface itself by a tool may be enough evidence of a tool's multiple dimensionality for the user to know how to adjust it. The relationship need not be simultaneous therefore, but may occur in a staggered before and after fashion.

4.5.4 Summary

The multiple degrees of freedom must be most apparent in the tool. Setting the parameters for these degrees of freedom must be available to the user, but need not be made simultaneous in time with tool movement. Similarly, if adequate traces and marks of a tool's movement are visible on a surface, sequential visual feedback on end geometric results may even in some cases be preferable.

4.6 Conclusion

This chapter reviewed the individual components of sculpting – tool, material, method, and simultaneous, multiple degrees of freedom. A sculpting tool functions as a conduit between different geometric representations of a surface. Digital surface representations possess both internal and external representations; and the correspondence between the two may be quite disparate. That two representations may be formally equivalent, however, offers the potential for digital representations to fulfill sculpting's requirement for a material. For a user to experience simultaneous, multiple degrees of freedom via methods, a digital sculpting tool needs to define how to convert between these internal and external representations. With this vocabulary to discuss sculpting in both traditional and digital terms, the next chapter 5 presents the conceptual design for a generic sculpting tool.

Chapter 5: Generic Surface Sculpting Tool; Conceptual Requirements

5.1 Introduction

So far this thesis has concentrated on sculpting in broad and traditional terms in order to distill its essential components. This chapter and the next two present the translation of the sculpting ideas presented so far into digital form. We present the conceptual design for a generic surface sculpting tool, the specifications presented for which, significantly, are not confined to a topographic representation, but pertain to any digital surface sculpting endeavor working in true three-dimensions. In this case, therefore, we are not confined to 2.5-dimensional surfaces, therefore. Not until chapter 7, when we narrow to a particular implementation of the functionality do we focus specifically on topographic representation. This chapter therefore completes the extended analysis of sculpting and topography, and presents the object-oriented analysis step in the object-oriented design process for direct translation into a class hierarchy presented in chapter 6. A particular, more narrow, implementation of the essential features of the tool definition in the form of the *Topographic Surface Sculpting System (TSS)* is reported on in chapter 7. Application and evaluation of the tool are discussed in chapters 8 and 9, respectively.

5.2 Tool Description

As discussed in section 4.2, a definition of tool tailored to the computer graphics environment as presented by Wake (1992) consists of the following elements: a *form* (i.e. a physical shape), a *function*, an *action*, and a *visible state change*. This definition primarily refers to the relationships between a user and features of a tool (e.g., controls, state change, properties, like spinning, or blinking); i.e. user interaction, "through their direct operation or... through operation of their controls", Wake says.

McCullough (1996) clarifies the distinction between *user action* and *tool action* with his definition, "A tool is a moving entity whose use is initiated and actively guided by a human being, for whom it acts as an extension, toward a specific purpose."[1], where moving entity is tool action and actively guided refers to user action. Both of these definitions, it is important to keep in mind, either explicitly (Wake) or implicitly (McCullough) refer to the computer-aided-design, or construction of objects approach to sculpting. Wake even tries to recapture more of the richness of traditional tool use in a digital environment via a "combination of tools" solution, which really is a combination of tool metaphors. Both definitions focus on parameterized primitives and transformation functions as the primary form-giving operators in computer-aided design. Specifically the term "constructions" is frequently interchanged with "models" in both of their texts, confining their definitions to only one of the five traditional sculpting processes outlined in chapter 2.

Figure 5.1 extends the diagram comparing tool definitions presented previously as figure 4.1 to include the *tool action* and *user action* tool components of the *generic sculpting tool components*, and illustrates the parallels between all three tool definitions:

Wake	McCullough	Westort: *Generic DTM Sculpting Tool*
Form	"entity"	**Shape**
Action	"actively guided" "moving entity"	User Action: **Path**
Function	"acts as an extension"	Tool Action: **Shape-Path Relationship** Orientation Static/Dynamic **Effect** Shape-Path Complex Relationship w/ DTM surface Absolute/Relative
State Change		End Kinetic Action: Complexity Index

Figure 5.1: Tool definitions diagram comparing the tool definitions of Wake and McCullough with the author's *Generic Sculpting tool*.

The generic sculpting tool tries to draw a distinction in the two previous definitions between *user action*, *tool action,* and *end kinetic action*. In so doing, the differences between *form* and *action* and *function* in Wake's and McCullough's definition become blurred. Basically, the generic sculpting tool consists of the following components: a *shape*, *path* and two sets of relationships: *shape-path relationship*, characterized by *orientation* and *static/dynamic* behavior, and *effect*, which is the relationship of the shape and path parameters to the target surface geometry. All surface sculpting tools may be derived from these generic parts, each of which is described more explicitly in the sections which follow.

One of the simplest abstractions of both kinds of movement takes the form of a shape moving along a path. Many tool forms described in the previous chapter take this form. The following sections describe the elements of this abstraction in more depth.

1. Ibid. p. 68

5.2.1 Shape

Every tool has a tactile or visible form, as Wake points out; tools are "entitites" according to McCullough. The discrete characteristics of tool may be parametrizable, or otherwise able to be understood in quantitative terms. Often a tool is identified only by its shape or form. A shovel is a shovel because it takes the form of a shovel. Our definition of tool for surface sculpting, however, does not stop at form and the combinations of form. A shape is only one characteristic of tool, and the path the form follows when used, their relationship and other *behavioral* characteristics of tool are abstracted further and bundled into our definition here.

As for the shape component itself, possible forms a user may wield are summarized in figure 5.2. There are four tool shape "types": planar polygon, non-planar polygon, volume, and a grid. The primary distinction between the different choices is their number of degrees of freedom. A user may select the shape from a library of pre-defined forms, or design a new shape via parameters. The shape selected may further be edited and tweaked to the individual needs of the tool use instantiation.

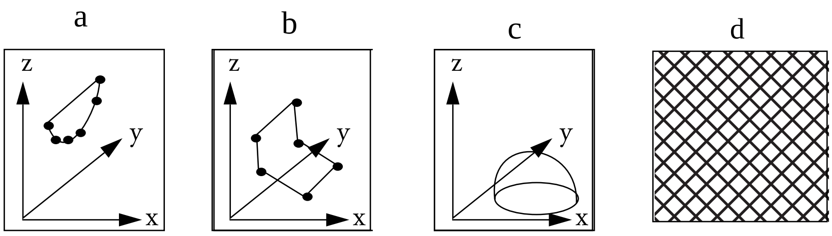

Figure 5.2: Tool Shape Categories. (a) planar polygon, (b) non-planar polygon, (c) volume, (d) filter, shown as a raster grid.

A shape must possess more than one point, but may take on the complexity of the most extensively parameterized topographic primitive form. Useful sets of topographic forms have already been inventoried in previous chapters. For relief sculpting specifically, a shape may be either a two-dimensional non-planar or planar form, a three-dimensional volume, or a filter, here depicted as a raster grid. A point or line may not function as a shape because they alone may not add or remove a form, but merely be either placed upon it (point case), or drawn through it, with neither case changing end geometry. A planar two-dimensional shape must also be used with a path of more than one point, otherwise it would not result in a target surface change (see section 5.2.2 on Path below)

Some additional ways to derive shape are offered in the sections below.

a) Mathematical descriptions of geometric forms

This approach describes a bounded geometric form mathematically, with an equation or formula. Known mathematical formulas are adapted to desired discrete topographic forms, like hemispheric mounds. One may work with 'pure' forms already defined mathematically and adapt their parameters accordingly.

Equations constitute the shape definition, the parameters describe a specific tool's shape instantiation. Both the equations and the parameter values for individual shapes are stored together.

b) Combinatorial strategies

Sub-shapes of a form are transformed and combined together to achieve a desired primitive form. Examples include revolving, skinning, patching, extruding, as Appendix A reviews. Both the subshape geometric parameters, together with the operations performed upon them are saved as the primitive representation. This strategy emerges from *Constructive Solid Geometry* from CAD approaches.

c) Raster

Raster is one way to represent surface shape. Kernel convolution is one manifestation of this, some masking and filter techniques are others. All of these cases have been discussed in chapter 3. The basic idea is for one elevation value to be assigned to each cell or vertex of a grid. The cells are mapped to elevation values corresponding to a grey-scale shading in one case, or the gridded area is blocked out or moved in the others. *KBT Bryce©* is an example of a bump-mapping technique which takes cell values and extrudes them to a grey scale elevation value. Bär, 1996's *Topographer©* program is also tailored to the raster data structure by offering a uniform grid window with which to sweep over a surface and change the underlying values.

d) Filter

The filter is a special case of Shape which does not necessarily have to be used with a path. All it needs is a scope of action to function (see Scope of Action section 5.4.1 below). Filter may assume its geometric effect from a mathematical description, an algorithm, or other shape parameters.

5.2.2 Path

All actions, whether user or tool, possess a track, or path, along which movement takes place. For tool action, a shape may either move along a path or be placed at a particular position. A path may therefore be a line or a point, respectively. All paths of more than one point possess also a *direction of movement.*

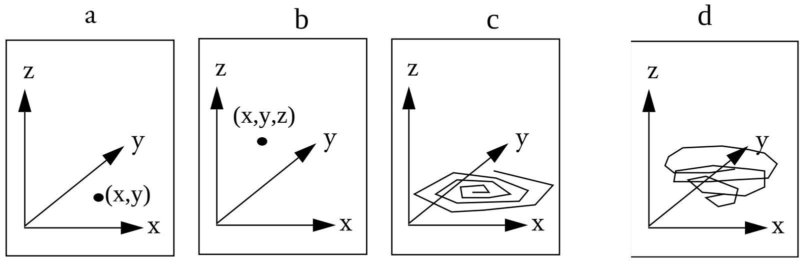

Figure 5.3: (a) a path consisting of a single placement point in one coordinate plane, (b) a path consisting of a single placement point in space in three-dimensions, (c) a planar line path in space, (d) a non-planar line path in space.

The path for user action matches that for tool action. Mapping of user action to tool action occurs via GUI interface methods of interaction. Both kinds of action are represented by one path representation.

The shape and path of our tool definition represent the starting geometric components of the generic sculpting tool definition. The parameterized primitive approach to shape definition lends itself nicely to these two generic tool components. The individual strategies for shape and path definitions may be compiled into a library of topographic primitive forms for selection and placement into a target surface by a user at run-time.

In the special case of a filter, a polygonal shape may be placed at one point and this polygonal area defines its scope of action. This placement point is the official path, while the polygonal area is the area to be affected by the filter. The rest of the model is essentially “masked”. Within the polygonal area to be filtered the associated algorithm may have a direction. A filter is generally a global function that is commonly delimited by masking.

What remains for clarification are the relationships between the tool path and how its parameters affect the target topographic surface. The shape's relationship with the path also requires clarification. These relationships contain the verb-like behavior of surface sculpting and are discussed in the sections which follow.

a) Absolute/Relative Path Mode

An important attribute of path which governs its relationship with the surface is its *absolute* or *relative* behavior. Absolute means the path follows its own parameter values. Relative means the path defines its position relative to some other parameter, e.g., an existing elevation value. For every point in the path, there is an (x,y) coordinate pair location with an associated elevation, or z-coordinate value. The source of this elevation value may be the underlying terrain (the relative case), or from another source (absolute case). This absolute or relative path mode choice holds for every point in the path, whether there is only one or not. One may also speak of the entire path as relative or absolute where all of the points in the path are relative, or take their elevation value from the existing target surface, respectively, figure 5.4 c. An entire path which does not lie on the target surface is an absolute one, figure 5.4 a. Some path points may lie on the surface, while others do not. In these cases, the individual path points take on values from other sources. Such sources may be directly from the user, or from some criteria like slope or aspect or a boundary condition, to name a few examples.

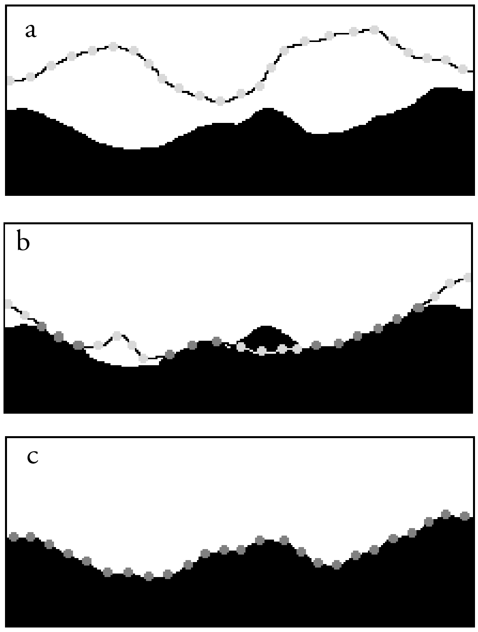

Figure 5.4: **Absolute / Relative Path Modes.** Light grey dots are path points in absolute mode, dark grey dots are path points in relative mode. (a) the entire path is in absolute mode, i.e. all path points are in absolute path mode. (b) Some path points are in absolute mode, others are in relative mode, (c) All path points are in relative mode.

The following figure 5.5 shows an example of an entire path connecting two points and behaving in an absolute fashion. Figure 5.6 depicts the same path cutting relative to the underlying surface dataset:

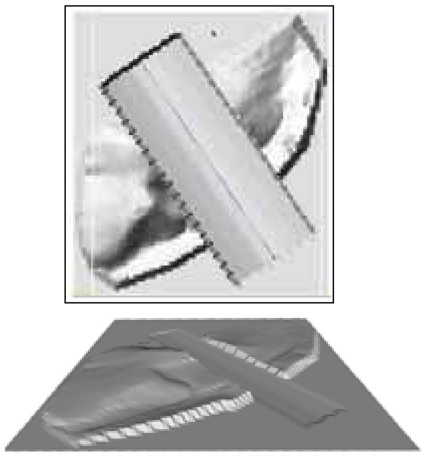

Figure 5.5: Absolute path. (Westort's TSS, 1998)

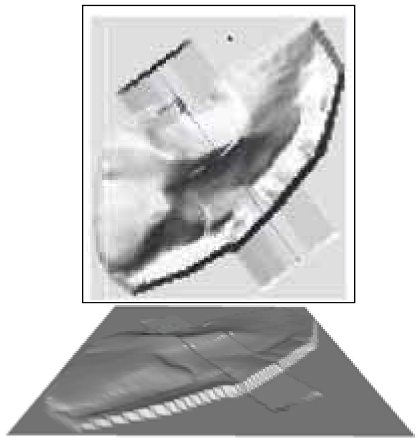

Figure 5.6: Relative Path. (Westort's TSS, 1998)

b) Static/Dynamic Path Mode

The path's relationship to the surface may also experience a static and dynamic relationship based on some external factors. For example, if a road is being laid out at a constant slope, and the path is intended to reflect this slope except for certain conditions. As the blade moves along the path at the constant slope the path may wish to adjust itself based upon whether the conditions for slope uniformity are met or not.

5.3 Shape - Path Relationship

The relationship between the shape and the path is always a relative one. Shape and path may behave independently of one another, and their relationship may be characterized by two variables: *Orientation*, and *Static/Dynamic mode*.

5.3.1 Orientation

Orientation of the shape with respect to the path poses a significant range of possibilities and corresponding geometric results, depending on which shape and path are selected and the following two factors: *Angle* and *Track Point Placement*. The track point is the point of the path along which the shape travels. (see figure 5.7). To illustrate these factors, we consider a path consisting of more than one point. A planar shape may experience an orientation angle change with respect to the path as illustrated in figure 5.7, where in each coordinate plane the angle of the shape profile may be moved with respect to the track point. The track point is a point placed relative tot he shape which the path travels along when the shape is extruded along it.

a) Orientation Angle

Orientation angle with respect to a path must conform to the geometric constraint of having only one elevation per x,y coordinate position. If the shape were to be revolved around the path's trackpoint, for example, no overhangs or tunnels could result.

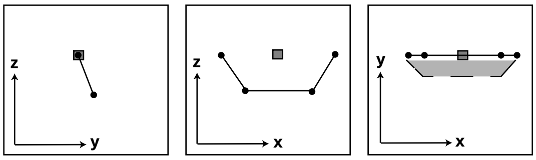

Figure 5.7: **Orientation Angle.** Orientation of the Shape with respect to the Path track point. Angle may be adjusted from all angles of orientation. The shape is symmetrical with respect to the path in the x-z and x-y coordinate planes, but not in the y-z.

b) Orientation Track Point Placement

A track point may move, or be placed, anywhere with respect to the shape. This is called *track point placement.* The angle of the shape may also move with respect to the track point.

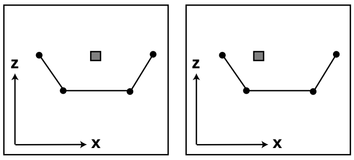

Figure 5.8: **Orientation Track Point Placement.** The track point is placed off center in the z-x coordinate plane (a) symmetrical track point placement, (b) track point shifted off-center, i.e. a-symmetrical placement.

c) Orientation - Special Cases

There are two cases of Orientation worth special mention: The first is the symmetrical shape case, where the shape's plane of symmetry aligns itself with the direction of a path segment. Figure 5.8 illustrates an example of this case. Notable is how symmetry occurs only in two of the three coordinate planes. The shape is not symmetrical with respect to the track point in z-x space, for example. Symmetry greatly simplifies the extrusion functionality. Its absence both greatly complicates the shape-path relationship, but also affords the user several opportunities for geometric control (methods for which are described in chapter 7).

The second special case regarding orientation is when the track point does not lie within the shape's bounding box area. For this case, the *infinite extensibility* factor applies. *Indefinite extensibility* is an attribute of shape. The basic idea is that if a shape completely or partially overhangs an area which is far below it, the bottom of the shape may extend down to meet the terrain far beneath it. Such an extension may occur in several ways. It may be either a vertical drop, or follow another parameter, like slope. There may also be a parameter like "round the base" for where the edges meet. In traditional contour line use such junctures are referred to as daylight lines, and infinite extensibility would enable one to govern their form. The same applies to shapes which are partially or wholly surrounded by existing target which rise far above the shape, in which case the shape would have to extend up to meet existing grade. This case also applies only for a track point which is placed either above or below the shape's bounding box, not further to the left, or further to the right. Except for this mention of these two latter cases, this thesis does not explore them further.

5.3.2 Static/Dynamic Mode

Another parameter describing the relationship between shape and path is static or dynamic mode. Geometric attributes of either the whole shape or individual components of the tool shape may change *along the course of the path*. This static/dynamic mode differs from the static/dynamic mode for the path discussed in section 5.2.2-b above because they include changes different than those for the path alone. Such changes may include the following types of changes:

a) Scale changes

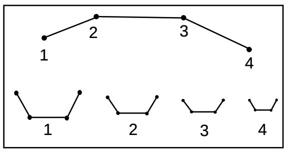

Figure 5.9: A shape in dynamic mode changing in scale. In this example the shape's scale changes along the course of the path, shown in plan above, while the corresponding shapes are profiled below.

b) Orientation changes

- The track point placement may change dynamically.
- The angle may also dynamically change with respect to the path.

These cases are not developed further in this thesis.

c) Shape parameter changes

The shape, together with the shape-path orientation and track point position represent a State of the relationship at specified points along the path. The points along the path where the shape is placed are intervals. These intervals may or may not correspond with the true path segment points, e.g. in figure 5.9 they do correspond. These dynamic intervals may correspond with the actual path points, or other user-specified points or intervals along the path.

5.4 Relationship with the surface: Effect

The result of applying the shape to the path constitutes an *effect* on the surface. Effect results in either a positive or negative change to the model's existing elevation value or both. Effect may be described by the following characteristics discussed in the next four sections: *scope of action, corner options, end options,* and *overlap options.*

5.4.1 Scope of Action

Scope of action is the area of influence of a particular pass or move of a tool. For surfaces in general, example scopes of action include *local* scope, which incurs changes to the value of only one point (or vertex) in a model, a *global* scope, which operates on all vertices in a particular data set, and a *regional* scope. Regional scope consists of a *move*, which is an incremental geometric operation performed between two points, or a *pass* which is a collection of moves. Regional scope means the area of influence is user-specifiable in shape and size.

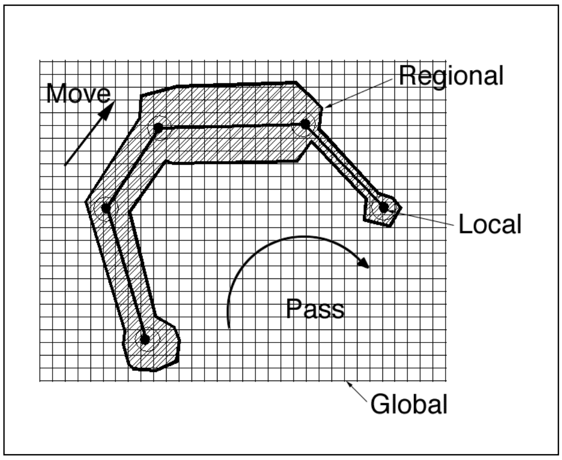

Figure 5.10: Scope of Action. local = a change to one vertex, move = an incremental geometric change to the surface (more than one vertex), pass = a collection of moves (more than 1 move), global = a global change to the dataset (all vertices)

The case of contour lines and whether they possess local, regional or global scope of action remains an open question. The decision rests with the scope of influence a particular contour line change, or set of changes, has on other existing contours. This thesis does not attempt to rest the case, but merely state that contour line changes influence at least a regional scope of action, and frequently require a re-working (calculating and drawing) of the entire collection of contour lines for a site. Delineation with a bounding polygon of the topographic influence of a particular change, or a collection of changes, would be the equivalent move or pass scope of action designation specified here.

a) Masking Option

The footprint of a pass upon the surface is the scope of action of the shape and path. This scope of action may function as either a mask or a filter. As a mask, it is possible to perform other geometry changing operations while preserving the existing values under the masked polygons. Filter sweeps over this same area.

5.4.2 Corner options

For a static shape-path relationship, extrusion of a shape along a path consisting of straight, linear segments, the three-dimensional geometric complexity of the shape expresses itself is at the path corners, overlaps, and ends. Otherwise, along the straight segments of the path the geometric result may be characterized by a cross section of the shape oriented perpendicularly to the path along its length. The generic tool definition needs to offer geometric control for a trial and error way of proofing and editing of model results at these junctures.

For example, for round corner options, a shape positioned perpendicularly to the track point, and positioned in the middle of the z-coordinate plane of the shape, and at grade with the existing surface, the corners would look as follows (figure 5.11),

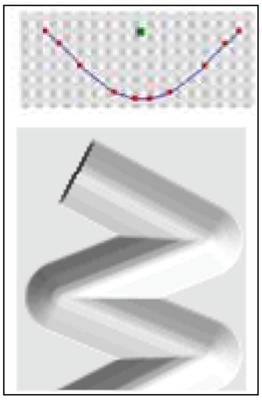

Figure 5.11: Corners with centered track point.

As shown in figure 5.12 below, there are two areas which need to be set for this asymmetrical case. Region **a** is the outer corner, region **b**, the overlap corner between consecutive segments.

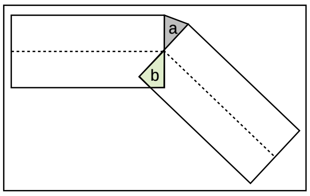

Figure 5.12: Symmetrical Path Corner Option Diagram.

The symmetrical shape case is simple with only two areas of concern as compared with the case where the track point is placed off-center (figure 5.13), the behavior at corners would look like the following:

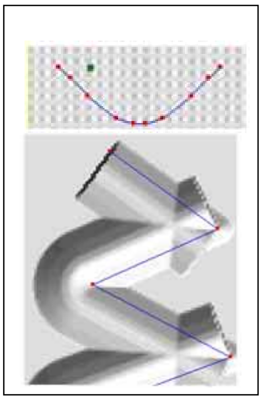

Figure 5.13: Corner option with track point off center

The case of an off-center track point placement complexifies the corner situation because instead of only two areas of concern (*a* and *b*), there are now at least five for the same corner (figure 5.14). And what about the next corner?, involving decisions for *b* again, and *f* and *g*? Since no real-life bulldozer or extrude tool would create such geometry, the user must now decide on the desired geometry for all of these junctures. For example, should one eliminate the e regions? Round the corner as d depicts? Or leave it flat with just *a*? And what about the next corner

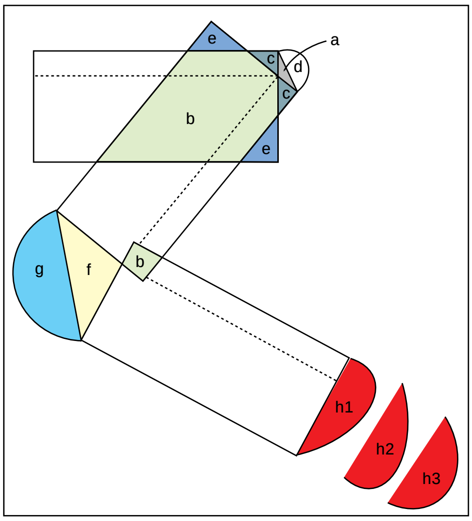

Figure 5.14: Corner Option diagram for an a symmetrical path.

a) Other Corner Shapes

Of course there are also many alternatives to rounded corners, e. g. *flat* (figure

5.15) or *pointed* corners:

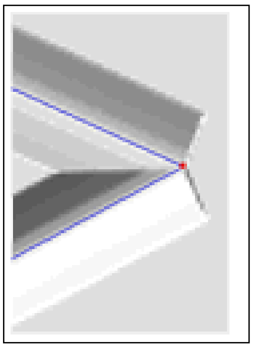

Figure 5.15: Flat corner option.

Geometric control over these corner opportunities enables an extension and broader range of possibilities than any real-world simulation of behavior of known tools or methods; extending automation beyond mere mimicry.

5.4.3 End options

End options primarily govern the shape and the beginning and closing ends of a pass. For example in figure 5.15 above, should a round corner of a shape whose track point is placed off center take on shape *h1*, *h2*, or *h3*? If the shape is volumetric, the ends may be very complex reflecting a fraction of the volume. Which fraction depends on the end option desired.

This option is of course greatly simplified for a static shape, i.e. one which does not change in scale, parameters, orientation, or track position along the course of the path. As previously noted, a cross-profile through the shape suffices along the path segments under these conditions and the volume itself is only expressed at path corners and ends. Alternatively, one may wish for the ends to be flat or round or pointed, or some other shape.

5.4.4 Overlap options

There are three distinct overlap cases: *overlap at corners* (*b* in figure 5.14), *overlap over segments,* and *overlaps with previous passes.* These cases distinguish between areas in the scope of action which are affected by the overlap. They identify the overlap regions. The overlap options actually determine how to handle the geometry within these regions.

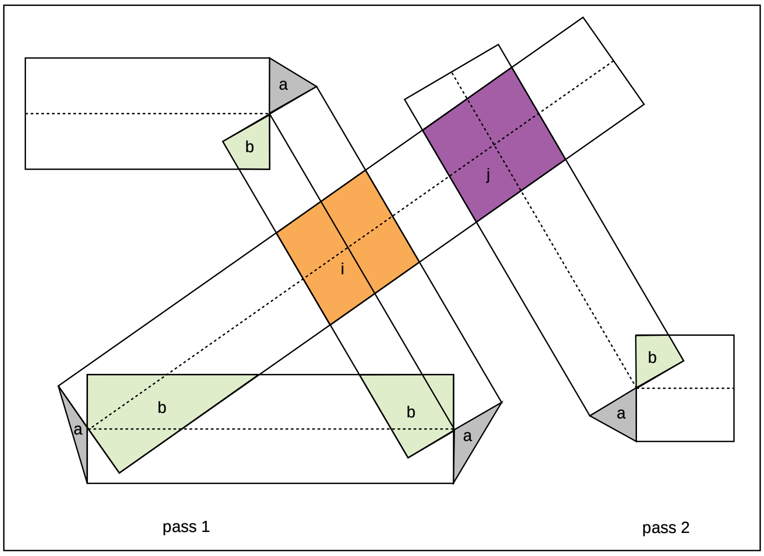

Figure 5.16: Overlap options diagram. *b* represents overlap the overlap option between consecutive segments. *i* represents overlap between non-consecutive segments, and *j* represents overlap between different passes.

a) Overlaps at corners

Overlapping at corners occurs between consecutive segments as depicted in figure 5.16

b) Overlaps over segments

Overlaps over segments are overlaps which occur over when a path doubles back upon itself, an example of which is shown below 5.16

c) Overlaps between passes

Overlaps between passes of a tool are generally handled whereby the previous pass, unless explicitly indicated to be treated differently, is treated as existing terrain.

d) Other Overlap options

Overlap options govern the geometry between the overlap areas specified above. Example solutions include the following algebraic combinations between existing and new elevation geometry, e.g., +, -. *, min, max, average, <, >. Other solutions may include going to existing grade in these areas, raising all values to a set height, or another function.

Figure 5.17 depicts the average and the maximize cases, respectively:

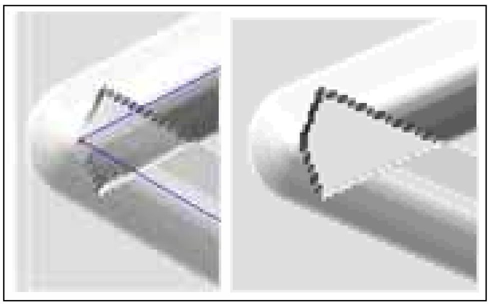

Figure 5.17: Example algebraic corner overlap options. Left is an average, Right is a maximum corner overlap option.

5.5 Complexity Index

Given the large number of parameters which may simultaneously change, there is a need for a kind of metric – or index – for keeping track of, or recording how many of these parameters change at one time. In addition to measuring the system itself in terms of degrees of freedom, the metric would also be useful for posterior testing of the success of the entire system. Whether such a metric is feasibly derivable at all, and what kind of direct influence it could have remain open questions of this thesis, but worthy of mention here nevertheless.

5.6 Conclusions from Generic Tool Definition

In summary, the generic sculpting tool definition consists of four components: (1) a shape, (2) a path, (3) a relationship between shape and path characterized by orientation (angle and track point position) and static and dynamic mode, and (3) the effect, or result of the application of a shape to a path, which is ultimately an addition and/or subtraction to the surface. Effect's parameters include its scope of action – local, regional and global, and move and pass, together with corner, overlap and end options.

This quite simple definition of tool has several important implications for sculpting. First of all, remarkably, any geometry may be achieved from it, and geometric control follows directly from this point. And second, most cases are achievable from a simple line shape and line path. That two simple line description may have that breadth is very powerful. With very few means – often simple line editing functionality is enough – one may easily create and/or transform an entire three-dimensional form. The complex functionality often deemed necessary to directly edit a full three-dimensional surface is not the case here. Indirect adjustment of the simple, internal component parts offer a flexible and predictable means to achieve powerful geometric changes in the resultant form (see examples of these shapes in chapter 8), perhaps expressive enough to approach real geometric control.

Moreover such a pure simple internal description is importantly de-coupled from, and therefore not limited by, the external surface representation. As far as the tool definition is concerned, it no longer matters what the underlying surface representation is; whether it is contour line, TIN, or raster representation is irrelevant to the internal definition described in this chapter. In this way this representation differs from most other digital approaches because it does not tailor itself to such constraints. For each line shape and path, there exists a 1:1 equivalence in geometry; for every blade and path mathematical description there exists exactly one and only one geometric form, a fact that does not change between TIN, raster, contour line, etc.

In addition to the 1:1 geometric equivalence between a blade and a path internal description, there is also has a temporal equivalence. For every position along the path, there is a corresponding shape. This means that a shape can be associated temporally with a position along a path. The shape travels along this path over time, therefore, which is an attribute with precedents in both the definition of sculpting, and the history of how sculpting has been understood theoretically. A traditional sculpting tool also experiences such temporal equivalence, making it opportune to exploit this possibility in a digital environment via animation, scripting and other known devices to complement processes such as CAD-CAM, construction sequencing, and physics-based simulation, to name a few examples.

An approach which focuses on adjustment of simple constituent parts possesses a number of other advantages. The parts may be modularly replaced, saved, placed in and selected from a library, and otherwise handled independently from the entire shape. Often this is more efficient in terms of time and space. Factors like cost, time, cut and fill calculations, etc., which other approaches depend on analysis of the terrain surface for, may here be tailored to some very simple internal descriptions. Chapter 9 discusses these possibilities further.

As a general rule, to reduce complexity, the more complex the path, a simple shape is called for, and a more complex shape, the simpler the path. What the generic tool definition does not resolve is where the threshold between the two degrees of complexity lies. Indeed reducing the complexity at each of the end, corner, and overlap junctures may be achieved by adhering to the following conditions:

- planar shape
- perpendicular, perpendicular orientation of the shape to the path, with placement of track point on center.

And these are the conditions adhered to in the implementation described in chapters 7 and 8. The next chapter translates this conceptual tool representation into a class representation abstraction.

Chapter 6: A Class Hierarchy Description

6.1 Introduction

This chapter presents a translation of the generic sculpting tool definition into object-oriented terms. The chapter takes on the object-oriented design step in the object-oriented development progression to answer the question, "How would a minimum set of classes represent the generic sculpting tool?" We remain in conceptual design mode with this chapter, and still do not tailor our definition to a topographic surface specifically. We maintain the claim that a software tool based on the class hierarchy presented here would be able to achieve any three-dimensional surface geometry. Description and justification of the class hierarchy representations are offered. First we discuss the decision to opt for an object-oriented solution. The base classes comprising the minimum class hierarchy are then described: *CTool, CShape, CPath, CEffect, CTarget,* and *COrientation.* Other important classes necessary to the hierarchy, but either not a base class themselves or are not part of the minimum set, are described last.

6.2 Why an Object-Oriented Solution?

Our definition of a generic sculpting tool described in chapter 5 nicely lends itself to an object-oriented abstraction of its properties. Booch, 1991 tells us:

> "...in the OO context, method refers to those functions and procedures contained within a class that perform work on data as a service or to produce a result, respectively."[1]

Our sculpting tool consists of both discrete parameterizable components (shape and path), i.e. Booch's "data", and relationships between these components (orientation and static/dynamic behavior), and relationships with the surface (Effect), i.e. "procedures and functions" in Booch's object-oriented terms. Since class abstractions of reality consist of both instance variables (data) and methods (procedures and functions) to work on that data, a translation of tool components into classes is both suitable and relatively direct.

As discussed in section 4.4, sculpting methods consist of the application of a tool to a material. Our definition of a generic sculpting tool has been broken

1. Booch (1991) p18

down into *user action* and *tool action*, so the object-oriented notion that a method performs some "task", or action, on data is a parallel concern. In the case of a surface, the data reflect a sculpting material, a parallel this thesis substantiated in the discussion of material in chapter 4. In addition to performing actions on a class's own data, class member procedures and functions also perform tasks on instantiations of data from another class, i.e. on objects. That the object-oriented paradigm allows for both kinds of verb activities – within a class and between classes via instantiations of objects – recommends it for performing actions on material and for interacting with components and functionality of other discrete objects, like tool actions, for example.

Object-oriented allows "higher level" thinking about a problem; "real-world" or "more intuitive" strategies for abstraction and breaking a problem down. Moreover, it allows for an hierarchical breakdown of the real-world components which make it up; so that a generic "thing", or object may, in a non-redundant fashion, cause for the derivation of like "things". We take advantage of all of these benefits in the construction of the hierarchy presented in the following section.

6.3 Naming Conventions

The naming conventions adhered to in this thesis is a modified version of those used by *Metrowerks Code Warrior™'s Power Plant* Class Library. They are as follows:

C starts class names
m begins all instance variable names
a begins local variable names
Capitalization of all letters representing the first letter of words making up a member function or variable. E.g. ComputeNormals()
e enumerations
k constants
U utility classes
L start classes belonging to *Power Plant*

6.4 Individual Descriptions of Base Classes

At its highest level, the class hierarchy consists of six base classes: *CTool, CTarget, CShape, CPath, CEffect, and COrientation*. The individual class descriptions follow below; their attributes first, then their member functions.

6.4.1 Class: *CTool*

The CTool is the class representation of the generic sculpting tool conceptual description of the previous chapter. The *CTool* base class possesses as member fields the attributes described in chapter 5. They are: *mTarget, mShape, mPath, mEffect, mOrientation, mDynamicMode,* and *mPassCount.* Except for the last variable, each of these is an object of another base class. As already discussed previously, the important distinction needs to be maintained between the class definition and the underlying data structure of the target surface. This separation happens by containing the data model parameters in the CTool's mTarget instance variable. Such a clear separation allows the class definition presented there to function on any digital surface, regardless of its internal definition.

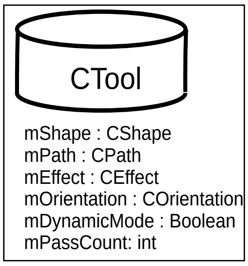

Figure 6.1: ***CTool* Class.** Generic sculpting tool base class.

a) Attributes

- *mShape* is a CShape object which is applied to mPath. When mDynamicMode is set to true, mShape may consist of many shapes, but when false, consists only of one.
- *mPath* is a CPath object which contains a line along which the mShape is applied.
- *mEffect* is an object of class CEffect and stores variables determining the result of application of mShape to mPath on mTarget's surface. This includes the scope of action, together with corner, overlap and end options.
- *mOrientation* is a COrientation object containing the angle and track point position information describing the relationship between the mShape and mPath.
- *mDynamicMode* is a Boolean variable indicating whether the mShape or mOrientation changes along the length of mPath or not.
- *mPassCount* counts the number of passes made by the tool; i.e. the number of times the procedure DoApply() is called.

b) Methods

- *DoApply()*

This member procedure applies the mShape to mPath. Herein lies the process kinetic action described in section 3.8. Once this function is called, the user is able to see the external representation of the geometric effect on whatever output device is specified by CTarget. The geometry-determining elevation changed data, together with the graphic-display output routines, are orchestrated from within this procedure.

c) Sub-classes

The sub-classes derived from CTool are depicted in figure 6.2, and include: *CExtrusion, CFilter, CStretch, and CLayer*. The distinguishing characteristic between each of these sub-classes is their path, or movement behavior. A path-based categorization of tool types is consistent with our interest in action-based sculpting functionality.

• *CExtrusion*

For CExtrusion the linear path constitutes the movement-determining component along which a Shape is extruded. This class is the one most fully worked out in this thesis. The others (CFilter, CStretch, and CLayer) are sketched out here and presented primarily for completeness. *CExtrusion* subclasses into *CKernelConvolution* and the set of classes, *CBulldozer, CShovel, CDrill,* and *CStamp*. CKernelConvolution takes a polygonal area and moves it along a path, changing the values underneath. This subclass usually depends on a CTarget representation that matches the structure of the kernel (usually a grid, see Baer 1994), but it need not. The moving window for this class need not posses regular rasterized cells, but may consist of an algorithm or other parameters which deform the underlying geometry accordingly. The path attribute it inherits from CExtrusion, while the rasterized cell and polygonal boundary attributes it receives from CFilter. The other four subclasses of CExtrusion may be distinguished by the basic form of their path.

- *CBulldozer* - has a path which is relatively parallel with the ground surface.
- *CShovel* - has a path at an angle to the target surface
- *CDrill* - has a path which is basically perpendicular to the target surface.
- *CStamp* - possesses a path consisting of one point.

• *CFilter*

Discussed in section 5.2 is the special case of CFilter and how it must possess both a standard mPath consisting of a single point, and a polygonal footprint within which the desired filter functionality operates. A CFilter object may therefore function either as a mask itself, or as a bounded area delineating where a filter may pass and outside of which remains unmodified.

• *CStretch*

The CStretch tool is its own class of tool because it consists of a “neighborhood” area which responds to being pulled or pushed at a point within it. The amount of distortion would be proportional to the amount of elasticity and tolerance, i.e. area of influence the point in question would have. This functionality has not been developed further in this thesis.

• *CLayer*

CLayer is another tool dependent on the output representation of the CTarget object, in this case usually contour lines. It would be a tool for construction of horizontal layered models out of contour lines. It could plausibly function in concert with CStretch, as a tool useful for simulating natural effects like erosion and depositional forces, for sheets, i.e. layers, of topographic material could be deposited at varying thicknesses. This functionality has not been developed further in this thesis.

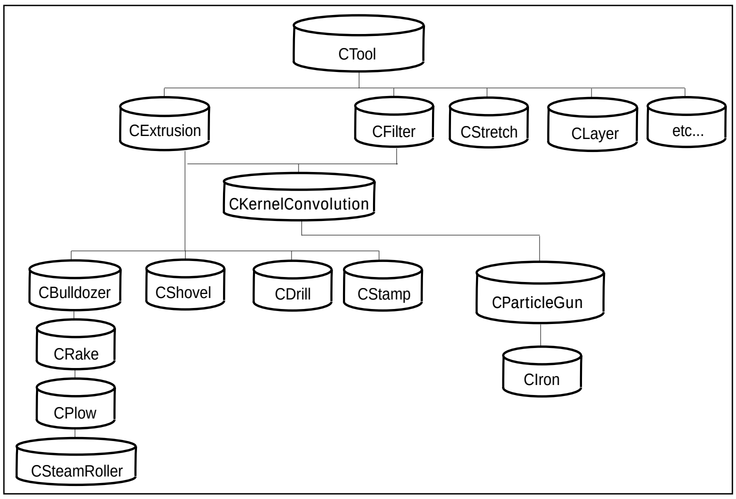

Figure 6.2: *CTool* Class hierarchy

6.4.2 Class: *CShape*

CShape and its derived sub-classes are called upon by CTool to define its geometric attributes of the sculpting system, namely mPath and mShape.

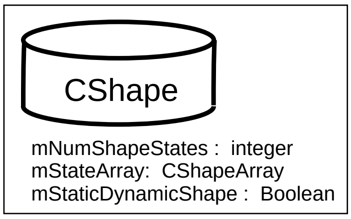

Figure 6.3: *CShape* Class

a) Attributes

The CShape class possesses the following member variables:

- *mNumShapeStates* is a count of the number of shapes called for by a particular pass of the tool.
- *mStateArray* stores the shapes called for by the tool.
- *mStaticDynamicShape* switches off or on depending on whether the shape-path relationship is a static or dynamic one, respectively.

b) Methods

In addition to initializing, storing and drawing and writing itself, CShape possesses methods to keep track of which State of the shape is in use by a tool's pass at any given time.

c) Subclasses

The subclasses of shape are three: *CPointShape, CFormulaShape,* and *CFilter*. All shapes, except filter may be defined either by a collection of points or an equation. CLine and CPolygon may be non-planar or planar, with classes reflecting these differences. CFilter may be an Equation based filter or a raster one.

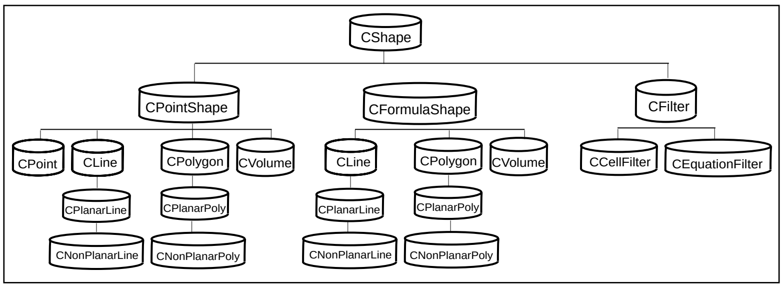

Figure 6.4: ***CShape* Class description**.

6.4.3 Class: *CPath*

The CPath class is one which inherits, i.e. is sub-classed, from CShape or a CShape sub-class.

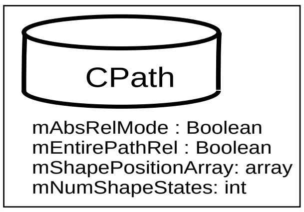

Figure 6.5: CPath Class

a) Attributes

The CPath class contains the following member variables:

- *mAbsRelMode*, is a two-dimensional array which stores whether each path point possess an absolute or relative behavior.
- *mEntirePathRel* is a Boolean variable set to true if the entire path is a relative one or not;
- *mShapePositionArray* is an array of points indicating where the Shape states are located along the length of the path.
- *mNumShapeStates* is an integer which receives the number of states the shape takes on for this path. Each path represents one pass.

b) Methods

CPath's methods include the standard, reading, writing, drawing, and updating of itself, but also functions responsible for determining its own bounding box and active area. These areas are computed together with the shape and the shape's orientation, and are important for limiting the number of points in the model to evaluate for change.

6.4.4 Class: *CEffect*

CEffect class possesses member variables to determine both the area the tool is operating upon, and the addition and/or subtraction resulting on the surface from application of the shape to the path.

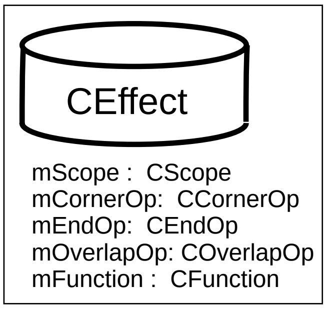

Figure 6.6: CEffect Class Description

a) Attributes

- mScope is an object of the CScope class and is responsible for computing the targeted area for tool-operation. (see description of CScope in section 6.5.1 below).
- mCornerOp is an object of CCornerOp, and keeps track of which corner option is to be applied to which corner of the path.
- mEndOp is an object of CEndOp, which computes which end option is desired for the pass.
- mOverlapOp is an object of COverlapOp, which is determines which overlap option is to be applied to the overlap junctures within passes and between passes.
- mFunction is an object of CFunction, which determines which Boolean or algebraic equation to apply to the shape-path composite's effect on the surface elevation. (CFunction is described in section 6.5.2 below).

6.4.5 Class: *CTarget*

The CTarget class is the target surface of the generic sculpting tool. This subclasses into either the surface itself (the typical case), i.e. the *CElevModelTarget* class, or another shape that is a surface, for example a polygon, raster or volume surface, i.e. the *CShapeTarget* class. It may also target some external surface, like an actual on-site topographic surface, in the case of a remotely controlled bulldozer, for example. *COutputDevice* is a subclass designed to keep track of the destination of the external representation. It is significant that CTarget is not a member variable of CTool, because as previously mentioned, the functionality between the blade and path internal representations which CTool handles is independent of the desired external representation, i.e. the target.

a) subclasses

- *CElevModelTarget*

This class possesses all of the attributes necessary to define a target surface. For a raster representation of the target surface, they include the following:

- int mNoOfCols - the number of columns
- int mNoOfRows; - the number of rows
- int mXOriginOffset - the position of the origin in the x direction
- int mYOriginOffset - the position of the origin in the y direction
- int mXCellsize - the size of each cell in the grid, x direction
- int mYCellsize - the size of each cell in the grid, y direction
- float mMaxZ - the highest elevation value in the model
- float mMinZ - the lowest elevation value in the model
- float **m2DArray - the two-dimensional array which stores the elevation values.
- eAbsRelMode mAbsRelMode - marks whether the path is a relative or absolute one with respect to the blade.

- *CShapeTarget*

CShapeTarget is a class containing the data from a shape if it would like to be a target of a particular tool iteration. It may also be any other surface, not necessarily a topographic one. This subclass serves to stress that this generic tool definition may function as a tool beyond just the topographic sculpting context.

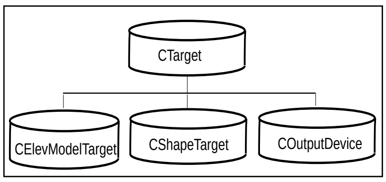

Figure 6.7: CTarget Class description.

6.4.6 Class: *COrientation*

The COrientation class possesses the necessary attributes and methods with which to govern the orientation relationship of the shape with the path.

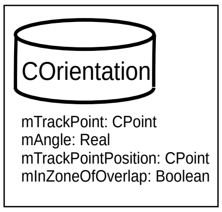

Figure 6.8: COrientation Class

a) Attributes

- *mTrackPoint* is a point in space designating the position of the path with respect to the shape.
- *mAngle* is a real number designating the angle between the path and the shape. A true implementation would have to possess angles for every coordinate plane, but we name only mAngle in the interest of brevity here.
- *mTrackPointPosition* is the position of the track point in space relative to the path.
- *mInZoneOfOverlap* is a Boolean variable designating whether the track point lies within the minimum bounding box of the shape.

6.5 Other Classes

6.5.1 Class: CScope

The CScope class represents the scope of action of the shape and path relationship contributing to a tool's effect.

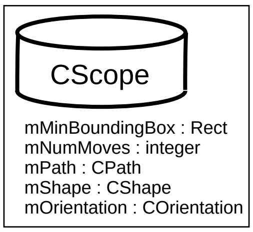

Figure 6.9: CScope Class

- *mMinBoundingBox* is the rectangle surrounding the entire targeted scope of action.
- *mNumMoves* is the count of the number of moves a particular path consists of.

6.5.2 Class: ***CFunction***

CFunction maintains all of the functions and utility operations which the tool requires to operate. It possesses one member variable which is a record containing the operands in a function. These may be several. Typical operands are the shape, the path, and the surface.

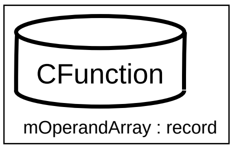

Figure 6.10: CFunction class.

CFunction possesses several subclasses as depicted in figure 6.11:

- *CAlgebraic* - covers such function like add, subtract, multiply, divide, etc.
- *CComparative* - includes Boolean operations comparing two operand values.
- *CEquation* - includes filter functionality and other formulas which we will not explore here.

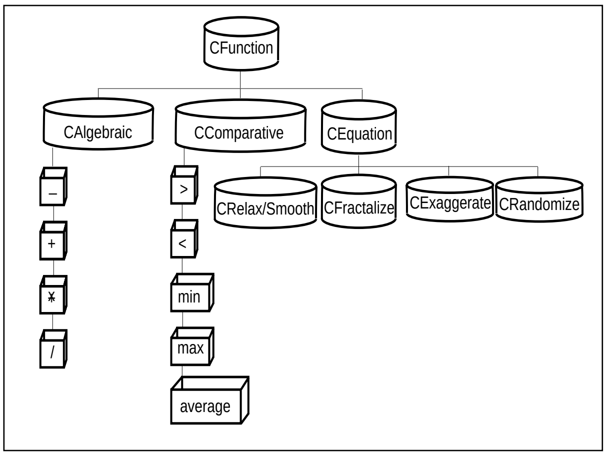

Figure 6.11: CFunction's class hierarchy.

6.5.3 Class: ***CCornerOp***

As described in section 5.4.2, the CCornerOp class governs the behavior at the corners of path segments. They are subclassed according to which corner options are specified, e.g. CRoundCorner, CFlatCorner, CPointyCorner, etc.

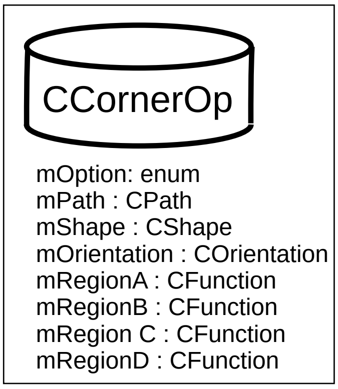

Figure 6.12: CCornerOp Class

a) Attributes

The attributes reflect

- *mOption*: enum - the corner option the user chooses
- *mPath*: the path object for the pass from CTool
- *mShape*: the shape object for the pass from CTool
- *mOrientation*: the orientation between the path and the shape
- *mEffect*: the effect for the pass from CTool
- *mRegionA*: CFunction - a function governing the corner region *a* of figure 5.14.
- *mRegionB:* CFunction - a function governing the relationship region *b* of figure 5.14
- mRegionC: CFunction - a function governing the relationship region *c* of figure 5.14
- *mRegionD*: CFunction - a function governing the relationship region *d* of figure 5.14

b) Methods

The methods of CCornerOp are specific to the corner option specified.
RoundCornerOption
FlatCornerOption
Pointed Corner Option

6.5.4 Class: *COverlapOp*

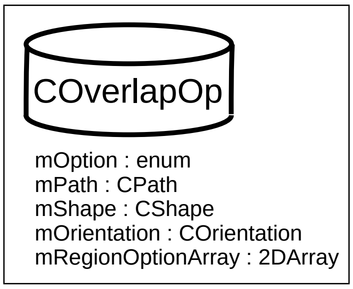

Figure 6.13: COverlapOp Class

a) Attributes

- *mOption*: enum - a variable for storing the overlap option if all overlap regions in the pass are to be treated the same. If not, the different choices are stored in the mRegionOption below.
- *mPath*: CPath
- *mShape*: CShape
- *mOrientation*: COrientation
- *mRegionOptionArray*: 2DArray - an array which stores the overlap region (see figure 5.16) and the overlap option function for that region.

6.5.5 Class: CEndOp

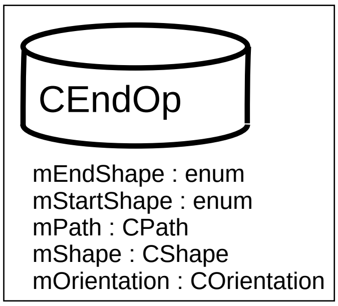

Figure 6.14: CEndOp Class

a) Attributes

- *mEndShape*: enum - the shape at the end of the pass.
- *mStartShape*: enum - the shape at the beginning of the pass.
- *mPath: CPath*

- *mShape*: CShape
- *mOrientation*: COrientation

6.6 Conclusions

The class hierarchy described in this chapter reinforces the generic sculpting tool definition of chapter 5 by representing it as object-oriented classes. In summary, the individual base classes are CTool, CShape, CPath, CEffect, CTarget and COrientation. Other classes include CScope, CFunction, CCornerOp, COverlapOp, and CEndOp. The definition of these classes concludes the object-oriented design phase of the object-oriented development progression. We make the claim with this class abstraction that any three-dimensional geometry may be created and/or changed, i.e. sculpted, from its implementation. We now turn our attention to just that, and conclude the conceptual phase of our investigation. The next chapter deals with topographic surfaces specifically for a particular implementation of the essential elements of the abstraction presented in this and the previous chapters in the form of the *Topographic Surface Sculptor (TSS)*.

Chapter 7: A Prototype Implementation; *Topographic Surface Sculptor (TSS)*

7.1 Introduction

This chapter describes a prototype software implementation of the generic sculpting tool definition described in chapters 5 and 6 as *Topographic Surface Sculptor (TSS)*. It represents the object-oriented implementation phase of the object-oriented development progression.

We first discuss a minimum working subset of the classes described in the previous chapter. The objective of the implementation was to directly and quickly arrive at a working proof-of-concept prototype of the ideas encapsulated in the generic DTM sculpting tool definition. This means all of the base classes need to be represented in the system in some form, either as independent classes, or appropriately bundled as member functionality. As Ervin and Westort, 1995 specify, the metaphor of a bulldozer, a virtual one, possesses the essential characteristics called for in our generic definition. The implemented features are presented in the form of a user walk-through. This is followed by description of desirable functionality not yet realized. The specific internal step-through of the code and the development specifics are covered in appendix A.

7.1.1 Minimum Subset of Classes - Overview

A CBulldozer class requires the following minimum set to function: a DTM, or a CElevModel class, point, line, and polygonal shapes with which to instantiate paths, and blades shapes. The additional class, CBlade has been subclassed from CNonPlanarLine to bundle the geometry approximating a bulldozer's blade with the a bulldozer object. This minimum set of classes for a virtual bulldozer implementation are highlighted in grey in figure 7.1.

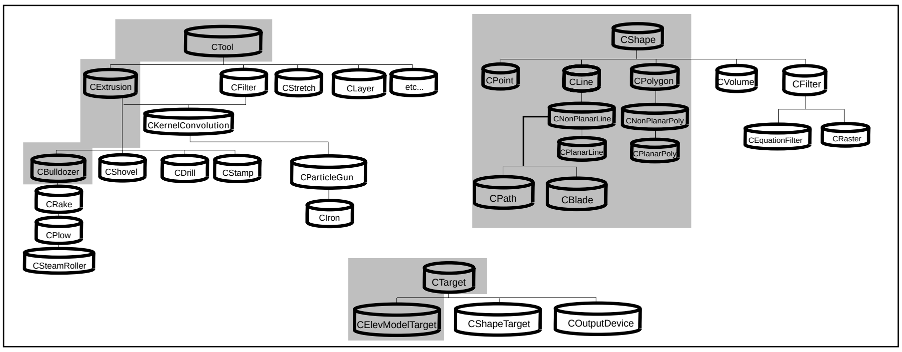

Figure 7.1: Minimum Set of Class for a Generic DTM Sculpting Tool implementation. Those classes highlighted in grey constitute this minimum set.

The following classes have not been implemented in *TSS* as separate classes, but are encapsulated into the CBulldozer class as member functionality: COrientation, CScope, CFunction, CCornerOp, CEndOp, COverlapOp.

7.2 Implemented Classes

7.2.1 CElevModel

The CElevModel class approximates the CElevModelTarget discussed in section 6.4.5. It is responsible for all of the parameters for a raster DTM. Future implementation would delegate this class to handling other data models like triangulated irregular network (TIN) data models, and also contour line representations. Here, only the following digital terrain data model parameters are defined as member variables to this class:

The CElevModel class is responsible for reading, initializing, storing, writing, and drawing its data to and from the disk to an output device, in this case a screen. Individual member functions reflect these tasks. A simple double array is used to store the z coordinates. The array indices for the array are the implicit columns and rows, or x and y coordinates for the (x,y,z) points. The model must have a uniform number of columns and rows, although it need not be square.

7.2.2 CBulldozer

The CBulldozer class is a subclass of CExtrusion, which is a subclass of CTool. It is responsible for performing the key algorithmic functionality for changing the elevation values in each cell in the DTM.

The most important task of CBulldozer is to evaluate whether a particular cell's elevation value changes or not, and if so, then to compute its new value and to change it. This task involves determining whether the cell in question is within the scope of an action pass of a tool. Since the end value of a cell may be influenced by whether an overlap situation exists, separate accounting must be maintained for whether a cell in question is changed by more than one "move" in the pass. If an overlap between path segments occurs, the following instance variables are arrays which create and initialize these arrays.

- BoolArray *InitStateArray(BoolArray theStateArray, int theSegs),*
- FloatArray *InitNewZArray(FloatArray theNewZArray, int theSegs);*
- BoolArray *CreateStateArray(CView* theView, int theSegs);*
- FloatArray *CreateNewZArray(CView* theView, int theSegs);*

7.2.3 CPath

The CPath class inherits directly from the CLine class, which is a CShape. Its key components are listed below and are depicted in figure 7.2:

- int *mNoPathPts* - the number of points which make up a path
- int *mPathSegs* - the number of path segments
- CBBox**mPathBB* - the bounding box rectangle around the entire path.
- CArray **mAASet* - an array which stores the active areas for the entire path
- CArray**mBBSet* - an array which stores the bounding box areas for the entire path
- eEndOp *mEndOp* - the end shape option desired for both ends of the path
- eCornerOp *mCornerOp* - the corner option for all corners of the path
- eAbsRelModem *AbsRelMode* - marks whether the path is a relative or absolute one with respect to the blade.

Like the CElevModel class, CPath is responsible for initializing, storing, drawing and reading its points in and out. In addition, it records them initially, and computes the end and corner options for itself. The overlap option at the corners is the only overlap situation dealt with in this implementation and it is handled by the corner option functionality. These scope of action functions are encapsulated within the CPath class because they are mostly determined from parameters native to it. *TSS*'s implementation if CPath only hosts paths defined by points. I.e.

no equation representations of paths are accommodated.

Figure 7.2: Example Bounding Boxes and Active Areas for CPath. The thick black line represents the path segments. The next larger box is the minimum bounding box, the second larger box is the active area, including the width of the path, and the largest box around each segment represents the minimum bounding rectangle including the corners and ends.

7.2.4 CBlade

The CBlade class like the CPath class in this implementation consists is a subclass of CLine, of the CShape class. It too is responsible for its own reading in and out, drawing and gathering and storage of blade points. In addition, it is responsible for handling its own window for display and editing. It also takes care of the location of the track point and the orientation information with respect to the path.

Member variables of CBlade include the following:

- float *mBladeWidth* - the width of the path
- int *mBladePts* - the number of blade points
- LWindow **mBladeWindow* - the window within which the blade view exists
- CBladeView* *mBladeView* - the view within which the blade functionality is displayed
- Rect *mBladeBB* - the bounding box around the blade for determination of whether the track point exists inside or outside of it.
- FPoint *mTrackPt* - the “after” location of the track point in the blade view.
- FPoint *mOrigTrackPt* - the “before” location of the track point.
- float *mTPDeltaX* - offset of the moved trackpoint in the x direction
- float *mTPDeltaZ* - offset of the moved trackpoint in the y direction
- float *mLeftBW* - for a blade which sits off center with respect to the track point, this is the width of the blade to the left of the track point.
- float *mRightBW* - for a blade which sits off center with respect to the track point, this is the width of the blade to the right of the track point.

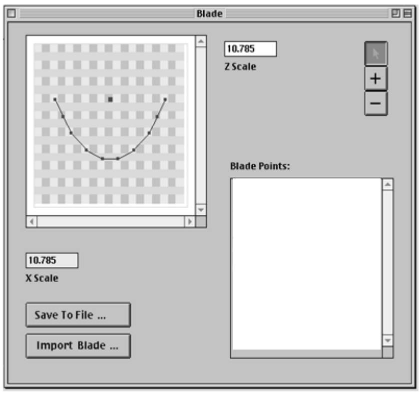

Figure 7.3: CBlade's Window. (TSS, Westort)

7.2.5 Overview of Interface with PowerPlant™ Classes

Figure 7.4 displays TSS's class hierarchy presented by the Metrowerks Code Warrior programming environment. If one follows the naming conventions for the classes, one notices how the classes beginning with "L" are PowerPlant Classes which TSS classes sub-class from. TSS built primarily on the following PowerPlant Classes to take advantage of Macintosh-specific GUI functionality[1]:

- *LDocApplication* - to have a document-based stand-alone application for the MacIntosh. This class helped issue commands that open, close and create new documents. It is also responsible for issuing the command to print a document.
- *LSingleDoc* - helped to provide the connection between an LDocument object, a single document on disk (our TAFF file containing our DTM), and a single window on screen.
- *LWindow* - for creating a Macintosh Window object for displaying the model and blade information.
- *LView* - for managing panes and sub-views and fields within a window.
- *LArray* and *LList* - Allowed for easy implementation of a dynamic list of objects of arbitrary size and takes advantage of the memory allocation and deallocation functionality. It was a primary means of storing geometric information.

1. Code Warrior® PowerPlant Book.

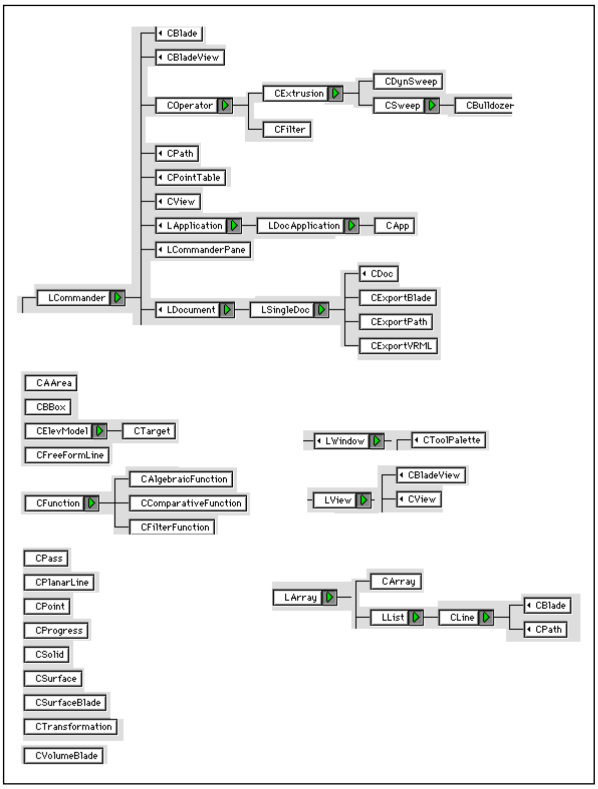

Figure 7.4: Overview of Power Plant Classes

7.3 *TSS* GUI Representation

Every component of the bonsai set of classes for the Topographic Surface System (TSS) software has a specific relationship, or set of relationships, with a GUI representation.

The CElevModel class is represented by a planimetric model in the Main Model window of the GUI. Reading the model in occurs with the Open command under the File menu, while saving versions of the model occurs with the Save command also under the File menu. Drawing the elevation model has a default cosine shaded planimetric view of the model, but other representations are possible under the Render sub-menu, where wireframe, and color-coded renditions of a model may be chosen and displayed, also in the main model window.

The GUI representation of the CPath class results from clicking of the path points onto the main model window with the mouse, where they are then connected by line segments to represent the path segments. The path may be imported or exported with the respective commands under the File menu, Import Path, Export Path. Paths may be reading from and written out to a file with these commands. The corner or end or overlap options of the path are also selectable from the Specs Menu.

The CBlade class' GUI representation consists of the Blade Window as shown in figure 7.4. A default blade has been pre-defined and is automatically displayed when the blade window is called up by selecting the Blade Window command from the Window menu. The Blade window consists of five main elements. First, there is the blade view, where the profile of the blade is displayed and the track point are displayed, and which is scrollable and zoomable. The grey grid in the background corresponds to the actual cell-size of the DTM displayed in the main model window, which is useful for judging scale. The blade profile is drawn in blue, the track point in green. Second, there is the blade mouse palette in the upper right of the window, where the user may select either an *arrow* mouse (the default case), an *add* mouse, or a *minus* mouse. These mouse options allow one to move, add or remove points of the blade, respectively. The third component of the blade window is XScale and ZScale fields. These fields exaggerate the x or z dimensions of the blade-window. The fourth component of the blade window are the *Import Blade* and *Export Blade* buttons. These buttons read in an ascii blade file, and read out the blade points to an ascii blade file respectively. Any time the blade window is open one may exercise these import and export options. The fifth component of the blade window is the Under Construction Blade Point Box, which is intended to display the blade points numerically in edit fields, but this part has not been implemented fully yet.

The bulldozer icon represents the CBulldozer class quite directly. Find it below in the Tools palette of figure 7.5. Pressing it instantiates a CBulldozer object within the program, and enables one to begin clicking a path onto the main model window, double clicking to end it, or one may elect to import a pre-defined path from a file. Once a path has been defined, one may either press the Apply button directly to change the relevant cells in the model, or opt to view the blade window where the shape of the blade may be edited, or a pre-defined one imported.

Prior to pressing the Apply button, one may also set whether the path is to behave in an absolute or relative manner by turning on or off the corresponding commands in the Specs menu. At any time after the path has been defined also one may select a corner, end or overlap option. The only end and corner options possible at this point are curved or flat ones. Once the Apply button has been pressed, the bulldozer blade is "extruded" along the length of the path according to these settings.

The next section presents a user's perspective on the functionality described so far, and how it differs from the ideal features described in the previous chapter, and complements our sculpting objectives. A step-wise summary through the tutorial is available in appendix B.

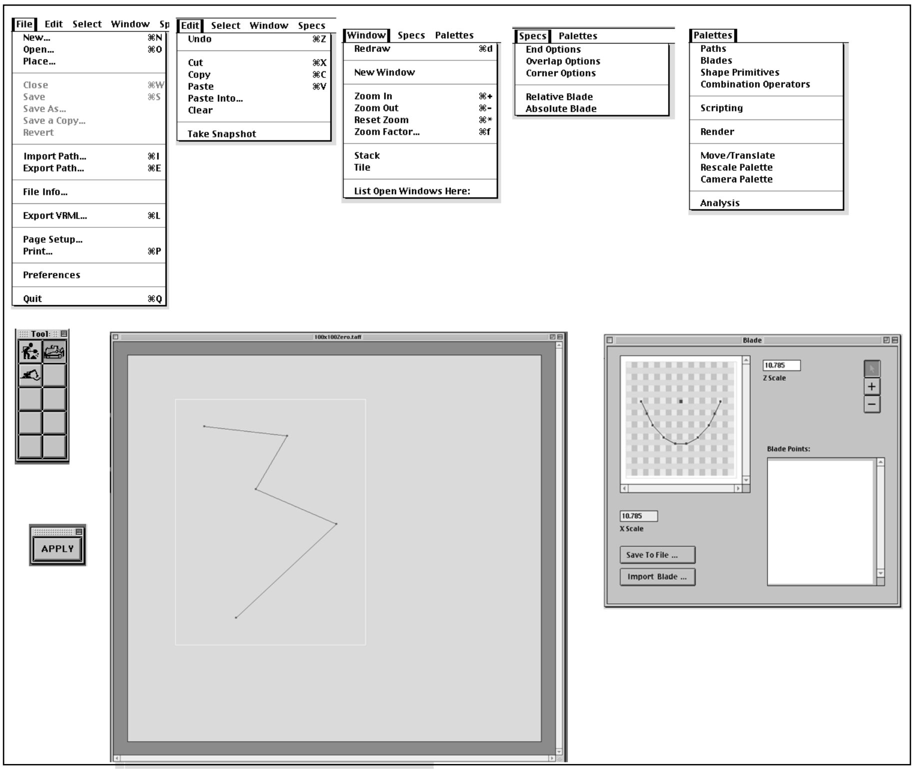

Figure 7.5: TSS Interface components.

7.4 Walk-Through of *TSS*

7.4.1 Overview

The basic idea for TSS's bulldozer is to (1) select the tool, (2) click on the screen for a path, (3) adjust the shape of the blade (optional), (4) select corner, end and overlap options (also optional), and (5) press the apply button. This loop constitutes one pass of the tool, one iteration around the design loop.

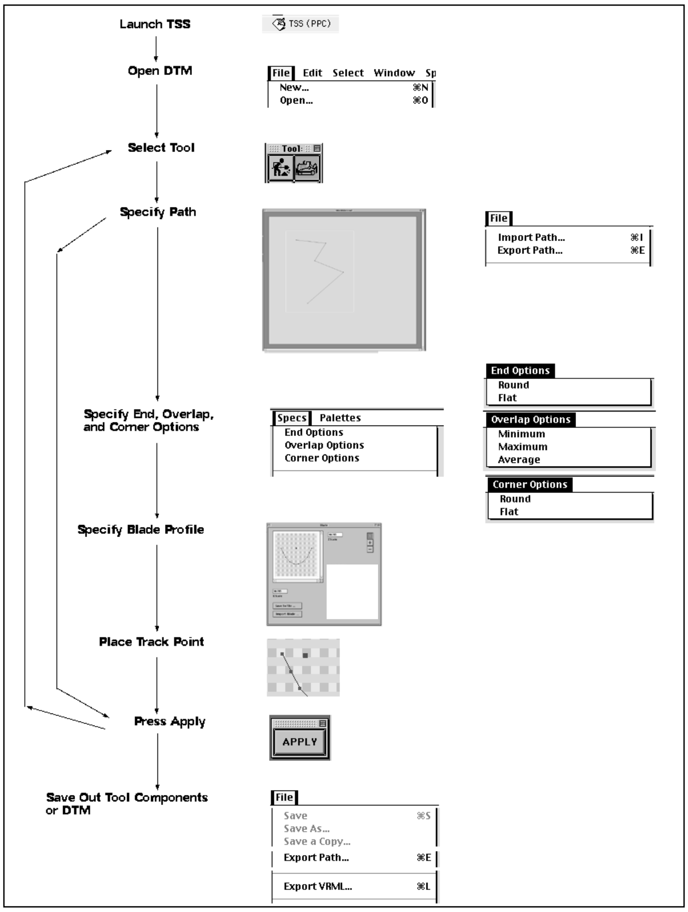

Figure 7.6: Diagram of Iterative Walk-through of TSS GUI components.

7.4.2 Launch the Application

The user launches *TSS* by double clicking on its icon. The GUI shown in figure 7.5 appears on the screen, consisting of two palettes: A tool palette, and a mouse palette. An *Apply* button also appears, and the following menus appear across the top of the screen: *File, Edit, Specs, Window, Palettes*. From these palettes the only buttons which are functional are the bulldozer button and the *Apply* button.

The next step is to load in a DTM by selecting *Open* from the *File* menu. A DTM file in the *TAFF* file format may then be loaded in. Its plan view is immediately displayed on the screen. The user then selects the bulldozer tool by pushing the *Bulldozer* button. *TSS* then waits for definition of a path.

7.4.3 Path Definition

There are two ways to define a path in *TSS*. The easiest way is to simply click with the mouse path points onto the DTM target surface, double clicking to end it. The points and lines connecting them are drawn as the points are clicked. The other way to specify a path is to import one from a file by selecting *Import Path* from the *File* menu. A path file is simply an ascii file containing a list of points. Importing a path in this way loads it in and displays it on the target DTM surface. Once defined, the path may be exported to a file by selecting *Export Path* from the *File* menu.

Once the path is defined in this way, the user may wish to either select the *Apply* button directly, or edit the default blade definition. The next section describes the blade editing option.

7.4.4 Editing Blade Shape

Anytime after the bulldozer tool has been selected, one may choose *Blade Window* from the *Windows* menu. The blade window as depicted in figure 7.3 appears. To move a point, select the arrow mouse and click and drag the blade to move to its desired new location. The point may only be moved within the area between the two adjacent points. This is so there are no overhangs in the blade profile so as to be consistent with our 2.5 dimensional criteria. To remove blade point, select the minus mouse button and click on the blade point to remove. It will disappear and the line segment re-drawn between its two adjacent blade points. To add a blade point, select the plus mouse button and click anywhere in the blade view for placement of the new point. Once clicked, the adjacent points will draw connecting line segments to the new point placed between them.

7.4.5 Track-Point Placement

The *Track Point* is represented in the Blade Window and is drawn in green. It is the point along which the blade is extruded along the path. TSS places the track point by default at the center-line of the blade shape, so that it is a “cut” blade. Clicking and dragging on the track point will re-position it anywhere in the blade view. The track point must lie within the bounding box for the blade shape. *TSS* does not yet correct for the case where a track point is placed outside of the bounding box for the blade shape.

7.4.6 End Options

TSS implements two end options: round and flat. The default is flat. To change the end options one needs to have the main model window front-most, and before selecting the *APPLY* button, select the desired end option under the *Specs* menu, *End Options* sub-menu. The round end option does not work for a track point placement which is not centered.

7.4.7 Corner Options

TSS implements two corner options: round and flat. The default is round. To change the corner option one needs to have the main model window front-most, and to select the desired end option under the *Specs* menu, Corner *Options* sub-menu.

7.4.8 Overlap Options

TSS implements three overlap options for the kind of overlap option that occurs between consecutive path segments described in section 5.4.4 (region b in figure 5.12). The options work only for a track point centered with respect to the blade profile. The three options are: *maximum*, *minimum*, and *average*. The default is maximum to correspond with the default track point positioned at the top of the blade profile shape. To change the overlap option one needs to have the main model window front-most, and before selecting the *APPLY* button, select the desired option under the *Specs* menu, *Overlap Options* sub-menu.

7.4.9 Absolute & Relative Path Behavior

Absolute or relative path behavior has been implemented for the entire path, i.e. options a and c in figure 5.4. Therefore, individual points may not behave in a variably absolute or relative manner. The default mode is relative, but once the path has been defined, one may switch to an absolute path mode by choosing *Absolute Path* under the *Specs* menu.

7.4.10 The APPLY Button

At anytime in this process the user may press the *APPLY* button to have the extrusion/bulldozer functionality use the current blade shape along the path.

7.4.11 Saving the DTM

Choosing *Save* or *SaveAs* from the *File* menu writes out a *TAFF* file of the *DTM* displayed on the screen. If elevation values have changed, it is the newly modified model which is saved.

7.4.12 Other *TSS* Visualization functionality

TSS offers additional functionality for visualizing the surface. In addition to standard zooming in and out functionality, the following representations are chooseable from the *Render* submenu under the *Palettes* menu: *lambert shaded greyscale wireframe* (see figure 7.7-a below), and *isopleth greyscale coded* (see figure 7.7-b below). It is possible also to export a *VRML* file for three-dimensional viewing and fly-through. Examples of these are shown in figures 5.5 and 5.6.

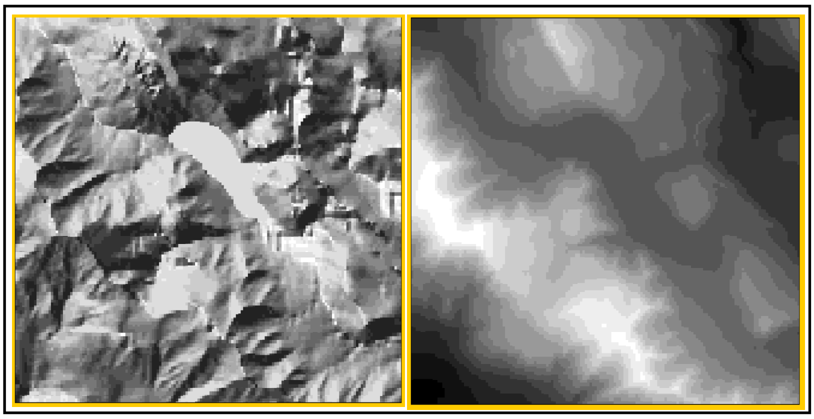

Figure 7.7: Other TSS rendering options. (a) cosine lambert shading (the default case, (b) isopleth greyscale coded. Dataset is of Albis, Switzerland (courtesy of Federal Office of Topography, Berne)

7.5 Other Desirable Features

The features presented in this section are desired functionality, but have not yet been implemented.

7.5.1 Primitives Palette

A primitives palette would contain five sub-palettes: Craters, Mounds, Berms, Swales, and Other. They would be derived from principles of concavity and convexity, where the Craters and Swales palette would be concave, and the Mounds and Berms would be convex. Craters and Mounds are point-based primitive features, and Banks and Swales linear ones. Under each shape icon, sub-palettes could unfold when a respective button on the Primitive palette is pushed.

One way of organizing the collection of primitives under each individual sub-palette could be to have the six methods for deriving the forms represented. They are: formulaic, revolve, skin, extrude, fractal, bump-maps.

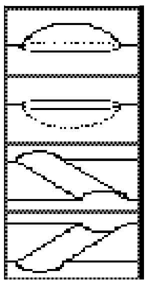

Figure 7.8: Primitives Palette Example. Mounds, Craters, Berms, Swales.

7.5.2 Path Palette

There would have to be a display method which offers the user opportunities to select pre-defined paths.

7.5.3 Editing a Path

The user would be able to perform transformation functions to the entire path or individual path points. These features would include rescaling, rotation, translation, changing between absolute and relative mode for the entire path or individual points, deletion and addition of points.

7.5.4 States Window

States window would be chooseable which would display different shapes along desired intervals of the path. The different shape's relationship to the path, their Orientations, would be adjustable at these intervals. The intervals need not be regular, and the use may click these locations onto a path via this window.

7.5.5 Scripting

Scripting functionality would record a series of moves and passes, together with the shape characteristics of such moves, so that the entire assembly may be edited, reproduced, or "replayed". There may be global changes to these assemblies as well. For example, the entire suite of moves may be re-scaled, or rotated, moved, or edited. It would work via recording of a session. Starting, pausing and stopping a session would be selectable from the menu, under. Once start is selected, all subsequent user actions would be recorded to a script.

7.5.6 Section tool

This tool would take two clicks on the plan model and display them in the section window. Numerical entry and scroll bar adjustment for exaggeration in the z value would also be reflected here.

7.5.7 Slope

The slope tool would work similarly to the section tool. By taking two clicks and calculating the slope between these two points. The method for calculation may be set in a preferences dialog box.

7.5.8 Report tool

This tool would report on the elevation value at the mouse location at all times. Double clicking would also report on the parameters of the target model.

7.6 Conclusion

This chapter described the prototype implementation of the generic tool definition described in chapters 5 and 6 in the form of the TSS software. In summary, the virtual bulldozer prototype was selected as an example which possesses all of the primary tool components, including a likely metaphor for topographic change, which is the bulldozer itself. Other essential characteristics were the abstractability of its behavior to the simple blade and path representations. This implementation essentially provides algorithms for converting between these two line representations and a surface, and in so doing qualifies TSS as a legitimate sculpting tool. That two seemingly different graphic representations of terrain, a simple line blade and a simple line path, may be formally equivalent is very powerful. First of all, their simplicity is in fact different from most other methods which do not operate on such intermediary representations and via conversion algorithms, but which rather concentrate directly on the underlying data, i.e. they couple closely with the external representation desired. The pure simplicity of the alternative offered here is both different and advantageous in its very straightforwardness. Demonstrations of the range and simplicity of these attributes are presented in the next chapter, where these representations and algorithms are applied to known topographic manipulation tasks.

It is also important to note here how this TSS implementation of the virtual bulldozer differs from the author's previous work on the topic. First of all, the digital functionality was not achieved in the same way. An object-oriented solution was used in this case, which allowed the simple blade and path idea of Ervin, Westort's earlier work to be generic, and therefore more universal in its scope and extensibility. While the first virtual bulldozer implementation explored the notion of a blade and a path, their significance as multiple representations which appear dissimilar but which are geometrically equivalent was neither discussed nor developed further in the first version. The simple approach introduced by that experiment called for a much broader inquiry and an inventory of and argumentation link with traditional sculpting precedents in order to provide a generic tool definition with universal robustness. Its clear directions for extensibility were also not thought through as thoroughly as the conceptual definition provided in this thesis.

Chapter 8: Example Applications of the *Topographic Surface Sculptor (TSS).*

8.1 Introduction

This chapter evaluates the tool definition and its implementation with some example applications of it. First some examples of complex form are presented and discussed. Second, its utility for some typical landscape specific tasks is illustrated. Third, its application to a landfill site design project is described.

8.2 Example Applications of *TSS*

a) Ziggurat

An example of a simple form commonly desired as a landscape feature is the ziggurat. It is a small mountain or hill consisting of a spiralling ramp to its top. To sketch it is quite easy, indeed Morrish (1996) offers several convincing ones. To represent a ziggurat quantitatively accurately, however, on paper one would require a relatively sophisticated contour line abstraction. Digitally, without a pre-parameterized approximation of the entire shape, existing software would be hard-pressed to represent the form also without contour line. And manipulation of the form, to change it slightly or wholly would require another whole iteration of contour line redrawing or re-sampling.

Figure 8.1 presents two versions of a ziggurat produced by *TSS* which illustrate its advantages. To produce the form, all one needs is a spiral path and a blade profile, and TSS will extrude the latter along the former to produce the form. Two lines represent a very complex three-dimensional form. And modifying the ziggurat is quite easy. To make a ramp with a more rounded character, one need only modify the path shape, and using the same path, produce a ziggurat with quite a different character.

It is very easy for users to perceive the resultant three-dimensional geometry of a form simply from its simple parts. In this way, the blade and path may represent a kind of three-dimensional sketching in three-dimensions. Trial and error with tweaking different blade points or entire blade or path modules is very straightforward. Iterations may be saved, and copied and adjusted very simply, and iteration of their combined results may occur simply and in an intuitively straight-forward manner. Such possibilities start to sound more and more like a new kind of sculpting, one which takes advantage of natively digital possibilities.

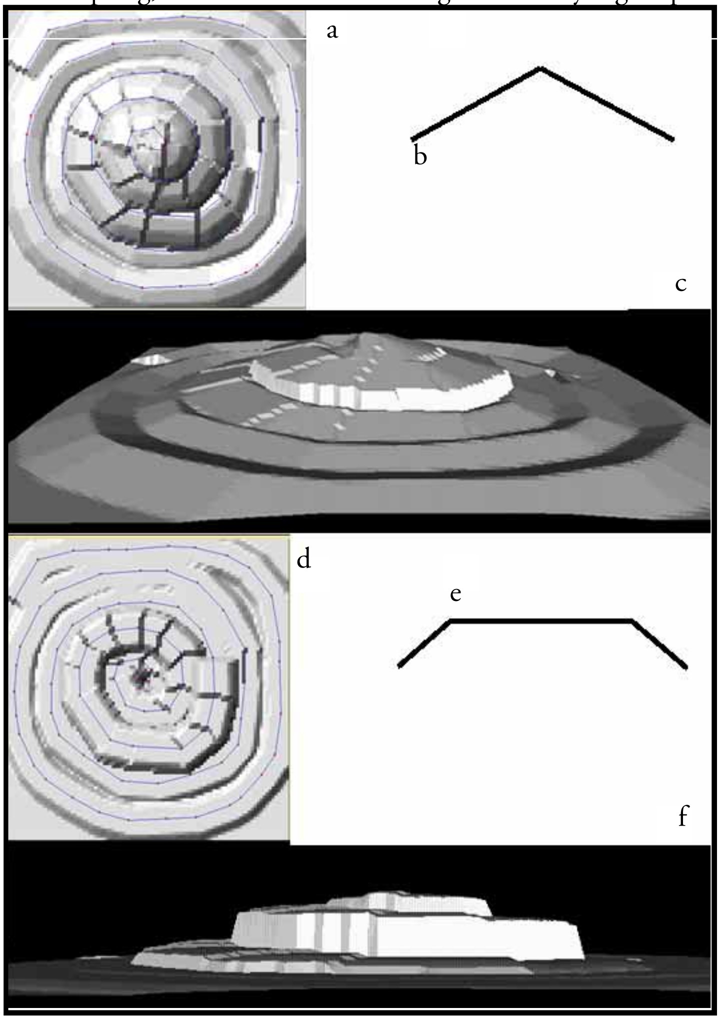

Figure 8.1: **Ziggurat example.** *b* and *e* represent alternative blade shapes. For both blades, the path is a spiral line shape. *a* represents the blade *b* extruded along the spiral path. *c* shows this pass in perspectival view. *d* and *f* represent the blade extruded along the same spiral path. The example illustrates how with only a very simple change to a linear blade profile, significantly different three-dimensional geometry may result.

b) Mill Creek Canyon Park (designed by Herbert Bayer, modelled in *TSS*)

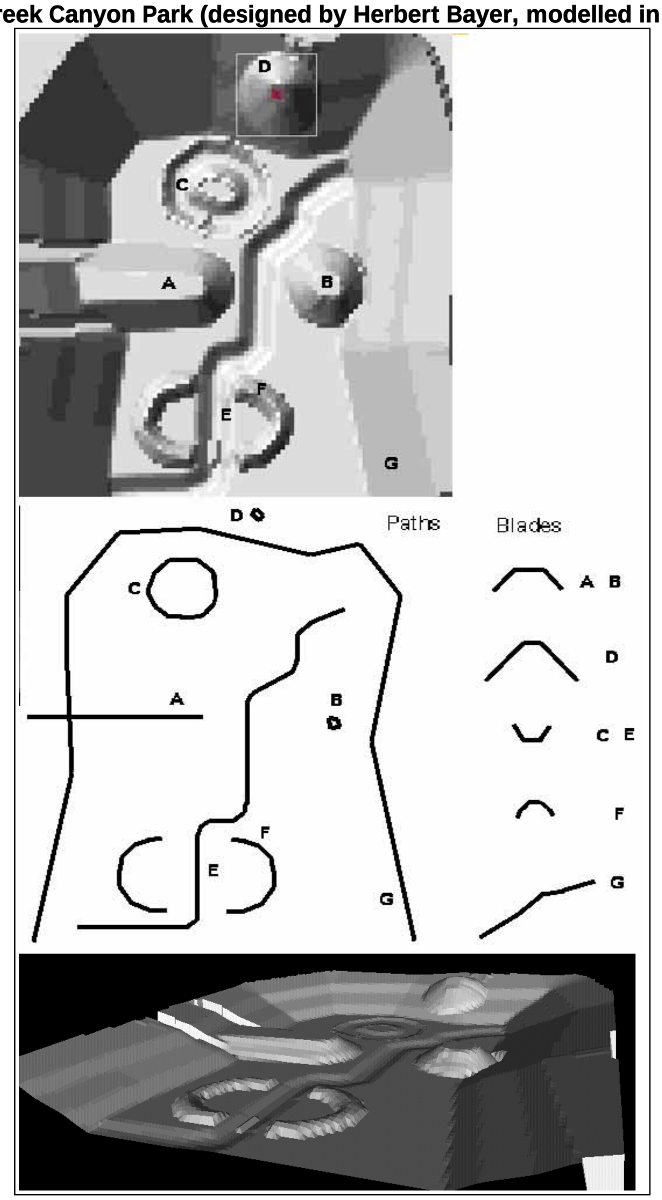

Figure 8.2: **Mill Creek Canyon Park Example,** represented by TSS. The set of line paths and blades represented in the lower half of the image were computed by TSS into the continuous surface geometry shown above. The column of blade shapes indicate which path they were used along. For example the first blade was used for paths A and B. The example illustrates how a set of simple lines may represent a quite complex three-dimensional surface form. The perspective view is a VRML file exported from *TSS*.

Please refer to our discussion of the parameterized primitive approach to sculpting in chapter 1. The example of the Mill Creek Canyon Park illustrated in figure

1.4 shows the disadvantages to a purely parametric primitive approach to designing a surface continuously. Here is a quick TSS version of the same space, achieved with the set of simple line arrays and blades illustrated above. Figure 8.2 represents how a quite complex outdoor space may be designed and represented with the *TSS* system. Discrete landforms A-G in the figure are representable with simple path and blade forms. Topographic and landscape designers are able to do many trial and error iterations with formal elements of the surface in an immediate and direct manner.

c) Standard Tool Behavior

Individual tool behavior of rakes and shovels, for example, as discussed in chapter 2 may be represented by TSS as well. Figure 8.3 shows how a blade shaped like a rake, run along a simple circular shape may approximate the gravel pattern designs standard in a Japanese garden, for example. Figure 8.4 depicts how a shovel shape may be approximated, which if extruded along several simple line segment paths may approximate the real behavior of a shovel digging a hole.

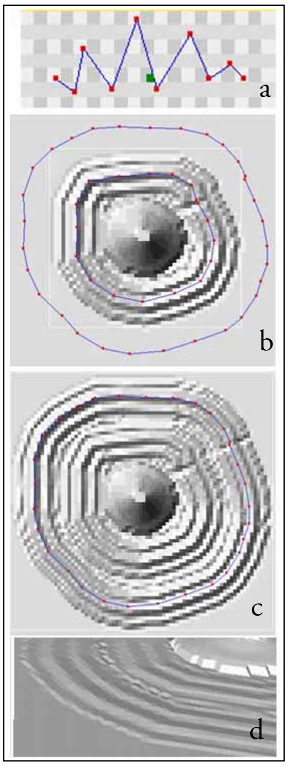

Figure 8.3: **Rake Tool Example.** *a* is a planar line shape with "teeth" similar to what a rake or plow would have. *b* shows in plan one of the two concentrically placed circular paths along which the blade passes. *c* shows the result in plan of both circular paths extruded with blade shape *a*. *d* is a three dimensional VRML close up of the surface. The example tries to illustrate how the topographic geometry of traditional construction and agricultural equipment may be achieved with the blade and path abstraction offered by *TSS*.

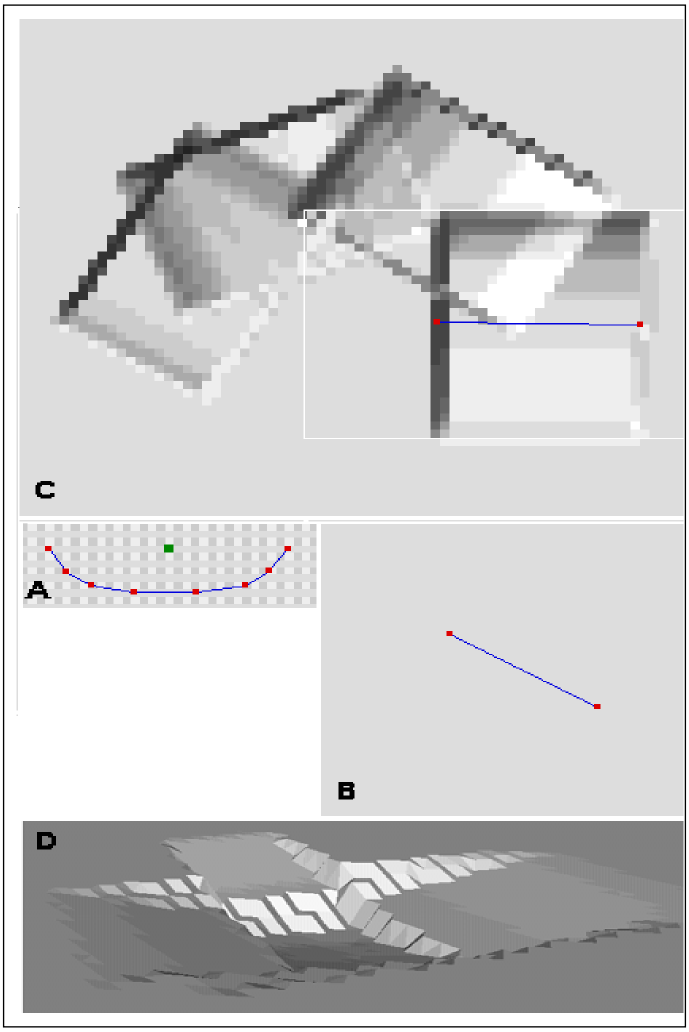

Figure 8.4: **Digging a Hole Example.** The blade shape A together with consecutive linear path shapes like B may be converted to a surface geometry as presented in C, which in perspectival view looks like D. The example tries to illustrate how a the geometry resulting from digging with a simple shovel tool may be convincingly represented as a set of blade and path lines by TSS.

The above two examples are intended to illustrate how TSS, and the intermediate blade and path representations of the three-dimensional geometry they are equivalent to, may convincingly represent landform tool and expressivity available in the “real-world” or landform construction as discussed in chapter 2. Not only may the actual geometry be duplicated with the simple blade and path geometry used to construct it, but such intermediate representations of the three-dimensional surface are not available in non-digital environments. Herein lies the desired geometric control and multi-dimensional expressive power sought after by sculpting.

8.3 User Feedback & Evaluation

Landscape architecture students at the Hochschule Rapperswil pre-ßeta-tested the software for a landfill design studio conducted in December, 1997 through February, 1998. (In German entitled, “Deponieplanung, Oberholz”) Eight teams of three members each participated in the studio. Three teams elected to utilize digital technology in their projects.

8.3.1 The Project – Existing site

The site is located at the intersection of the four communities, Buchs, Suhr, Gränichen, and Hunzenschwil in Oberholz, Kanton Aargau, Switzerland. It lies tangential to Autobahn A1 and has been designated by the Kanton to receive 2.8 - 3.5 million cubic meters (gross volume = the difference between the existing and proposed terrain) in deposits of 50,000 cubic meters per year. Figure 8.5 displays the existing topographic condition of the site. The task of the students was to design both how and where the site is to receive this quantity of waste material.

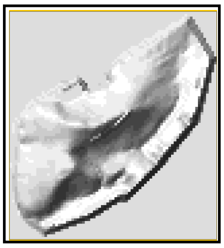

Figure 8.5: Oberholz Deponie, existing topographic conditions. Cellsize 20m.

8.3.2 The Process

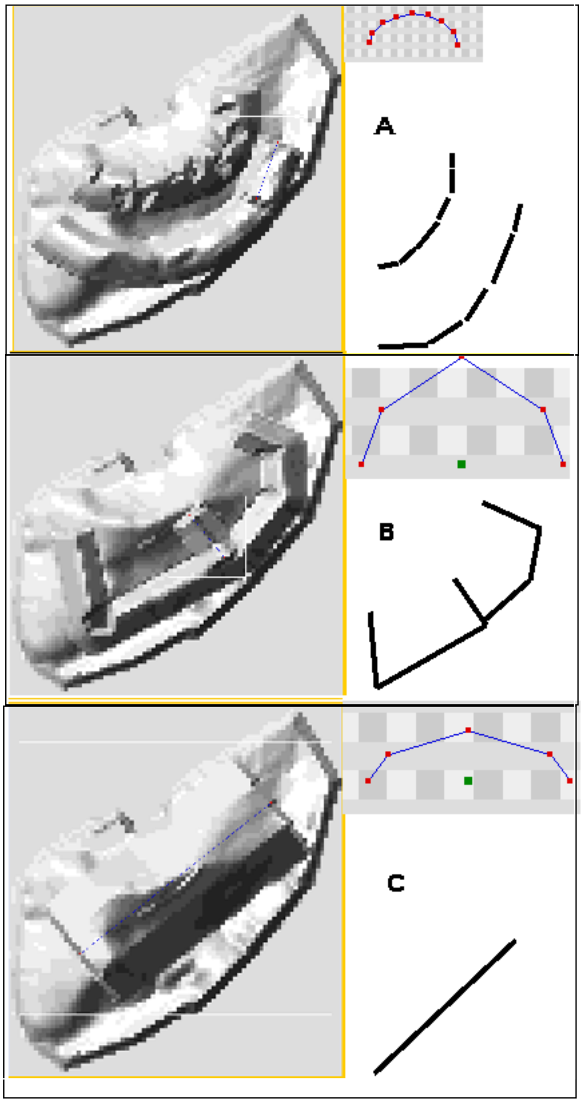

Figure 8.6: Deponie Oberholz TSS User Results. Team A, Team B, Team C, respectively.

The primary intentions behind using software at all on the projects were for analysis and visualization objectives. The product Softdesk® by Autodesk, which is an add-on module to AutoCAD was used by all three groups to calculate cut and fill volumes.

8.3.3 Interaction with TSS

It was decided early by all groups that without some essential functionality TSS would not be fully useful except as a topographic exploration tool. Instead, it was tested out early on in the deposit as a visualization mechanism of the proposed schemes of the various groups. All three groups worked out their solutions on paper before approaching the digital tools. They then digitized in their proposed plans and directly computed the cut and fill volume calculations. In general, all teams utilized TSS towards the end of their design processes to visualize their single solution, versus as a sculpting for exploration means as hoped. Feedback on the tool from the individual groups was nevertheless very helpful and valuable. It is reported on below.

a) Team B

This team was the most committed to working in digital media for the entire project. They tried out TSS at several stages. The first two images in figure 8.6 below represent their first attempts to use it. The first image shows how they did not adjust the blade shape to be an "add" blade in the Blade window, so their swatch through the site is a cut instead of a fill. Also, the width of their blade is too thick for their intentions, and on both the first and second images, the site boundaries are overshot. Later on just too "play around with it", they took up with TSS again to see if they could visualize their final topographic solution which they had already modelled in AutoCAD with contour lines. The second two frames in figure 8.6 are the results of this effort.

The comments while using TSS consisted of the following:
- "The blade's too fat."
- "How do you get a skinny blade?"
- "What if I move the track point down here." (TSS crashed.)
(after re-start)
- "How do you get it to be smooth in there" (pointing to the intersection between the two moves."
-"I need a thinner blade."
-"I'll try it again later."
(later)
- "Is there a cut and fill tool?"
- "The track point keeps moving..."

Team B used the last image as in their final graphic presentation only as an auxiliary sketch. They made a print out.

b) Team C

The second team's interest was to build a single form, like a mesa, on top of the site. They drew their scheme manually with contour lines, digitized them in and computed axonometric views within AutoCAD. TSS was used only once and briefly with one sample blade shape and a path consisting of two end points only.

The users were not satisfied with the image, and ultimately did not use it in their final graphic presentation to the design jury. Their feedback on TSS was nevertheless valuable. Their live comments while using the software consisted of the following:
- “We need another window to design the ends.”
- “Round and Flat ends aren’t enough for us.”
- “I wish we could do the cut and fill in here [the TSS software], so we wouldn’t have to use Softdesk at all.”
- “Can you fly around in here?”
- “Oh, so you have to go to Netscape on the NT to fly around? Ok, forget it.”

c) Team C

This team was very successful with their visualization objectives in AutoCAD and tried out TSS only “for fun”. Their comments:
-”It’s not exact enough”.
-”It looks like two hot dogs instead of what we want.”
- “How high is it there?”

8.3.4 Summary and Conclusions

From the above collection of “live” comments to the software use, one can easily conclude that the software remains a prototype which needs more refinement, and more analysis functionality, e.g. cut and fill calculation, profiling, and spot height reporting as well as more extensively integrated three-dimensional visualization functions. Such integration would enable faster times between constituent parts of the software so that users may be inspired to conduct more iterations with the tool. Significant is that being limited to before and after views did not seem to be disadvantage to the users.

The key point is that the users did “intuitively” grasp the relationship between the blade and path abstractions of their desired three-dimensional forms. Their modelled project results together with their comments are also testimony that many iterations were tried by each group, and that the iterative design loop, so essential to the creative process, remained intact in the digital environment. Although the look and feel of the “tools” were different from traditional sculpting, the students were in fact able to use iterations of the *tool*, in *multiple dimensions, expressively*, upon a digital *material* using *methods* provided by TSS. These results were possible despite that the software is in its infancy as a prototype proof-of-concept software, and that it remains unstable and incomplete.

Chapter 9: Conclusions & Outlook

9.1 Conclusions

This study allows for two different kinds of conclusions: First, on the implications of sculpting as an activity, and second what the specific implementation and experiment conducted in this project teaches us. To summarize, the thesis offers an argument for, and presents a demonstration of, how two seemingly different graphic representations (blade/path and surface) of terrain are formally equivalent, and how when they are coupled with a data structure and computer algorithm (extrusion) for converting from one to the other, new kinds of sculpting and ways of thinking about form may be undertaken in the digital environment.

To comment first on the implications for sculpting in general: This thesis argues that sculpting in the most basic sense consists of *tools*, *material*, and *methods*, and involves a feeling of *expressive geometric control* over geometric form in several dimensions. The notion of material may be thought of as either the tactile "stuff" that is sculpted, or a representation of that "stuff". In the latter case, digital surface representations possess both internal and external representations. Internal surface representations typically take the form of points, lines, grids, or triangulated regular or irregular networks. External representations may take a broad range of forms depending on the desired visualization; forms like planimetric or perspective views, cross sectional profiles, or animated fly-throughs. Alternatively the external output may be shaded, texture-mapped, wireframed, consist of either a subsection of the model, or the whole thing, or the output may be a remotely controlled actual bulldozer running on site in the field. The important point is that there need be *no correspondence* between internal and external digital surface representations. This distinction frees one to consider how to achieve the expressive geometric control on *alternative internal digital representations*.The case for blade and path representations functioning in this way has been made here.

The driving idea is that two lines – one for a blade and one for a path – when taken together are an alternative mathematically (i.e. geometrically) equivalent representation for a three-dimensional surface. This abstraction is uniquely suited to the digital environment, for computers are easily programmed to produce a surface out of two lines. The strength of this alternative rests with the realization that two lines extruded against each other may produce *any geometry*. And as we establish in chapter 4 – that a sculpting tool is actually a thing which functions as a *conduit* between different geometric representations – this finding means that methods offered by a software program to perform this conversion offer to the user an altogether new kind of *tool*. It is a software tool, and one that is tailored to sculpting surfaces. In addition to the conversion functions it performs, such a tool allows one to work in an iterative fashion. A user defines the parameters of the blade and path linear elements, applies them, the conversion to a surface is performed, only for the user/sculptor to then revise and apply the tool again. This iterative cycle occurs in keeping with a creative process we associate with design and artistic endeavors where trial and error and freedom of expression take precedence in the generation and manipulation of geometric alternatives. That this is achievable from the editing of simple line definitions is powerful in its simplicity and compactness, and it is therefore novel.

The statement that the extrusion of two lines may be translated into any surface geometry is a strong claim worthy of further comment. This thesis has demonstrated that modularly changing the intermediate linear representations of a "blade" and a "path" can both mimic known geometry achieved from earthwork construction equipment, i.e. equipment that works on actual earth, and it can also mimic changes traditionally achieved with representations of landform, like contour lines. That shovel and bulldozer marks can be generated and changed, as well as the complex geometry of topographic landscapes like a garden or park is itself novel. That these geometric options are available from a simple, and "intuitively" simple to understand modular and compact form is new and powerful. No longer is the three-dimensional geometric change tightly linked to the desired end output representation. It is far simpler to manipulate two simple lines than the end surface itself. A "translator" between the modular lines and the surface is all that is necessary to achieve the resultant surface – a task algorithmically achievable.

Editing two lines in order to generate a surface is an abstraction which may be conveniently linked with terrain analysis interests – another task computers are well-suited for. Cut and fill calculations, for example, may be performed on the "blade" and "path" representations intersected with the resultant surface. Insuring desirable constraint conformance, to slope say, or to drainage conditions, is also much more easily achieved when working with the intermediate linear representations of surface than the cumbersome end surface data structure. Several analytical and domain-specific parameters may also be addressed via this tool representation. The mathematical and temporal equivalence the tool offers lend itself nicely to such tasks as cost assessment, manufacturing efficiency, construction sequencing, among other issues. This potential identifies a suite of technical and research directions in which the work could proceed. Optimization of domain-specific tasks is a primary one.

Thinking about sculptural form in terms of modular intermediate representations of two lines also raises important theoretical questions about what sculpture, and sculpting, is. The issue discussed in chapter 3 as to whether a modelled work of clay which is ultimately cast in bronze is itself a work of sculpture, or whether only the end bronze product is, raises parallel questions here. When translating between linear to surface representation, where does sculpting occur? And what is the sculptural product – the lines? Or the surface representation? Or is the sculpture the built landform which comes later after a conversion between digital to on-site built form? Can there be sculpting without a sculpture? Is the translation of lines to surface an act of sculpting? Or is the editing of the lines the only geometry-determining step? What role does the translation process play between the different representations? Where does the corner, end and overlap options as formalized and prototyped here with TSS figure in the geometry-determination since they are bundled with the conversion functionality between line and surface representations?

The *Topographic Surface Sculptor* (TSS) software prototype provides (1) line definition and editing capabilities for the blade and path, and (2) translation functionality between the line path and blade representations and a gridded surface representation. Within a sculpting session with TSS one may experience several iterations with the sculpting tool, where an iteration includes the editing *along with* the translation methods. In this way, the software functions as a geometry-determining conduit both between representations – both its intermediate states (the lines) and the ultimate surface geometry desired. This two-tiered approach to sculpting is the primary conceptual contribution this thesis makes to the sculpting scene in the broadest sense.

As for conclusions we may draw from our specific technical prototype implementation, *Topographic Surface Sculptor*: That TSS was implemented in an object-oriented manner complements the tool's simple conceptual design. It allows for extensions and enhancements. The major algorithmic lessons learned concern the corner, overlap and end issues resulting from the extrusion algorithm between the blade and path lines. The formalization of the complexity at these junctures offers the potential for further coherent methods to be developed to more closely govern surface model-fidelity.

The current state of the software outfits the CElevModel class to function primarily with a raster representation. This class is kept deliberately distinct from the CTool class so that other data structures (like TIN's) may expand the CElevModel class' functionality without impacting the core extrusion code of the CTool class. This suggests itself as a rather immediate next step to take.

As for the *Metrowerks CodeWarrior Programming* environment for the *Macintosh*, the *PowerPlant* class library proved sufficient to accomplish the objectives of the prototype software. For further enhancements regarding performance and efficiency concerns, an environment more tailored to three-dimensional output would be called for. Fortunately an abstraction barrier has been maintained between that functionality specific to the programming environment and the essential functionality necessary to port the code to another platform.

9.2 Outlook

There remain several conceptual and technical directions in which this study may proceed. Conceptually, the study would benefit from inclusion of more in-depth coverage of the history of sculpting theory, including the latest writing on post-modernist deconstructivist trends. Also to include work on the role of the sketch, sketching processes, and their role in the translation between sketching and ultimate three-dimensional realization of form could greatly enhance the theoretical argument presented here. Linking such developments in art history and art theory with more in depth coverage of the history of topographic representation in cartography, the history of civil and excavation engineering, and military research would also add insight and help one extrapolate more smoothly trends to the digital medium. Identification of such trends would also be quite useful for predicting and initiating future directions for the technology.

Implementation-wise, the class breakdown as formulated offers several new directions in which the technical work could progress. As already mentioned, an expanded repertoire of DTM data structures would positively enhance the flexibility of the tool. Development of these to complement greater real-time performance and more immersive interactivity would greatly enhance the tool's utility. Optimization of these characteristics towards "level-two" domain-specific tasks, like road-building, or reservoir construction, would also expand its practical utility. Empirically testing and evaluating these enhancements would help quantify its real value. One effort in this direction has already been attempted by Plazanet, 1998.

In addition to modelling tasks, it would also be very interesting to expand the functionality to simulate environmental effects and natural occurrences. The natural three-dimensional geomorpholgy of the landscape would also be useful to expand the currently spare population of the topographic primitive library. Systematizing how to parameterize such primitive three-dimensional forms would be very valuable. Similarly, library palettes of standard, or "most useful" blades and paths would come in quite handy. Interfacing with photogrammetry and remote sensing applications and other relevant application software would greatly augment TSS's existing capabilities.

APPENDIX A: Implementation Details

1 Internal Step-Through

This section describes *TSS*'s internal sequence of actions between selection of the bulldozer icon on the Tools palette to the pressing of the *APPLY* button, and the post-*Apply* button sequence of actions for changing the elevation values of individual cells in the raster DTM.

1.1 Selecting the Bulldozer icon to pushing *APPLY*

User selection of the bulldozer icon instantiates an operator object in the class, COperator. COperator simultaneously instantiates an empty path and a default blade object. The program waits for definition of a path at this point. The user may then click a path on the main model window. These clicks are received by CView's overridden ClickSelf() function, which tells CDoc's HandleAction() function to inform CPath() to handle its own path point clicks. The CPath class receives and stores these points in a path array, and draws them on the screen. When a double click registers an end to the path, the *APPLY* button is activated. At this point, one may either press the *APPLY* button directly to utilize the default blade that was defined upon the blade's initial creation, or one may edit the blade in the blade window.

For the latter case, the Blade Window is selected from the Window menu. The CDoc class receives the command to open the blade window and sends this command to CBlade. CBlade is responsible for handling the command by appropriately opening the window and its corresponding view and drawing the blade. The CBlade class also handles the click and drag functionality for moving, adding and removing points in the blade. It updates the other classes of the changed status of the blade if such a change occurs.

1.2 Post *APPLY* – Changing Cell Elevation Values

At any point the user may press the *APPLY* button, and the CDocument class calls the DoApply() function in COperator. COperator delegates the command to the CBulldozer class which overrides the function with its own DoApply() function. DoApply() conducts the following series of actions to first, determine whether the cell is one that needs to be changed, how many times (whether there is an overlap situation, and computes the new value of the cell.

1.2.1 Is the cell one to change?[1]

For every cell in the minimum bounding rectangle of the entire path,
check all of the segments in the path,

Create 2 one-dimensional arrays as large as the number of path segments for the entire path: A state Array, and a Z-Value array.

Is the cell within the active area for a segment?

If no, ignore.

If yes, place True in the state array for that segment.

Once all of the path segments are selected, go back through and count how many segments the cell falls within. If more than one, an overlap situation exists, and so the OverlapOp() function handles this situation.

Assuming no overlap situation, and that the cell lies only within one segment, compute a new value for this cell.

1.2.2 If so, compute new value for the cell

For each line segment, each X, each Y
Compute distance along path line segment
Interpolate the bladeZ between startZ & endZ.
Compute the blade distance perpendicular to the path
BulldozerZ = interpolated blade Z value at the cell's XY
    (Repeat combination operator as above)
FinalZ = newZ combined with bladeZ
    NewGrid[X Y] = FinalZ

2 Development Environment Specifics

As discussed in chapter 6, the object-oriented paradigm was chosen for implementation because it allows abstract data types (*classes*) for "high level" and hierarchical approaches to a problem. It also avails "real-world" and intuitive strategies for abstraction through the notion of an instantiation of a class, i.e. *objects.*

2.1 C++

The programming language *C++* was selected because it is flexible, standardized, and powerful. There are also an abundance of class libraries available in C++. It

1. This algorithm developed in collaboration with Bernhard Schneider, Ph.D.

is moreover a professional, sufficiently standardized language. There are also several application frameworks supporting C++ available to choose from[2]. It was selected above the alternatives *Pascal*, *Lisp*, and *Java* largely because of the limitations they entail. *Pascal*, for example, does not support multiple inheritance. *Lisp* would have been a good choice except there were no robust class libraries available to take advantage of and the another programming environment would have been necessary to purchase to support it. *Java* has memory management limitations, together with speed and efficiency tradeoffs. These reasons, together with that it remains an un-standardized language made it an inferior choice for our needs here.

2.2 Macintosh™

The Macintosh platform was selected largely because of its ready availability and that it possesses a famously straightforward and user-friendly GUI implementation. Because user-interaction with the software is a high priority for this project, this was a major consideration. The disadvantages include difficulties with portability to other platforms and the transferability of data models. These were deemed to be outweighed by the advantages.

2.3 *Metrowerks Code Warrior™* Programming Environment

The Metrowerks Code Warrior[3] programming environment has been the market leading development environment for programmers of the Macintosh for five consecutive years. This is due mainly to their convenient and robust Power Plant Class library. In addition to platform specific stationary projects from which one may begin, it's possible to very quickly generate a stand-alone double-clickable application with menus, scroll-bars and palettes very quickly. It was also chosen because it was available and inexpensive, and there are other colleagues using it, and good on-line assistance offered.

2. Oualline (1995)

3. Sydow (1995)

APPENDIX B: TSS TUTORIAL

BASIC WALK-THROUGH of FEATURES:
----
* Launch the application

* Open a TAFF datafile
The 100x100Zero.taff file is a blank model 100 pts x 100 pts. (recommended for this tutorial)

Using the Bulldozer:
----
* Press on the Bulldozer button icon

* Click a path on the model, double clicking to end it.

* Press the APPLY button

* Notice the debug graphics displayed with the affected points drawn in different colors.

* Type ctl-D, or choose Redraw under the Window menu

* After image refresh, notice the corners are smooth.

Edit a Blade:
----
* Type ctrl-B to see the'Blade Window' or choose Show Blade from the View Menu. The grey squares in the Blade View are for scale and represent the grid cells of the model. The scales of the grid may be changed in the XScale and ZScale edit fields.

* Notice the default blade shape drawn in blue, and the'Track Point' drawn in green. The Track Point is the point along which the blade is extruded along the path. Since its default location is top center relative to the blade, the blade is a'cut' blade. Also, it is a symmetrical blade.

* Clicking and dragging on a blade point will move its location to anywhere in the region between its neighboring points.

* To subtract a blade point, click on the - (minus sign) button to the right in the Blade Window. Then click on the undesired blade point to remove it.

* To add a blade point, click on the + (plus sign) button and then anywhere in the Blade view to add a new point to the blade.

* At anytime in this process you may press the APPLY button to have the extrusion / bulldozer functionality use the current blade shape along the path.
Notice, however, that it will extrude over the same path at this point --- this
limitation is a bug (please see Implementation Schedule below).

* To make an a-symmetrical blade, click and drag the'Track Point'

* Close the Blade window.

Model Visualization features:
----
* Under the Window menu try the Zoom In, Zoom Out, and Zoom Factor features

* Under the Palettes menu, choose 2D and try the wireframe and color-coded model renderings.

UNSTABLE FUNCTIONALITY:
(WARNING: Under Current Development, especially for a non-symmetrical blade!)

Corner and End Options
----
*Under the SPECS menu, notice the default settings for End Options is Round, and Overlap Options is Minimum.

The End Option determines the shape of the ends of each path segment, including the beginning and last segment.

The Overlap Option determines the relationship between z-values in the overlap areas between path segments. These overlap areas are drawn with different dot colors on the screen before image refresh. Since the default Blade is a “cut-blade”, the MIN Overlap option makes sense as a default.

Symmetrical / Non-Symmetrical Blades

Absolute & Relative Path Behavior

Importing / Saving Out Paths

Importing / Saving Out Blades

KNOWN BUGS:

At this point, only 1 pass of the bulldozer is possible. One has to quit the program and then repeat the above steps to see another pass successfully executed.

* Program crashes:

- if you select the APPLY button without double clicking the end of the path.
- if you multiply click the APPLY button.

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