Chapter 2: Shape, Design, and the Skeleton

Imagination is more important than knowledge.

(Albert Einstein)

In this chapter we consider some salient aspects of natural shapes design. After examining the ubiquity of natural form, we consider its abstract representation by inner structure. This abstraction is the basis of our design paradigm and leads us to consider how a surface, with accompanying detail, may be produced from an inner structure. We discuss the implementation of a design system, its relation to animation. We also consider the usefulness of a catalog of shapes.

2.1 A World of Form

We inhabit a world of form. It enriches our vision and reflects our touch. Form defines, enables, and limits biological function. It is the ground upon which we walk and the chair upon which we rest. It is the root of a tree, the fold of a wing, and the curve of a fin. It is so ubiquitous that we may overlook its beauty and intricacy. The geometry of form has many theoretical and practical applications, and has long been a junction for art and science. For example, the classical Greeks believed the geometrical principles they developed had aesthetic meaning [Weyl 1952].[1] The relation between the scientific attributes and aesthetic values of form is a profound topic that continues to be examined [Birkhoff 1933], [B ézier 1986].

The study of form is not organized into a separate discipline. Rather, it is touched upon peripherally by various fields, including anatomy, archaeology, architecture, biology, botany, engineering, medicine, paleontology, the visual arts, and zoology. In biology, form is of use in the Linnaean taxonomy, the diagnosis of disease, the study of growth, and the competition between organisms. In medicine, form is significant in the treatment of illness. Bio-mechanical engineering concerns form and its relation to prosthetics. Archaeology and paleontology reconstruct the appearance of specimens from minimal remains and a knowledge of form. In the arts, the aesthetics of form plays a fundamental role in dance, ballet, theater, painting, and sculpture. In architecture and engineering, the function, aesthetics, and manufacturability of form are of great importance.

In this dissertation, our interest in natural forms draws us particularly to biology. The geometry of biological form has received considerable study (see, for example, [Sinnott 1963], [Thompson 1961], and [Whyte 1968]) and there is a growing use of geometry in the fields of biomorphology and biomathematics. Form is intimately linked to function, and this accounts for its significance to biology, which is highly correlated to function. In general, the shape of a biological organ determines, enables, or modifies its functioning [E. Russell 1916]. For example, a bone, which is straight and rigid, acts as a lever. A muscle, however, is pliable and, upon contraction, acts *upon* a lever. In many cases, the understanding of an organ's function allows one to predict changes in form that result from the exercise of that function. Similarly, function can be used to predict or categorize shape. Form and function are so intertwined in biology that ‘‘it is hardly too much to say that the whole science of biology has its origin in the study of form’’ [Waddington 1968].

Form and function also intertwine in engineering. Over a wide range of diverse mechanical, electrical, and chemical systems, function depends on shape. The parallel with biology is so strong that engineers may turn to natural forms for inspiration, as suggested in [Blossfeldt 1986]:

> The plant may be described as an architectural structure, shaped and designed ornamentally and objectively. Compelled in its fight for existence to build in a purposeful manner, it constructs the necessary and practical units for its advancement, governed by the laws familiar to every architect, and combines practicability and expediency in the highest form of art. Not only, then, in the world of art, but equally in the realm of science, Nature is our best teacher.

Function, therefore, must factor prominently in our design of natural forms; otherwise the resulting object will likely appear unrealistic. For some plant species, the computer generation of branches and distribution of organs has been accomplished with remarkable realism [Prusinkiewicz and Lindenmayer 1990], [Fowler *et al*. 1992], [Prusinkiewicz *et al*. 1993]. Detailed consideration of such simulations is beyond the scope of this dissertation, however. Instead, we focus on the relation between function and skeleton, the influence of a skeleton on natural form, and how this influence may be simulated by computer.

Not all organisms imply natural shapes, however. Humans construct objects that have a regularity, symmetry, or facetedness that may seem incongruous within a natural setting. Although function can imply regularity, symmetry, or facetedness (for example, the turning of a wheel requires radial symmetry), in Nature, the shape of an organism is often the solution to several functional requirements, and interesting asymmetries and irregularities often result.

In this dissertation we emphasize those natural forms whose underlying shape is *smooth*. Thus, the smooth flow of skin over muscle and bone will be of interest, and the rough surface of tree bark will not. Later, we will interpret those natural forms that are gnarled, rough, or contain minute, geometrically complex features as detail composed upon underlying, smooth surfaces. Another interpretation of complex natural forms may be found in [Mandelbrot 1983]:

> . . . many patterns of Nature are so irregular and fragmented, that . . . Nature exhibits not simply a higher degree but an altogether different level of complexity. The number of distinct scales of length of natural patterns is for all practical purposes infinite.
>
> The existence of these patterns challenges us to study those forms that Euclid leaves aside as being ‘formless,’ to investigate the morphology of the ‘amorphous.’ Mathematicians have disdained this challenge, however, and

> have increasingly chosen to flee from nature by devising theories unrelated to anything we can see or feel.

2.2 Structure from Form

The validity of our thesis, that the skeleton is a useful construct in the process of design, is empirically tested in later chapters with models of natural form. For now, we find some support for the thesis by considering the relationship between form, function, and the discernment of the skeleton.

Morphology is the study of structure or form, and, particularly, a branch of biology that deals with the form and structure of animals and plants. *Functional morphology* is the particular study of shape, form, and function, as well as those principles that unify internal structure with external appearance [Mish 1984]. Numerous morphological factors, such as the organization of bone, muscle, and vascular systems, influence the shape of a biological organism.

If function and form are intertwined, then the functioning of a form in its natural environment might suggest its inner structure. For example, given static and dynamic characteristics we may deduce function and, indirectly, the skeleton. The lines of a face, the posture of an animal, and the wrinkling of a hillside all manifest material and possibly the forces the material has encountered over time.

In other words, the countless patterns in Nature are more than delights for the eye; they are snapshots of dynamic equilibrium that result from struggles of organisms with other organisms and environmental factors. It is this dynamic interaction that produces the vast complexity we call Nature, within which are marvels of engineering that allow one organism to grow 300 feet tall, another to fly, or another to swim. [Hertel 1966] and [Stevens 1974] consider natural patterns, their causes, and their impact on the performance of organisms. ‘‘The task of science is to find pattern hidden in apparent chaos, to show that complexity, correctly viewed, is only a mask of simplicity’’ [Simon 1969]. If our deductions concerning skeleton, material, and function are correct, we may predict changes in shape that would result from a particular movement or articulation of inner structure.

Once a skeleton is deduced, it is available for the definition of the covering surface. This approach is well established in some design environments. In the visual arts, for example, Cezanne contended that all physical objects, including the human body, are composed of five basic structures: the cone, pyramid, cylinder, sphere and cube. Reduction into these basic structures is a method of painting; the structures are represented as two-dimensional regions that are refined to produce a three-dimensional appearance [Perkins 1992].

To fully understand the processes employed by artists and sculptors requires the study of psychology and perception. In addition to work dealing with the visual discernment of shape ([Uttal 1988] and [Duda and Hart 1973]), there are numerous studies concerned with the human visual system [Marr 1983]. The derivation of a compact representation from a three-dimensional shape is a difficult problem that has attracted substantial serious research. [Bolle 1991] reviews efforts in computer science, particularly with respect to robotic vision.

We may regard the skeleton as a *schema*, a ‘diagrammatic presentation, a structured framework or plan, an outline or a mental codification of experience that includes a particular organized way of perceiving cognitively and responding to a complex situation or set of stimuli’ [Mish 1984]. The deduction of a skeleton is comparable to *information schematization*, the representation of a large body of information in a smaller, abstracted, and structured form that is more efficiently processed [D. Russell 1992]. The validity of information schematization depends on whether the deduced smaller body of information allows a verifiable prediction of the larger body. Some large bodies of information cannot be schematized. For example, referring to turbulence, Murray Gell-Mann states, ‘There’s information in the system, no question. But it doesn’t produce a schema, a compression of information with which it can predict the environment’ [Lewin 1992].[2]

A characteristic of schematization is that it simplifies representation and facilitates integration of local detail. This is a useful mechanism in the creation of smooth shapes with secondary detail. The skeleton is a schematization that simplifies the representation and definition of the more complex, external shape.

Humans seem innately able to skeletonize objects, and to verify the resulting schema. For example, experiments demonstrate that positioning as few as nine lights on a person allows an observer in a darkened room to sense the connectedness of the lights and to recognize subtle characteristics, such as an individual's gait. Not only can a skeleton represent a complex shape, it can predict the shape that evolves by growth, articulation, or some other change.

We wish to mimic this ability to understand and mentally manipulate real world objects. We readily, usually automatically, apprehend shape from shading [Horn and Brooks 1989]; and we readily skeletonize a surface as well as imagine its articulation or metamorphosis. Understanding how the mind performs these tasks is a difficult challenge for psychology; for computer graphics the challenge is to determine which tools best allow a designer to exercise his or her mental abilities to define a desired shape.

Although the skeleton may be a useful schema, we should not expect skeletal methods to unify the design of all natural forms; many shapes are not readily schematized. We can examine but a few shapes, determine the demands they place upon a design system, and cite or develop appropriate skeletal techniques.

2.3 Form from Structure

In this section we consider the production of a surface from a skeletal representation of inner structure. The skeletal schema itself may be simple, but its relationship to outward appearance may be complex. Or the relationship may be simple and easily observed. For example, if the skeleton is symmetric about some axis, so will be the shape; if the skeleton is in some way recursive, the shape likely will be also. Intuitively, we expect similar skeletons to produce similar shapes. This often applies even if the material, function, or processes acting on two objects are different. In [Thompson 1961] and [Rashevsky 1948] we find attempts to relate inner structures and forces to outward appearance. At times these attempts yield an accurate mathematical relationship; for example, the shape of a honeycomb is readily determined by an analysis of the internal angles of cell walls. At other times, only a plausible cause for outward appearance is expressed.

We begin with the assumption that the relationship between skeleton and surface is *volumetric*. For example, if we regard a point to be the skeleton of a sphere, then the object is the volume of points whose distance to the skeleton is less than or equal to the radius of the sphere, and the surface consists of the boundary between object and non-object.

To maintain a correspondence between skeleton and object, we expect that the addition of a skeletal element would produce a corresponding addition of volume to the object. For example, were a skeleton to consist of two sphere centers, we expect the resulting object to be the union of the two spherical volumes. Let us apply this approach to a skeleton consisting of a triangle and a line segment, as shown below, left. The three-dimensional volumes (or, in the figure, two-dimensional contours) surrounding each skeletal element are shown below, middle left, and the union of the volumes (contours) is shown below, middle right.

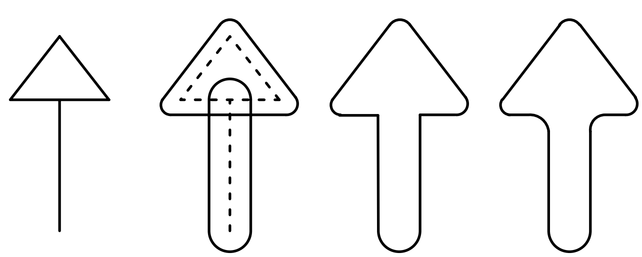

Figure 2.1 A General Approach to Form from Structure

The union shown above, middle right, is unsmooth (or *tangent discontinuous*) at its concave portions and, thus, contradicts our interpretation of natural form. To achieve the desired smoothness, the component volumes (contours) are *blended*, as shown above, right. The representation of an object as the blend of volumes defined by skeletal elements is central to this dissertation.

Although a skeleton is related to its resulting shape, its geometric complexity is not necessarily comparable to that of the shape. For example, consider the skeleton below, which contains a single loop. Depending on the radii associated with the skeletal elements, the resulting surface can contain a hole or not, can be convex or not, and can consist of one, two, or three convex regions.

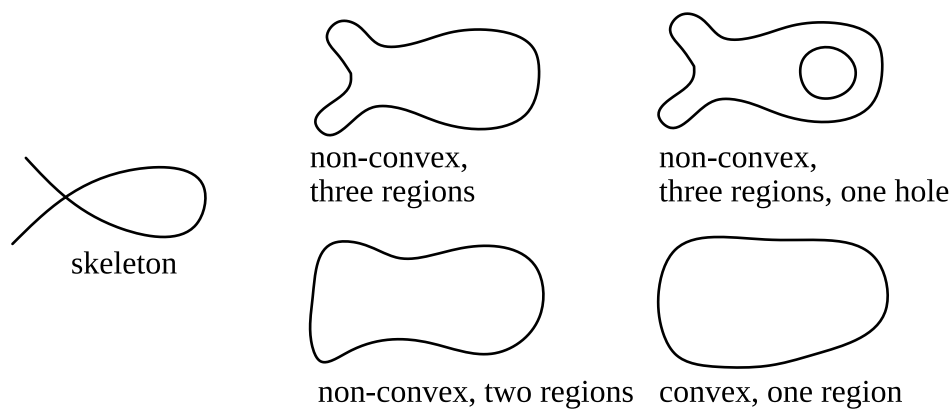

Figure 2.2 A Skeleton and Possible Resulting Surfaces

2.4 The Skeleton

In this section we examine further the skeleton, introducing new concepts and expanding on others mentioned in previous sections. We use the term ‘skeleton’ as in ‘something reduced to its minimum form or essential parts’ or ‘something forming a structural framework.’ Because inner structures usually define the functioning of an object as well as give rise to its form, *a skeleton abstracts form and manifests function*. That a skeleton corresponds to function is reasonably clear for animals; bones, for example, serve as mechanical levers as well as supports for muscle. The skeleton corresponds to function in plants and trees as well, defining branch placement and leaf venation.

Integument is a term meaning ‘something that covers or encloses, especially an enveloping layer (as a skin, membrane, or husk) of an organism or one of its parts’ [Mish 1984]. The integument of many organisms is a pliable surface that covers inner structures, such as bones, fiber, muscle, and vessels. According to [Wainwright 1988], its shape depends upon the rigid parts that define the mechanical support system of an organism, as well soft organs, connective tissue, and flexible ligaments that surround the support system. Nature is highly efficient in its use of these materials [Thompson 1961], [Wainwright 1988].

[Wainwright 1988] argues that the efficient use of biological material, the efficient movement within a medium, and the efficient articulation of an organism all derive from cylindrical shape, something ‘having an approximately round or elliptical cross section and an easily identifiable longitudinal axis’ [ibid.]. Indeed, natural forms, such as plants, trees, and animals, reveal an abundance of shapes that are smoothly formed upon an axis or set of axes.

The longitudinal, or *medial*, axis of a cylindrical shape need not be straight, as in the usual meaning of cylinder, but may be curved. In [Agin 1972] the resulting form is called a *generalized cylinder*[3] and is presented as an efficient representation for three-dimensional objects derived from two-dimensional images. Derivation of a medial axis from a two or three-dimensional shape is known as the *medial transform*. There is considerable application of the two-dimensional medial transform in areas such as optical character recognition and machine vision. A transform for arbitrary shapes is discussed in [Blum 1967]; the restricted case for simple polygons is considered in [Yao and Rokne 1991]. A three-dimensional medial transform for volumes is presented in [Yu *et al.* 1991]. In a design context, we use ‘skeleton’ to mean the medial axis or axes of the shapes’s inner structure.

When used in a biological context, ‘skeleton’ usually refers to the rigid, mechanical support system found in most animals. In such a system, a subordinate element rotates with respect to a superior one. For example, the lower arm rotates about the elbow joint of the upper arm. Such rotations are easily mimicked by software systems such as *GRAMPS* [O'Donnell and Olson 1981], *Bbop* [Stern 1983], or *Menv* [Reeves 1990]. These systems store one or more affine transformations at each joint (or *node*) of the skeleton. Animal and plant limbs do not stretch or shrink (except by growth or aging)[4], although the limbs of plants are more flexible and allow some bending along their length as well as rotation at a joint.

Although an organism's inner structure need not be organized hierarchically, for our purposes we assume that a skeleton is topologically equivalent to a directed acyclic graph. Such a graph, or *tree*, organizes the internal components of an object and is, therefore, a powerful means for the representation and manipulation of the object. The basic data structure for a skeleton, which we call an *element* (or, sometimes, *limb*), is recursive and contains the following fields:

parent:	*Pointer to Element*
children:	*List of Pointer to Element*
transformationFromParent:	*Matrix*
geometry:	*GeometricObject*
ancillaryData:	. . .

The transformation is Euclidean, allowing rotation and translation. Usually the geometry is a tapered cylinder defined by two three-dimensional endpoints and their associated radii.

Each skeletal element can readily define a surrounding volume, or *primitive*. Although the collection of these volumes may yield a topologically complex surface, the skeletal elements remain easily defined, articulated, and displayed. This is demonstrated, using relatively complex skeletons, in later chapters. First, we consider the problem of producing the integument from a simple skeleton.

2.5 The Surface

In many instances, an integument is stretched over soft tissue, and the overall shape is smooth; it obeys some constraint on geometric continuity. As illustrated in section 2.1, we obtain smoothness by blending the individual primitives that surround skeletal elements. As developed in this dissertation, the blend depends on the relation of volumetric primitive to skeletal elements. This differs from approaches in which a previously designed surface or volume is smoothed [Nasri 1987], [Colburn 1990]. For example, rather than combine a cylinder and a block, and then blend the result, we would explicitly specify the blend of the cylinder into the block. In chapter 5 we argue the generality of this approach.

The blend of individual volumes does not necessarily yield the surface desired by a designer. For example, consider the following skeleton; to the left we blend individual skeletal primitives, and to the right we form the convex hull of the blend. In some cases, the surface to the right may be preferred to the one at left.

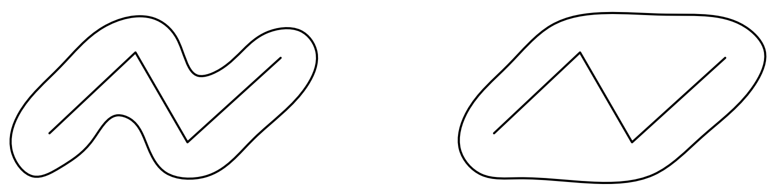

Figure 2.3 Different Integuments

The design of surfaces may be divided into two fundamental processes. The first process is intuitive: the designer, through creative insight, develops an abstract expression or specification for a form. The second process is productive: the designer uses the design system to convert the abstract expression to a concrete representation. For example, he or she may look at a sphere and express it abstractly as a ‘central point with radius;’ the designer may then employ the design system to create, for example, a polygonal approximation to the sphere.

Geometric modeling is a term sometimes applied to the entire design process. As studied in computer graphics, however, it usually refers to the productive process in which a compact yet concrete representation, such as a patch or set of polygons, is produced. We use the term in this more restricted sense. Geometric modeling is often classified into parametric and implicit methods. Both are well developed in computer graphics (early parametric methods are described in [Coons 1967] and early implicit methods are described in [Mathematical Applications Group 1968]. A survey of geometric modeling is a formidable undertaking. Several texts provide detailed surveys (see, for example, [Bartels *et al*. 1987], [Farin 1988], [Faux and Pratt 1979], [Gomes and Velho 1992], [Hoffman 1989], [Rogers and Adams 1990]) although none is ever complete in this rapidly evolving discipline.

Although skeletons have defined some parametric surfaces, such as lofted surfaces [Bloomenthal 1985] and patches [Forsey 1991], we select implicit surfaces because they readily capture the volumetric relationship between skeleton and surface. Before examining the application of these surfaces to natural forms, we introduce, in chapter 3, general concepts for implicit modeling. Then, in chapter 4, we extend the normal range of implicit surfaces to accommodate non-manifold surfaces. In chapters 5, 6, and 7 we develop models of natural form using these methods.

2.6 Details, Details

Although the underlying shape of a natural form may be smooth, detail is often visible to the naked eye. It can make surfaces appear fuzzy, hairy, prickly, splotchy, creased, gnarled, pinched, stretched, crinkled, or wrinkled. This complexity adds interest to the form, and is necessary for a realistic appearance. To simulate this degree of realism requires close observation. Although we may simulate objects observed in the past whose appearance is available only through memory, without close observation these simulations are likely to appear impressionistic, rather than realistic.

The object of image synthesis is not necessarily to simulate reality, however. Reality is simply a convenient measure of complexity, and the simulation of reality is, therefore, a reasonable measure of the capability of a design system.[5] Thus, if a design system can simulate a realistic object, it can also simulate a fanciful object of comparable complexity. The leaf we present in a later chapter is an example of a fanciful design inspired by reality.

In chapter 6 we consider complexity in terms of minute features added to a simpler, underlying shape. For example, creases and wrinkles can be added to skin, following paths defined by the skeleton, possibly with random variations. An alternative method to provide complexity is to combine parametrically defined surfaces with implicitly defined volumes. We describe the technical aspects of this approach in chapter 3, and apply the method to a natural form in chapter 7.

2.7 The Design Environment

Material forms are ubiquitous, and their design is a major undertaking within civilization. The fields of architecture, computer science, engineering, geometric modeling, manufacturing, and medicine devote enormous effort to advance the art and science of the design of form. There is every indication that new design methodologies, such as computed aided design, will continue their development.

Those who implement surface design systems must consider which tools are preferred by designers. This largely depends on the designs a system is expected to accommodate. In this dissertation we are restricted to those designs originating with a skeleton. We have defined several working concepts concerning function, skeleton, and form that affect the intuitive process, and several working concepts concerning skeleton, volume, blend, and surface that affect the productive process.

In this section we discuss the features a design system should offer the artist or engineer when he or she specifies a skeleton, determines whether it is organized hierarchically or not, whether it consists of straight segments or curves, how it is articulated, how surface detail is placed, as well as any ancillary information concerning the relationship of the three-dimensional volume and its defining skeletal element.[6] In addition, the system should provide for the merger of volumetric and surface representations. A designer is more likely to use a system if it provides a rapid response to his or her specifications. Thus, specifications provided by the designer should be interactive.[7]

User input devices have become increasingly flexible and varied, and their diversity and effectiveness will, undoubtedly, grow. Unfortunately, few of these devices were available for the research reported here. Instead, the sample skeletons used in this dissertation were sketched by hand, and, due to display hardware limitations, few could be displayed at interactive rates. With modern equipment, however, the real-time, interactive display of complex skeletons is quite feasible. With continued hardware development, we should expect skeletal design to feature not only the real-time display of the skeleton, but the real-time display of primitive volumes and, eventually, of surfaces.

Our system does not provide interactive skeletal definition or articulation, such as in [Stern 1983], [Reeves 1990], or [Oppenheimer 1986]. We were, however, able to create, measure, and transcribe the following skeleton and associated volumetric information in two or three hours, resulting in the surface shown in figure 6.14.

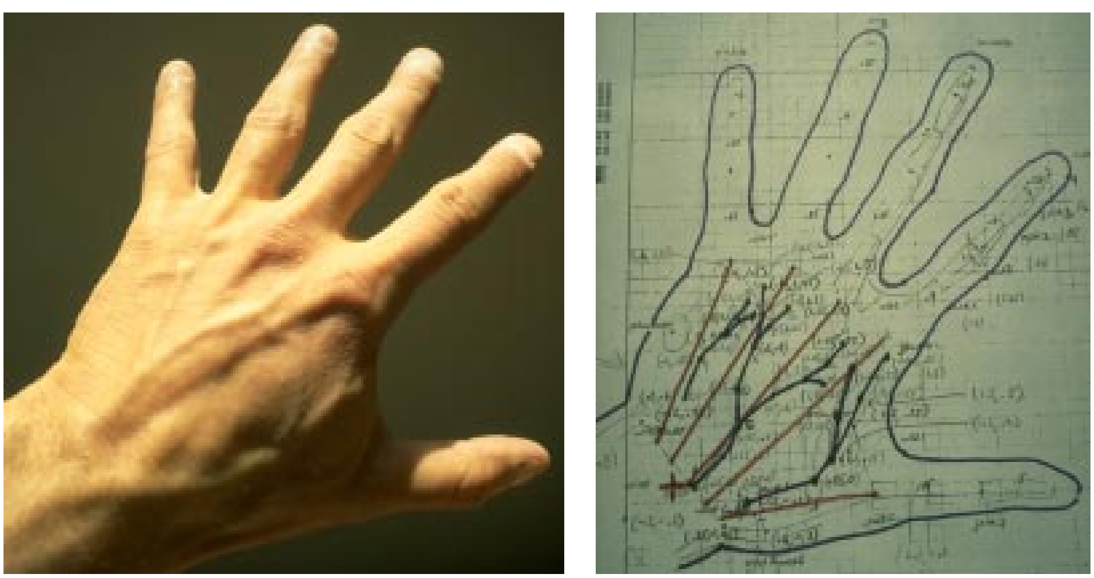

Figure 2.4 Hand and Sketched Skeletal Design (photographs)

In this case, articulation is provided by a procedural definition, in which the orientation and grasping of each finger is given as an argument to the procedure. Each finger specification contains the following fields (all angles are in degrees, all lengths are in inches):

θ, ϕ:	*Real -- Euler angles at finger's first knuckle*
grip2:	*Real -- angular rotation at second knuckle*
grip3:	*Real -- rotation at third knuckle (except thumb)*
length1:	*Real -- length between first and second knuckle*
length2:	*Real -- length between second and third knuckle*
length3:	*Real -- length between third knuckle and finger tip*
radius:	*Real -- finger thickness (taper is assumed constant).*

The full specification is compact, and was extracted from the graph in figure 2.4:

thumb:	*Finger* = [30., 20., 0., 30., 0.8, 0.8, 0.45, 0.1125],
index:	*Finger* = [10., 15., 30., 10., 0.75, 0.6, 0.25, 0.0875],
middle:	*Finger* = [0., 15., 30., 10., .9, 0.7, 0.25, 0.0875],
ring:	*Finger* = [-10., 15., 25., 5., 0.85, 0.6, 0.35, 0.0875],
pinkie:	*Finger* = [-25., 15., 25., 5., 0.65, 0.45, 0.3, 0.08].

Alternatively, finger parameters may be read directly from special purpose devices, such as the data-glove [Sturman 1992].

At least one commercial system provides a basic capability for volumetric blending, but its user interface is text-based [Roscoe 1993]. The design system we have implemented is not accessible to the non-programmer. The software interface is, however, readily utilized, as demonstrated by examples in chapter 4. A more interactive design system is desirable, and ''it will be interesting to see a system which provides a designer with a kit of tools for designing and combining such surfaces. How would [one] implement a system which permitted a non-mathematical user to construct elaborate objects from a sufficiently rich source of primitives?'' [Forrest 1988].

The designer may wish to provide ancillary information concerning volume primitives, such as a particular blend method, a particular blend parameter, a particular cross-section of the volume, or a procedural method that defines primitive volumes, surface characteristics, or articulation constraints. Interactive specification of procedural methods is not well understood, and few examples are available in the literature [Nelson 1985], [Fowler *et al*. 1992] Tools exist that permit interactive specification of surface characteristics [Hanrahan and Haeberli 1990], and these methods might be applicable to the specification of volumetric characteristics such as cross-section and blend.

The designer should not necessarily be responsible for all aspects of a design. For example, the covering of a skeleton and the metamorphosis between different skeletons should require a minimum of user interaction, so that a designer need not specify the precise relationship between volume and skeletal element. The implementation of reasonable defaults is considered in depth in chapter 5.

Also, the designer should not be required to specify the topological complexity of the surface. As a tailor or wall paperer might attest, it is difficult to fit pieces of surfaces, and this is true of a patch or polygon network. Moreover, the topology of the network may change if the object is animated. Our skill in skeletonizing objects suggests that skeletal, not surface, topology should be the topology of design for many objects. Therefore, we seek a design system that facilitates concise, abstract skeletal representations of form while isolating the designer from the need to specify the piecewise topology and geometry of the surface.

The design process may be analyzed in terms other than interactivity and surface geometry. For example, we might interpret design as a *syntactic* process in which an operation, such as ‘replace,’ is defined as a combination of operations, such as ‘delete’ and ‘add.’ Eventually an advanced design system may accept natural language instructions based upon an object’s ‘purpose.’ For example, joint angles of a skeleton may be derived from goal oriented specifications [Wilhelms 1987].[8] This ‘teleological’ definition of an object is argued for in [Barr 1991]:

> An object is more than its shape: intuitively, a teleological model is 'goal-oriented' modeling. It is a mathematical representation that calculates the object's behavior from what the object is 'supposed' to do . . . Unlike conventional cinematic modeling, in which an object is represented through its instantaneous shape, a teleological model incorporates time-dependent *goals of behavior* as the fundamental representation of what the object is.

A teleological approach seems inappropriate for interactive shape design because it circumvents certain roles, such as the use of intuition, of the designer. [Zeisel 1987] expressed the importance of these roles by stating, 'All lines and forms, whether the gnarled branch of a tree, or the gentle contour of a vase, evoke emotional responses through associations . . . The designer, sharing common associations with his audience, communicates his feelings.' Such communication is best achieved by 'hands-on' methods for defining skeletons and surfaces. There are, of course, methods, such as digitizing the position, orientation, or movement of skeletal parts, that are intermediate to teleological design and 'hands-on' design.

The needs of a designer evolve, and, therefore, no consideration of a design system can be complete. To a certain extent, the wishes of a designer depend upon the evolving sophistication of design techniques, and these in turn may depend upon commonly available computational power. As computer graphics has become more accessible and hardware more powerful, the methods of surface design have become more sophisticated. Designers have sought to model increasingly complex, more natural, and more constrained shapes. As the aspirations of designers evolve, so will design systems.

2.8 Animation

A designer may wish to modify, that is, *animate*, a shape over time, in order to create a computer generated movie or to evolve one design into a new one. Design evolution can be an efficient strategy to produce an improvement over or variation of a previous design. If a shape is based on a skeleton, then we expect the animated skeleton to yield a corresponding, reasonably behaved, animated shape.

Indeed, there are many natural shapes that have evolved from previous shapes without a corresponding change in function. The evolved form can be interpreted as a resolution of natural forces. For example, distribution of vegetation can be seen as the product of competition between organisms. Different natural forces can yield similar forms, such as the layering of sandstone produced by wind and the layering of bark rings as developed in a fire. We conjecture that phylogeny corresponds with the development of function, whereas ontogeny corresponds with the environment encountered. Thus, a person's face is genetically enabled to assume different forms, but the character lines that develop over time are a product of environment. We do not seek, however, to simulate the function of a natural form or the environment within which it evolved. To accurately predict from first principles a biological shape, for example, would require a model of biological growth. Such a model is beyond the scope of this dissertation; furthermore, such a model may complicate the design task in those cases where the goal is a specific shape. Our goal is to mimic the shape of a natural form and to simplify the process by providing useful design tools.

Skeletal animation may be separated into two classes: those animations that disallow a change in skeletal topology, and those that permit a topological change. We divide the first class into two categories: *articulation*, in which each skeletal element is fixed in length but may change its angular relationship to its parent, and *metamorphosis*, in which length as well as rotation may change. We divide the second class also into two categories: *growth* permits the addition of skeletal elements but not their removal, and *transmogrification* permits addition and removal of skeletal elements. Examples of articulation, metamorphosis, growth, and transmogrification are shown below.

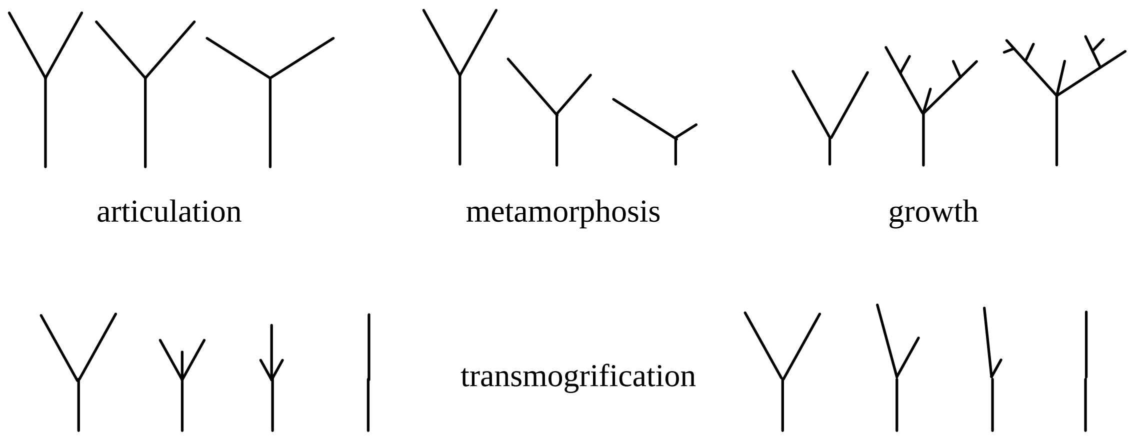

Figure 2.5 Animation Categories

The latter examples suggest that the transmogrification of nodes with a differing number of branches can be accomplished in different ways. For example, in the left transmogrification, two branches shrink while a center branch grows; in the right transmogrification, one branch shrinks while the other rotates. These examples also suggest that articulation corresponds to the usual notion of bodily action in which limbs rotate without changing length. In particular, the straightforward approach of linear interpolation, shown below, left, is less natural than rotation, shown below, right.

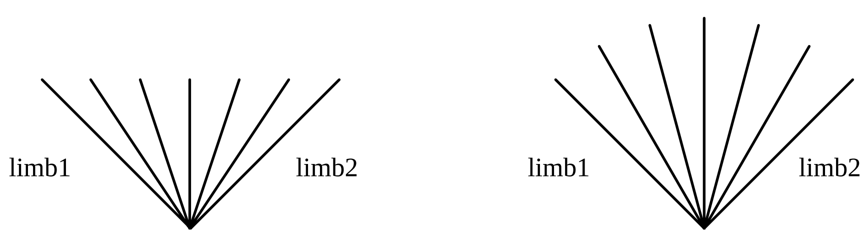

Figure 2.6 Linear and Rotational Interpolation of Two Limbs

The relationship between function and skeleton is often obvious; in higher life forms, the skeleton positions internal organs and defines the organism's ability for external movement. Thus, articulation of the skeleton represents an exercise in function, and the exercise of this function usually produces a change in shape.

During articulation certain attributes associated with the skeleton may also change. These attributes might influence the volumetric blend, the limb radius, surface color, or surface detail. For example, a skeletal element might represent a muscle that is to bulge whenever another skeletal element rotates.

The topology of articulation is directly represented by a tree-structured skeleton. Without such a skeleton, natural appearing articulation is not as conveniently expressed. Indeed, one could argue that, for the purpose of animation, a tree-structured skeleton is more important than its surface. For example, a stick-figure representation, which contains no surface, is more effective in displaying animation than is a smooth surface that has no discernible skeleton.

An animation that involves articulation only should not cause a viewer confusion (unless the articulation involves an unnatural rotation, such as a head turning fully around). If an animation involves the metamorphosis or transmogrification, however, the viewer is required to change the schema that he or she has developed as a compact representation for the object. This requirement may engender the emotional response of surprise [Gaines 1986]. It may begin as anxious puzzlement and develop into relief and understanding once the evolving form is recognized and a new schema is developed. The viewer, after some reflection, might then develop an appreciation for the aesthetic quality of the change [McCoy 1981]. Indeed, those classical animations that audiences find so magical are the products of designers who skillfully manipulate schematic representations. According to [Thomas and Johnson 1984, p. 333], in discussing the structure and anatomy of a bird, ‘‘the animator needs such information before he can begin his scene.’’

The skeleton is important to metamorphosis and transmogrification because it assists the viewer in tracking one recognizable shape through the transition to the second recognizable shape. The skeleton allows the viewer to interpret the change in shape as a change in structure. Meaningful interpolation of skeletons is, therefore, an important issue for designers. Although it is not strictly necessary that skeletal elements be organized as a tree, we believe such organization facilitates inter-skeletal interpolation.

As a thought exercise, we consider the interpolation of a maple leaf, a human hand, and a stingray. Functionally, these objects have little in common, but their overall shapes are similar. The skeletons for the leaf and the hand, below, are used in later chapters. Automatic transmogrification would be possible if an algorithm were developed to find corresponding structures between different skeletons. The complexities of animation and shape design suggest, however, that a meaningful interpolation of skeletons requires skilled intervention by the animator.

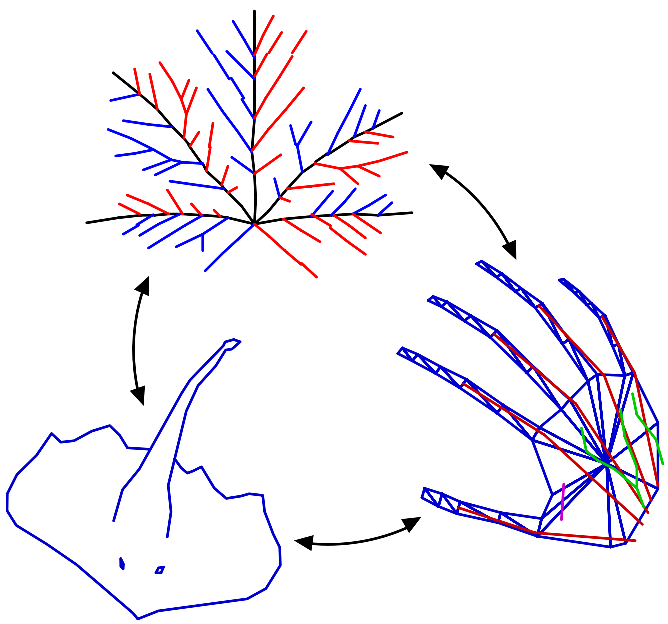

Figure 2.7 Complex Metamorphoses

2.9 Shape Taxonomy

Morphometrics concerns the measurement of similarity (also known as *shape affinity*, *morphologic similarity*, or *homology*) and dissimilarity of geometrical shape among biological objects. Morphometric methods usually rely on surface measurements, or *keys*, which are unsatisfactory for the more general purpose of design and animation. Some researchers suggest that skeletal keys are more appropriate for measuring morphologic homologues [Rohlf and Bookstein 1990]. Often morphologic similarity is highly correlated with evolutionary proximity [ibid.]. This correlation suggests that the Linnaean taxonomy, which is, in places, highly correlated with evolution, may provide some basis for understanding the form of biological organisms.[9] Indeed, a shape taxonomy, or shape vocabulary, could assist the designer by providing, for each biological shape class, a method of geometric representation and, perhaps, a corresponding skeleton. It could provide the designer the domain and characteristics of classical organic forms.

Taxonomy is defined as the 'orderly classification of plants and animals according to their presumed natural relationships' [Mish 1984]. In the ancillary definitions below, note that 'taxonomy' leads both to 'form' and to 'function.' Function often implies form, and form usually, but not always, implies function. Thus, although the biological taxonomy is clearly related to function, a taxonomy of shape cannot be based solely on biological function.

> systematics: the classification and study of organisms with regard to their natural relationships: taxonomy.
>
> classification: systematic arrangement in groups or categories according to established criteria, specifically, taxonomy; class, category.
>
> category: a general class to which a logical predicate or that which it predicates belongs; one of the underlying forms to which any fact known by experience must conform.
>
> conformable: corresponding in form or character.
>
> correspond: to be equivalent or parallel.
>
> equivalent: corresponding or virtually identical esp. in effect or function.

Alternatively, a shape taxonomy could depend on those semantic distinctions that concern shape and form. For example, in architecture we find structural terms such as arch, hollow, saddle, *etc*. Shapes are semantically distinguished in other fields as well. For example, the following words describe the shape of various botanical leaves: elliptic, hastate, linear, oblong, oblanceolate, obovate, orate, peltate, reniform, sagittate, and spatulate [Sandved and Prance 1985].

There have been previous attempts to categorize shape for the purpose of design. One taxonomy relates historical developments in the world of art [Latham 1989]. [Fleck 1988] considers the role of geometric categories, particularly regular polyhedra, in the development of form and function. [Kimia *et al.* 1989] considers a classification of shape according to parts and protrusions. And in [Ovtcharova *et al.* 1992] shape features are classified, primarily within a solid modeling context.

In a previous section we considered reality as a departure point for fanciful shapes, but noted that fanciful designs may loose their appeal if they appear unrealistic. A minimum level of detail often aids in the realism of a fanciful object, but there may be more fundamental requirements for realism. For example, Nature has not developed all possible evolutionary permutations; there are unoccupied places in the general taxonomy [Raup and Stanley 1978]. It may be that shapes corresponding with these unoccupied places would be perceived as unrealistic.

2.10 Conclusions

In this chapter we suggested that many natural shapes are amenable to skeletal design. These shapes derive from a straight or curved skeleton, a skin that covers a smooth blend of tissue, and microstructure that is partly chaotic and partly patterned. Synthetic shapes, however, may be designed more readily with to non-skeletal methods such as traditional computer aided design, conventional free-form surface design [Farin 1987], hierarchical patch refinement [Forsey and Bartels 1988], and volumetric sculpting [Galyean and Hughes 1991]. In many cases, however, a skeleton, facilitates animation, procedural definition, developmental processes, and replication with alterations.[10] A skeleton by itself allows articulation, but provides insufficient surface detail. A skeleton with covering provides both articulation and realism, as we hope to demonstrate in chapters 5, 6, and 7.

The intuitive aspect of design, in particular the apprehending of the skeleton from a real or imagined shape, is something we must leave to the artist, engineer, or designer. It is his or her task to observe, analyze and understand a shape before attempting to represent it skeletally. In this, the relationship between function and shape concerns the natural appearance as well as the visual impact of a shape. The design system can assist the designer by displaying, preferably at interactive speeds, the skeleton, the volume surrounding the skeleton, and the surface covering the volume. A design system should be evaluated in terms of the articulation, representation, interaction, and display capabilities provided to the designer and, ultimately, the ease with which a designer can translate his or her intuition into an intended shape. The techniques developed for a design system not only influence the aesthetic aspects of the resulting shape, but may have engineering and manufacturing applications as well.

We have emphasized the intuitive aspects of skeletal design because we believe a design system should accommodate all who wish to work with surfaces. A similar populist sentiment may be found in [Hawking 1988]:

> However, if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason . . .

To understand the design process is not as ambitious as discovering a complete theory of the universe. But, in keeping with this populist statement, the underlying principles of design should, eventually, be as accessible to an ordinary person as they are to the specialist.

Finally, we discussed the possibility of a shape taxonomy that would categorize natural shapes. The categorization of shape, the study of the relationships between shape categories, and the different demands these categories place upon a computer representation of shape, remain fertile areas for future work.

2.11 Notes

1. For example, Plato maintained that a mathematical idea is the origin both of symmetry in Nature and its aesthetic value [Weyl 1952].

2. For a general consideration of information and form within the context of aesthetics, see [Moles 1966].

3. The generalized cylinder as described in [Agin 1972] does not require a round or elliptical cross section.

4. Interesting exceptions include the squid's ability to extend a tentacle [Wainwright 1988].

5. This notion is attributed to Alvy Ray Smith.

6. An analysis of the creative process itself is beyond the scope of this work. A collection of essays on the process of design may be found in [Kepes 1965]. A general discussion of automatic design derivation from functional specifications may be found in [Kalay 1987].

7. For example, the popularity of equipment manufactured by Silicon Graphics, Inc. over more robust but slower renderers (such as RenderMan®) indicates a

general user preference for interactivity.

8. For additional discussion of goal oriented animation, see chapters 2 and 3 of [Badler 1991].

9. Convergence, in which two distinct evolutionary trends yield the same function or shape, is a counter-example to this notion.

10. It would be interesting to survey users of non-skeletal design systems as to whether they employ a ‘mental skeleton’ during the design process.

Resting the forehead against a surface can be
very soothing to the nervous system.
(a yoga teaching)