1. INTRODUCTION TO MORPHOMETRICS

The study of form may be descriptive merely, or it may become analytical. We begin by describing the shape of an object in simple words of common speech: we end by defining it in the precise language of mathematics; and the one method tends to follow the other in strict scientific order and historical continuity.

Morphology and mathematics (1915)
D'Arcy Thompson (1860-1948)

1.1. INTRODUCTION

The idea of form is one of the most fundamental concepts underlying all of the sciences. All forms consist of a large number of shared aspects that include size, shape, color, patterning, etc. In the most basic sense, the human ability to readily discriminate forms by noting differences in color, size, shape, etc., is so well integrated that the required behavior responses are largely unconscious. The heavy human dependency on the visual system in contrast to other aspects, such as smell, hearing, etc., is the result of an evolutionary process. The successful evolutionary survival of man, over more than 4 million years is, in part, a consequence of bipedalism (Washburn and Dolhinow, 1972; Washburn and Jay, 1968; Howells, 1973; Lestrel and Read, 1973; Lestrel, 1975; Conroy, 1990). This placed man into a unique eco-niche by totally freeing the upper limbs, resulting in a concomitant development of a comparatively large brain, and leading to an increasing use of the forward arrayed eyes (binocular vision being an important aspect within the primate Order). While a large, complex and developed brain is an asset, the use of binocular vision in conjunction with this large brain, was presumably important for the survival of early hominids. Thus, among the senses, vision in particular has played, and continues to play, an essential part in our adaptation to our external environment. While the initial details remain quite sketchy, it is not unreasonable to suggest that these evolutionary processes (such as the initiation of bipedalism, the subsequent development of a comparatively large brain, and binocular vision) played a critical role in the eventual development of human language. These steps led to the attainment of knowledge (and to the dispersion of knowledge to others in the group), initial steps which ultimately led to culture, science and technology.

Of the five senses (sight, touch, hearing, smell, and speech), we probably rely most heavily on vision, as already emphasized. However, all the senses come into play. The basic units of the sciences come from the utilization of the senses. Gerard (1961) has outlined these as: [1] *space* (metrics, *e.g.*, centimeters) derived from vision, touch, muscle sense and the vestibular system (balance organs of the ear), [2] *substance* (mass, *e.g.*, grams) from smell, taste, touch, muscle sense, and also vision, and [3] time (seconds) from primarily hearing. From these notions of space, substance and time, comes the notion of the existence of an *entity* or *object*. Such an entity or object, while potentially external with respect to the observer, is initially defined in terms of the sensory system, which is internal to the observer. These entities comprise the basic sensory data leading, eventually, to descriptions of form: although, in the beginning this sense data was only treated in qualitative and often subjective terms. We will eventually return to the problem of how to capture, in numerical terms, the visual information that resides in all forms. This will be taken up subsequent chapters. The next section focuses on the fundamental importance of the visual system.

1.1.1. The Visual Process

Modern society bombards us every day with visual information of one type or another. Commercial advertising assails us with carefully designed forms of objects, often in bright colors to catch and hold our attention. All intended to convey a message that will convince us to readily part with our hard earned money and dash out and purchase the advertised product. However, this is only one example, and a rather trivial one at that (notwithstanding claims to the contrary of the advertising community), of the use of visual information. In actuality, we are dependent on our visual system in much more basic ways. In fact, our very survival depends on it. We depend overwhelmingly on vision and some 3 million sensory nervous fibers are involved in the transfer of optical information to the nervous system (Gerard, 1961).

From the moment we wake in the morning, we make use of our visual system. We detect whether it is daytime or nighttime. We identity objects that are around us and act accordingly to avoid obstacles, we operate on directions to locations we want to reach. We recognize people and places we deem important. Additionally, we are able to store and recall images of places where we have been, events we have experienced, and faces of persons we have encountered in the past. We also use the visual system in even more sophisticated ways such as in reading and writing in which visual, locomotor and language skills are all simultaneously required. All this implies that the structure of the human visual system is highly integrated in complex ways, with many of the functional processes involved in the reception and recognition of visual stimuli remaining incompletely known (Spoehr and Lehmkuhle, 1982; Zeki, 1993).

It is no accident that even the language that we use is influenced by space, substance, time considerations, and ultimately, vision. As Gerard (1961) has noted, the English language contains numerous examples of such metaphors as: we "apprehend" a meaning, refer to a "tangible suggestion" or a "weighty problem". We may say it "looks heavy", but almost never that "it feels green". The importance of the visual system influencing language is also clearly apparent from such terms as vision (*video*) itself meaning seeing. Vision is evident in the very word *evident*. No matter how intellectual we attempt to be, we cling to *insight*. A philosophy is a worldview (eine *Weltanschauung*), that is, something seen, while contemplation comes from *contemplor,* to gaze at. Consideration is from *considero,* to look at closely, etc.

The visual images that are perceived by the human eye are a combination of specific properties that are inherent in all forms; namely, consisting of size, shape, texture, color, movement, etc. We are able to function normally in the external world only by being able to rely on and process this visual information, the one exception being those who have lost their sight. Our visual system is so well developed that we are able to effortlessly classify and compare visual images and rapidly act on the information perceived. What is not so well developed has been our ability to measure or quantify this visual information for storage and future retrieval. In other words, in contrast to the human capability of rapidly identifying and classifying this visual information, the mathematical description of the content of these visual images has been extremely slow in forthcoming. The next two sections take up the issues of what exactly is meant by quantification and how this interacts with the elucidation of process an ultimate goal of biology.

1.1.2. A Dual View of the World

In this visual world, we are surrounded by forms of objects of one sort or another. In one sense one can consider these visually perceived forms as consisting of a duality. This duality is composed of two types of forms, those that are *artificial* or man-made, and those that are *natural*. The natural world includes the planets, geological formations, and biological organisms to name a few. Artificial forms will be considered below. How we approach, this duality has important practical as well as theoretical ramifications.

Enter most man-made structures in the world and you will generally be confronted by a dizzying array of verticals, horizontals, angulars, circles and regular curves, representing uniformity and regularity. Examples include large objects such as the Parthenon in Greece, the Twin Towers in New York, and objects of smaller scale such as automobiles, watches and even computer microchips. The list is endless.[1] These objects in a man-made world are often built to demanding standards, some requiring exacting precision (tolerances of ±0.005 of an inch). This is a requirement if the separate parts of, for example, an aircraft engine or a watch, are to fit correctly. Moreover, such precision in the manufacturing process is required if many copies of a complex item are to be reliably constructed. Thus, the emphasis in a man-made world is on uniformity, and exactness; that is, with little *variability* (which if it arises would be treated as error, and if great enough, in need of correction). The success of technological progress is undoubted, and we will briefly focus on the rise of scientific knowledge that produced it (Chapter 3). Nevertheless, it will also be demonstrated that this very success which has led to this modern technology, the rise of what have been called the exact or 'hard' sciences, is, in some ways, inappropriate for an understanding of the biological sciences and even more so of the social sciences. Reasons for this inappropriateness will be explored further in this chapter.

In contrast to artificial or man-made objects, naturally occurring phenomena, with very few exceptions (perhaps crystals, etc.) generally exhibit considerable 'irregularities' or variability when one views the individual members of a class of such objects.[2] As indicated above, this stands in direct opposition to the man-made world. Variability is of central importance in the natural world. Naturally occurring structures, whether large or microscopic, always exhibit variability (even identical twins will exhibit variability due to environmental influences). This is even the case of those forms that in some way display symmetry. Symmetry abounds; consider the form of plant leaves, clamshells, and even human anatomy. Nevertheless, because of variability, this

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[1] It is, thus, not surprising that the architecture of Gaudi in Barcelona, Spain, stands out as a notable exception from the rule of regularity of artificial forms.

[2] However, even such naturally occurring objects tend to display variability, however small.

symmetry is never exact in the sense that the 'left' side is identical to the 'right' side. In biological organisms, the presence of this variability is an essential ingredient of evolution and can be considered an important facet of species survival.[3] Thus, this contrast between a man-made world (where one would like 'zero tolerance'; that is, no error or variability) and the natural world is profound and has a direct bearing on the use of quantification in the biological sciences. We will return to this issue in a moment, but first we need to examine why, in some ways, the physical sciences are simply not appropriate models for understanding biological processes.

There are a number of reasons for this state of affairs. These reasons can be summarized with three principles listed as: [1] *variability*, [2] *complexity*, and [3] *history*. The importance of variability has already been alluded to. The study of complexity, an emerging discipline in itself, refers to a basic aspect of all life forms. All organisms, whether single-celled or higher up the evolutionary ladder exhibit increases in complexity during their life cycles. The issue of complexity is briefly taken up in Chapter 5. The third principle, history, has to do with the fact that all organisms go through two types of developmental cycles. One is *ontogeny* or individual growth and the other is *phylogeny* or evolution. Both time-dependent processes lead to changes in the biological form.

These three principles distinguish the biological sciences from the physical sciences. It has been generally held since the start of the so-called scientific revolution in the 17th century, that variability (requiring the application of statistical theory), if its presence was acknowledged at all, played a decisively minor role in fields such as physics.[4] This is less the case currently, for example, quantum mechanics is now viewed in probabilistic terms. Nevertheless, the prevailing view, until recently, held that the physical phenomena observed in astronomy and physics was subject to readily predictable laws, which were unchanging with time. Although, it was recognized that the origin of stars as well as the origin of the universe, both implicitly implying change, such change was very slow, on the order of millions of years. Moreover, the orbital positions of planets could be predicted with a high level of reliability for many years into the future. Consequently, within this framework, the idea of evolution or change was not of major importance in physics.[5]

Two other aspects, associated with the successes of science since the 17th century, and which became the prevailing ideology at least until the middle of the 20th century, were the ideas of *mechanism* and *reductionism*. In brief, mechanism refers to the presence of regular order to the universe and everything in it, allowing prediction and mathematical laws. Thus, once the laws describing orbital motion were correctly deduced, process in physics and, especially, astronomy seemed to be immutable and unchangeable for all time. Reductionism refers to the ability to reduce all phenomena, including living organisms, to the same fundamental laws that comprise chemistry and

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[3] To meet changing environmental conditions, species have to have the capability to adapt. This adaptation (based on mutation, the ultimate source of variation, and natural selection) is dependent on the gene pool, which must contain enough variability to insure survival in a constantly changing environmental landscape.

[4] The serious study of variability can be traced to the rise of statistics at the ending decades of the 18th and the beginnings of the 19th century (see Chapters 2 and 4).

[5] For a recent and novel view of the physical sciences from an evolutionary perspective, see the works of Sheldrake (1988; 1995).

physics. While at one level, living organisms are subject to biochemical laws, such knowledge has become of increasingly limited use in discerning the nature of those processes acting at the organismal level. As Mayr has cogently indicated:

> Living organisms form a hierarchy of ever more complex systems, from molecules, cells, and tissues through whole organisms, populations, and species. In each higher system, characteristics emerge that could not be predicted from knowledge of the components (Mayr, 1997:*xiii*).

The direct application of the laws of physics and chemistry to biology in a reductionist program, while attractive, has had only limited success. Such efforts should be largely abandoned because of the three principles: variability, complexity and history, preclude the direct application of such laws, except in specialized cases. The next section introduces the idea of quantification, which is a central theme of this volume.

1.2. THE ISSUE OF QUANTIFICATION

Why is measurement important? Three broad reasons can be provided. These are: [1] in the process of observing natural phenomena, the need to record its occurrence, [2] in identifying relationships and generalizing about the phenomena, and [3] in developing theories leading to prediction of new phenomena.

It can be said that without quantification there can be no mature science. This is largely true in the physical sciences. Nevertheless, progress in quantification in the biological sciences; that is, the 'softer' life sciences such as anthropology, biology, zoology, etc., has been considerably slower in contrast to the 'exact' or physical sciences (physics, chemistry, astronomy, etc.). As mentioned earlier, one reason for this state of affairs is that the objects of study in the biological sciences, at least on one level, are notably more variable and complex.[6] This has made it considerably more difficult to apply the quantitative methods that have proven so successful in the physical sciences (Bailey, 1967). Initially, with the rise of the natural sciences, the need for quantification of biological organisms was rarely contemplated, except for simple enumeration. Accordingly, it can be presumed that quantification was simply not considered particularly relevant to the issues being addressed. Therefore, most of the biological sciences were initially (and it can be argued that to a considerable extent, still are) largely descriptive. Fauna and flora, for example, were and continue to be described in terms of color, structural differences, behavioral considerations, adaptation to environments, and so on. These aspects determined similarity and differences between organisms and led to systems of classification (taxonomy). Another reason that may have initially acted to inhibit the use of numerical techniques, may be the fact that the human brain, concomitant with a highly well-developed visual system, provided descriptive information that served the biologist's purposes and answered the questions being then raised. It was only when the issues considered important changed; especially, as *process* in contrast to classification became more important, that it was gradually recognized that the descriptive approach, by itself, was not sufficient. The definition of

[6] This complexity arises because the subjects of study in the biological sciences are (or were at one time) living. This confers them with additional attributes not found in the materials studied in the physical sciences.

process as used here is intended to convey the following meaning. By process, what is broadly meant is the elucidation of those forces that shape the biological form during development, evolution, or due to functional or biomechanical constraints.

Any discussion of quantification in science must necessarily start with a basic discussion of the nature of measurement. That is, measurement must: [1] be an *operationally definable process*, [2] be *reproducible*, [3] have *validity*, and [4] be based on *aggregates* (Wilks, 1961). An operationally definable process means that the procedures involved must be defined in objective terms so that comparable results can be independently obtained by other investigators. Measurement may be as simple as counting or as complex as measuring with sensitive instruments, phenomena as elusive as the speed of light. The second basic requirement is that of reproducibility. That is, repeating the process of measurement to produce a reasonable agreement among different investigators. Unfortunately, the need for the reproducibility of measurements is often not cited adequately in the relevant scientific literature. This issue of reproducibility is briefly taken up in Chapter 2.

The third aspect, validity, is not to be confused with reproducibility. Validity is considerably more difficult to obtain. It does not refer to the replicability of repeated measurements, but rather to how close the numerical value of a measurement is to the 'true' value as either determined from an independent procedure or derivable from statistical considerations. Clearly one should strive for both high reproducibility and high validity. Unfortunately, the problem that arises is that such an independent procedure (or theoretical model or expectation) is the exception rather than the rule, especially in the biological sciences. Therefore, one has to rely not only on the experimental rigor of the measurement procedures used but also on logic to prevent contradictions or inconsistencies in the data and subsequent analysis. In addition, careful attention is required to insure that the measurements are derived from independent sources.

The last issue of quantification, aggregation, is concerned with what Wilks called 'aggregates or systems of measurements'. This is particularly important because you cannot base reliable conclusions on the study of a single individual object or single measure. This requires an aggregation in some fashion of the measurements from each individual member of a *sample* of objects drawn from the *population* of all objects. A primary and important purpose of such an endeavor is to arrive at some measure of the variability in the sample as well as estimating some statistical measures such as means, variances, and more sophisticated parameters. Moreover, for this process to be scientifically valid, it is necessary that the samples selected from the population be based on randomization principles. These three quantification principles are developed further within the framework of the scientific method (Chapter 2).

Finally, one may raise the question of why the need for measurement at all. Interest aside, how many undergraduate majors still choose the biological sciences in the hopes of avoiding the need to learn mathematics beyond the absolute basics. The reader may be assured that this is by no means a modern dilemma. As D'Arcy Thompson indicated:

> The introduction of mathematical concepts into natural science has seemed to many men no mere stumbling-block, but the very parting of the ways. (Thompson, 1942:11).

Additionally, description, in contrast to quantification, still forms a large part of the subject matter of the biological sciences today. Nevertheless, one reason for the use of mathematical descriptions in contrast to purely descriptive or verbal ones is that much greater clarity, objectivity and precision can be attained. Again, in D'Arcy Thompson's words:

> The mathematical definition of "form" has a quality of precision which was quite lacking in our earlier stage of mere description; it is expressed in few words or in still briefer symbols, and these words or symbols are so pregnant with meaning that thought itself is economized (Thompson, 1942:1026).

Finally, there is one more reason why a quantitative approach is to be preferred in the analysis of the biological form. The human visual system, while highly sensitive to movement and color, is considerably less sensitive to small structural details in a complex image or to subtle changes in the contour of an outline. When confronted with, for example, irregular outline data, unless the differences are pronounced, the visual system can be overwhelmed, with the result that fine distinctions can be missed. This is another justification for the use of quantitative descriptions of form. Moreover, today most published papers in the biological sciences will contain quantitative aspects (Chapter 2).

1.2.1. What is Morphometrics?

In a very basic sense counting and measuring are extensions of observation and induction, ancient methods that have been developed for the purpose of exactness and precision (Searles, 1956). Accordingly, all of us use morphometric principles on a daily basis, even if we are not consciously aware of the procedures involved. Our language *even reflects morphometric descriptions. For example, when traveling and we ask how* far is it to the next town we are asking a morphometric question. The answer of 25 kilometers represents a distance, in effect a morphometric variable of the type grounded in everyday experience. If we are attempting to repair the leg of a table, we will have to use a ruler and carefully measure the wood to be used to replace the broken leg. Again, morphometric principles come into play and lead to what might be called naïve morphometrics. The use of naïve here is intended in the philosophical sense (*e.g.*, a naïve realist). Clearly, morphometrics has ancient roots since the need for measurement goes far back in historical times, if not earlier (Chapter 3). The act of measurement then, is central to morphometrics, but as will be seen in this volume, modern morphometrics is much more than just measurement.

Although the etymology of the word 'morphometrics' seems to convey a straightforward meaning (Greek: *morph* = form, *metrikos* = measure), this is misleading for a number of reasons that will be made clearer subsequently. To begin with, the naïve morphometric examples given earlier generally represent solutions to practical everyday needs. While undoubtedly essential, and the very fabric of many occupations and professions, carpentry, engineering, etc., they tend to be ends in themselves. That is, once the measurements have been obtained, it becomes a relatively simple matter to construct the object (say a table leg) of interest. In other words, here mensuration is largely the means to an end. The validity of the measurements themselves is scarcely questioned as long as they are perceived to satisfactorily facilitate the desired result.

In contrast to such practical solutions, scientific endeavors cannot be so easily characterized because the measurements utilized may be complicated and often require sophisticated instrumentation and, more importantly, can have a direct influence on the outcome. This issue will be explored in some detail in chapter 4. Consequently, the application of morphometrics to biological data (the central focus of this volume dealing, after all, with biological morphometrics) turns out to be a considerably more challenging affair than might appear at first glance. Two reasons for this situation are: [1] none of the methods currently available are generalized enough to serve as a complete representation of form; and [2] of the lack of a formal unifying model underlying the measurement of form in terms of recognizable general factors that provide explanations for biological processes. With respect to these issues, little substantial progress has been made since the Zuckerman symposium on growth and form fifty years ago, which touched on some of these issues (Zuckerman, 1950).

The first volume to use the word morphometrics in the title was the pioneering work called *Multivariate Morphometrics* (Blackith and Reyment, 1971), which was followed with a considerably slimmer second edition (Reyment, *et al.*, 1984). These two volumes focused attention on morphometrics, although in rather narrow terms characteristic at that time.

Morphometrics is currently a dynamic field of study undergoing major changes. In particular, the last three decades have been instrumental in the development of new approaches, which have led to significant changes in the way morphometrics has been fundamentally viewed (Rohlf and Bookstein, 1990; Rohlf and Marcus, 1993; Marcus, *et al.*, 1996). Consequently, what has emerged are not only new, more sophisticated procedures, but an increased recognition of the need to model the morphological form as it really appears in two and three dimensions. Thus, since the 1970's, theoretical developments have made the comparatively new discipline of morphometrics into a flourishing, robust and expanding research area. Presumably, these developments will greatly accelerate in the next century.

Morphometrics consists of procedures, which facilitate the mapping[7] of the visual information of form into a mathematical (symbolic) representation (Read, 1990). Thus, morphometrics as viewed in this volume, consists of a considerably broadened definition that encompasses, at this moment, a number of separate and distinct approaches that are intended to deal with the numerical description of form. These approaches are briefly outlined below (Section 1.3) and represent the subject matter of Chapters 7 through 10. Ultimately, these diverse approaches will need to be merged into a coherent and unified model. Chapter 6 attempts to incorporate various aspects of an object into a formal model of form.

Finally, in parallel with the increasing number of morphometric methods aimed at numerically describing the biological form, there have also been developments in imaging, data acquisition and storage procedures. This has become a necessity for the

[7] Another word for mapping is *function* or *transformation* Given two *sets*, S and T, a function, *f*, is a mapping (rule) from S to T such that for any member of the *domain* set S, one can find a corresponding value in the *codomain* set T (the *range*). This mapping is generally *one-to-one* unless stated otherwise.

efficient collection, management and analysis of large data sets. It is of special importance for boundary outline methods (Chapter 9) and in the extraction of numerical information dealing with structure from complex images (Chapter 10), where one may need to repeatedly retrieve stored images. Nevertheless, ***image acquisition*** per-se, can be considered as a distinct and separate development from ***numerical description***, the central focus of this volume. A number of authors have dealt with the issue of automatic 'image acquisition' (White *et al.*, 1988; Rohlf 1990; Jacobshagen, 1981; Glasbey and Horgan, 1995), and these may be profitably consulted by the interested reader.

1.2.2. From Morphology to Process

While quantification of the biological form must be viewed as one, if not the most essential step in the elucidation of *process* in the biological sciences, it is essential not to lose sight of the purpose of the scientific endeavor in the biological sciences. This is to provide explanations of process based on appropriate deterministically acquired facts. However, facts alone, either as descriptive data or subsequently as numerical data, while critically important to the research enterprise, in themselves, do not constitute explanations of process. As Read has noted:

> Directly or indirectly, form is central to our understanding of biological and genetic processes. The form mediates between internal genetic information and external environment; it is the means by which genetic information is evaluated and acted upon by natural selection (1990:417).

For example, it has been implicitly obvious for a long time now that the biological form not only changes its size but also its shape in rather complex, and at times, unpredictable ways during growth. In D'Arcy Thompson's words:

> And while growth is a somewhat vague word for a very complex matter ... It deserves to be studied in relation to form: whether it proceeds by simple increase in size without obvious alteration of form, or whether it so proceed as to bring about a gradual change in form ... (Thompson, 1942:15).

The biological form is subjected to numerous forces, some known and some potentially still unknown. Some of these forces are known to act concomitantly. These forces include long-term time-dependent processes such as evolution, as well as shorter-term ones occurring during growth and development. In addition, functional forces such as biomechanical loadings imposed on the individual during the life cycle; need to be considered (Oxnard, 1980).

Figure 1.1 (adapted from Giordano and Weir, 1985) is an attempt to illustrate the relationship of the measurement endeavor to the biological process, as a simple closed system. This closed system is composed of five distinct procedural steps, which are: [1] observation, [2] simplification, [3] analysis, [4] interpretation, and [5] verification. In brief, we start with a biological system from which we gather sufficient data to formulate a model. Data to be used in formulating the model must be: [1] sufficient and [2] simplified. Simplification is generally indicated; otherwise, it may become impossible to build the model.

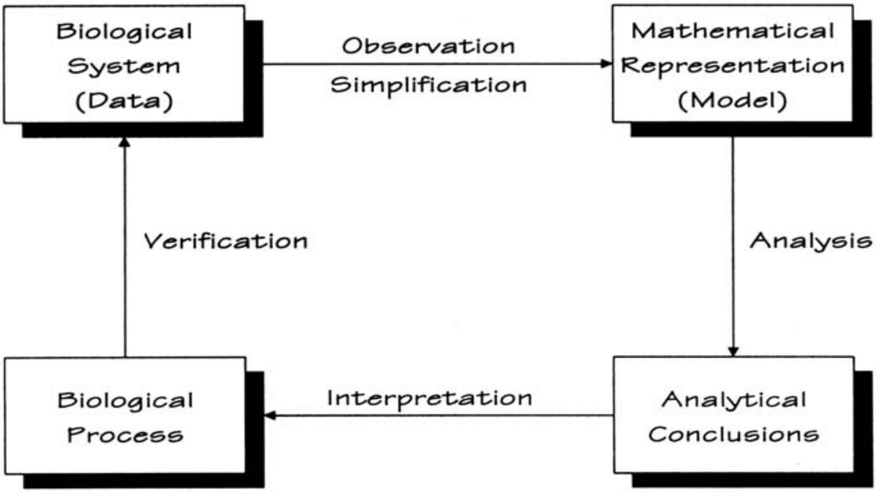

Figure 1.1. Modeling of biological processes.

The model is then analyzed and conclusions are drawn about the biological process being modeled. These conclusions lead to interpretations about the biological process. These interpretations, in turn, lead to changes, refinements and improvements in the implementation of the model. The validity of the model is then tested using new and/or independent data.

Ideally, this approach should guide the eventual development of tentative 'predictions' about the biological process. While such predictions, in all probability, will not have the exactitude of the physical sciences, their utility should not be discounted. In other words, numerical description should eventually lead to explanations of process. Nevertheless, as mentioned earlier, it is essential not to lose sight of the fact that morphometrics and the numerical data produced are not explanations of process (see Chapters 5 and 6 for more details). A discussion of some of these issues can also be found in Lestrel (1997).

Finally, if the focus is on time-dependent processes (*e.g.* growth), these require that changes in form be measured over time. Such measurements, if they are to precisely capture global changes of form, are not at all trivial and present a number of unresolved problems. These problems continue to persist, in part, due to a long-held but unwarranted assumption that the measurement procedures applied to biological organisms, are straightforward, easily invoked, and therefore requiring little consideration. That this is illusionary should become increasingly apparent as one proceeds through the chapters of this book. This volume then, is an attempt to provide an introductory background to these and other issues, as they relate to the description and analysis of morphological forms as viewed in the biological sciences.

1.3. CONTENTS OF THIS VOLUME

Currently, morphometrics, as viewed here, represents the combination of a number of distinct approaches dealing with the numerical description of form. Each utilizes data sets in unique ways and focuses on different aspects of the form. Moreover, these approaches have tended to be considered independently from each other because of a lack of a formal unifying model.

This book is divided into two parts. Part I, which is both introductory and theoretical in tone, is composed of chapters 1 through 6. The discussions here are an attempt to place morphometrics into a scientific framework starting with a brief description of the scientific method (Chapter 2).

One justification for approaching the study of modern morphometrics from a historical viewpoint is that by reviewing the activities and beliefs systems of ancient and medieval societies, can greatly assist in an understanding of the various developments that have led to modern science in general and to measurement in particular. Therefore, chapter 3 presents a brief historical treatment of the developments in science, especially where they impinge directly on the idea of quantification or measurement. The eventual development and increasing use of quantification in biology is covered in chapter 4. Part I ends with a discussion of complexity, leading to a tentative development of a formal, if heuristic, model of form (Chapters 5 and 6).

Part II, composed of chapters 7 through 10, focuses on the various morphometric methods currently employed by biological investigators. No attempt is made at completeness as the field is constantly changing, new methods are developed, and old ones are applied in new and novel ways. Four distinct strains of morphometrics can now be distinguished. The first one is *multivariate morphometrics,* which is typically applied to data sets composed of distances, angles and ratios (Chapter 7). *Coordinate morphometrics,* which focuses on deformations, including biorthogonal grids, finite elements and thin-plate splines (Chapter 8). *Boundary morphometrics,* is concerned with the boundary outline of the biological form, and involves methods such as median axis analysis, Fourier descriptors, eigenshape analysis, elliptical Fourier functions and wavelets (Chapter 9) and, *Structural morphometrics,* consisting of techniques such as Fourier transforms, coherent optical processing and, again, wavelets (Chapter 10). It is the author's hope that future research efforts will be devoted toward approaches that will provide for a more complete analysis of the morphological form, and especially how it changes in response to biological processes.

1.4. A NOTE TO THE READER

The purpose of this volume is to relate the subject matter consisting of the various strains of morphometrics into a unified and understandable fashion. This should allow the interested reader to see possible applications and encourage the utilization of these techniques in their own work. This book should not be construed as being, in any sense, complete in scope. That is not realistically possible given the explosive developments in the various disciplines concerned with morphometrics, rather it should be considered as 'work in progress'. It is intended, however, to reflect some of the current trends in the field as visualized by the author.

While technical terminology will be kept to a minimum, at times its use is unavoidable. Specialized scientific and philosophical terms are explained as they arise, particulars of which can be obtained from the references provided. A basic knowledge of mathematics is helpful, such as an elementary statistics course, matrix algebra and some exposure to the calculus. However, mathematics is not essential or stressed here for a basic understanding of the morphometric ideas presented. The material is presented with a minimum of mathematics so it should be understandable by a capable undergraduate or first-year graduate student in the biological sciences. Some equations are necessarily provided for the sake of completeness, but the details are largely omitted, since they are, generally, readily available elsewhere. The student is encouraged to initially skip those areas that may seem mathematically forbidding when first encountered. This will not affect an understanding of the subject matter. The emphasis is not on mathematics per-se, but rather on the utilization of the various techniques currently employed in the analysis of appropriate data sets.

Because of the author's background, initially in engineering and subsequently as a physical anthropologist, the emphasis will be primarily on the types of data encountered in the biological, medical and health sciences, but by no means limited to them. Further, to keep this volume within reasonable limits, space limitations preclude discussion of Procrustes analysis,[8] splines, fractals, fuzzy sets, neural networks, artificial intelligence (AI), chaos theory,[9] etc., all of which are also playing an increasing significant role in morphometrics. Thus, the techniques presented here are not the only ones in common use and no attempt at completeness is intended.

Finally, it might be useful to indicate what this book does not cover. While chapter 2 is a didactic treatment of research principles, it does not deal with statistics per-se. Statistical procedures form an independent although closely related topic to research methodology and books on that subject are readily available (Dunn, 1964; Afifi and Clark, 1984; Zolman, 1993). Although the subject matter of chapters 3, 4, 5 and 6 deals briefly with measurement, initially from a history of science framework and subsequently leading to a number of theoretical issues within what might be termed a 'science of measurement', no attempt is made at comprehensiveness.

Each chapter ends with a summary of key points, exercises to help illustrate the essential issues of the chapter, suggestions for student projects, and extensive references to assist the student with access to the available literature. Finally, a comment with respect to the exercises at the end of each chapter, these should increase understanding of the subject matter. Most of the questions are straightforward in nature; a few do not admit easy answers. These latter ones are intended to stimulate interest in, as well as gain an appreciation and awareness of, the numerous problems inherent in morphometrics.

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[8] Issues dealing with Procrustes analysis can be found elsewhere (Siegel and Benson, 1982; Benson and Chapman, 1982; Chapman, 1990).

[9] Introductory materials dealing with, *e.g.*, fractals, fuzzy sets, neural networks, chaos theory, etc., are now widely available and easily obtainable.

KEY POINTS OF THE CHAPTER

This chapter introduced the concept of morphometrics as measurement within a scientific context. It touched upon the fundamental distinction between natural and artificial forms as seen by the human visual system. This was followed by a brief discussion of the inappropriateness of the uncritical application of mechanistic and reductionist notions to the biological sciences. The chapter then concluded with the need to understand that morphometrics is the first, critical, step toward the ultimate goal of explaining biological processes.

CHECK YOUR UNDERSTANDING

1. Why is morphometrics important in daily life? Cite some examples.
2. Given the examples in #1, some of which might be termed *naïve morphometrics*, contrast them with what you think would be a more rigorous scientific approach to morphometrics.
3. Describe the differences between artificial forms and biological forms. Why have artificial forms been easier to describe in numerical terms?
4. Make a list of English words that are influenced by visual considerations.
5. Can you think of a successful example of the application of reductionism in the biological sciences? Can you give an equivalent example for the mechanistic view?
6. Why is a quantitative explanation preferable to a descriptive one? In addition, when is it preferable?
7. Given the importance of process in biology, can you provide examples of some quantitative models, which have been successfully applied in the biological sciences? What characteristics do such successful models share?

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