On Growth and Form Study Guide

On Growth and Form by D'Arcy Wentworth Thompson

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Introduction

On Growth and Form, first published in 1917 and then republished in 1942 by Cambridge University Press, is D'Arcy Thompson's radical departure from standard zoology. Looking outside the scope of comparative morphology and evolution, he sought to study nature from a mathematical perspective. He looked to both ancient as well as modern texts to pull together his observations on the development of form and structure in living things. The resulting text is a poetic treatise dedicated to the wonders of nature.

What makes his observations so rich is his careful consideration and blending of philosophy, literature, and mathematical principle. The reader may hope to encounter the philosophy of Goethe or Hegel or perhaps the mention of Darwin (who was a personal acquaintance of Thompson's) or Galileo, among others. But what makes the text so remarkable is the melding or blending of the literary and the mathematical. In addition to being a brilliant mathematician and scientist, Thompson was a thoughtful teacher. When discussing the relationship of a sphere to its volume, for example, Thompson looks to Swift's character Gulliver and to the everyday world to illuminate his ideas.

What shines through and adds value to the work as a whole is the author's love of and deep respect for nature and the pursuit of knowledge. As a zoologist, scientist, and philosopher, Thompson leaves very little to chance in his rich and multifaceted approach to biological study, exploring the concepts of growth and form with objectivity that is persuasive to any audience.

Author Biography

Thompson attended Edinburgh Academy and studied medicine at the University of Edinburgh, publishing papers in scientific journals on hydroid taxonomy, or the classification of invertebrate animals, at age nineteen. Eventually leaving Edinburgh, Thompson attended Trinity College, Cambridge, where he tutored Greek to pay for his tuition. He also translated Herman Müller's German work "The Fertilisation of Flowers," which was published with a preface by the naturalist Charles Darwin.

Thompson began his career as a professor of biology at the University College in Dundee in 1884. He worked at the university throughout his life, establishing a teaching museum of zoology and writing papers on various zoological subjects. In 1896, Thompson traveled to Alaska to investigate a dispute between Great Britain and the United States over fur-seal expeditions. The following year, he was recognized for his efforts, earning the title of Companion of the Order of Bath in 1898, and in that same year, he was also appointed scientific adviser to the Fishery Board for Scotland.

A Glossary of Greek Birds was a reflection of Thompson's classical background, a mix of ancient Greek literature and medieval and modern ornithology, (the study of birds as a branch of zoology); it was published in 1895. Considered a companion to the work, *A Glossary of Greek Fishes* followed the effort but would not be published until 1947. The work explored the fish not only from a scientific perspective but considered fish within the realm of art, folklore, and religion. An annotated translation of Aristotle's "Historia Animalium" and a published presidential address from Thompson to fellow members of the classical association constituted subsequent or later publications. *On Growth and Form* followed in 1917, identified in its radical use of mathematics and physics to interpret biological phenomena.

Thompson received many honors during the course of his career. He was elected to the Royal Society in 1916, became president of the Classical Association of England and Wales in 1828, and served as president of the Royal Society of Edinburgh from 1934 to 1939. Thompson was also knighted in 1937 and received the Linnean gold medal one year later. On June 21, 1948, Thompson died after contracting pneumonia while traveling as a member of the Royal Society delegation to the Indian Science Conference in Delhi.

Plot Summary

Chapter 1: Introduction

The author sets up the basic premise behind the title *On Growth and Form* in this introductory chapter. Thompson describes the framework for the text, stating that the study of science is not alone dependent on mathematics, nor is it simply to be viewed as unexplainable, divinely created phenomena. His criticism is that both the scientist and the naturalist, among others, attempt to explain the natural world with a limited focus. The intent of his book is to foster a more diverse approach to the study of the concepts of growth and form from a mathematical perspective.

Kant declared that the criterion of true science is in its relation to mathematics. Adds Thompson, "numerical precision is the very soul of science." Thompson is very careful to point out that he has no interest in reducing the wonders and mystery of the living body to a mechanism (to mathematical formula). He remains an individual who in all creatures is impressed by the beauty manifested in adaptation, that is, the flower for the bee, the berry for the bird. However, he maintains that inquiry into the way in which both living things and physical phenomena grow and take on a specific shape should be approached in the spirit of both scientific theory and mystery. Thompson describes his objective in writing the work as follows:

We want to see how . . . the forms of living things, of the parts of living things, can be explained by physical considerations and to realize that in general no organic forms exist save such as are in conformity with physical and mathematical laws.

More simply put, growth deserves to be studied in relation to form. Both growth and form are necessarily related by mathematical principles, hence the need for a mechanical approach to morphology, or the study of growth and form.

Chapter 2: Magnitude

The form of an object is defined, says Thompson, when we know its magnitude and direction related to the further concept or dimension of time. Growth in length and growth in volume are both parts of one process or phenomenon. Understanding the correlation between length and weight enables us at any time to translate one magnitude to the other by means of mathematical formula. From a philosophical perspective, the author claims that, concerning magnitude, there is "no absolute scale of size in the universe, for it is boundless towards the great and also boundless towards the small." Magnitude presents itself conceptually or as an idea in any combination of ways, based on contrasts such as big and small or near and far, for example.

Chapter 3: The Forms of Cells

Surface tension is due to molecular force, arising from the action of one molecule upon another. In the case of a liquid, the molecules of a surface layer are being constantly attracted into the interior by those molecules more deeply situated within the liquid, explains Thompson. He continues, stating, "the surface shrinks as molecules keep quitting it for the interior, and this surface shrinkage exhibits itself as surface tension. The cell forms explained in the chapter are those forms that a fluid surface can assume under the mere influence of surface tension. This surface tension accounts, for example, for the spherical form of a raindrop. It is smaller organisms or small cellular elements of larger organisms whose forms will be governed by surface tension. Forms of other larger organisms are dictated by entirely unrelated, non-molecular forces. The author points out, for example, that the surface of a larger body of water is level because it is dictated by gravity, but the surface of water within a narrow tube is curved due to molecular attraction (as in the case of a raindrop).

Thompson discusses various surface tension forms and their surfaces of revolution (surfaces symmetrical about an axis), using soap bubbles to illustrate what happens to create various surface tension forms. For example, if a soap bubble is caught by the end of a pipe and the other side of that same bubble is caught by another pipe, the slow pulling apart of both pipes will cause the bubble to take on a cylindrical form. Eventually, the bubble will break. The fragility of the bubble illustrates Thompson's next point-that such surfaces realize complete equilibrium within particular dimensional limits or only demonstrate a certain amount of stability, with the exception of the plane or the sphere, whose perfect symmetry allows for perfect stability.

Chapter 4: Forms of Tissues or Cell Aggregates

The movement of the text has been to discuss the nature of solitary cells and then to discuss the action between two cells. This chapter discusses the impact of cell aggregates, or clusters of cells, and the impact of such groupings upon form.

Thompson begins his discussion by restating a general principle underlying the theory of surface tension, namely, that in the case of fluid to fluid or fluid to gas contact, "a portion of the total energy of the system is proportional to the area of the surface of contact." The author goes on to say that total energy is also "proportional to a coefficient that is specific for each particular pair of substances and is constant for these," with the exception of changes inspired by temperature or electrical charge. In other words, there are numerical measures (coeffi- cients) that dictate the total energy of a system. Equilibrium, or the state in which minimum potential energy is realized in a system, will be achieved by a reduction in surface contact.

In the case of three bodies, the solution to such a problem becomes a bit more complex. In the example of a substance floating on water, there are three surfaces involved in the process of equilibrium, namely, the water, the air above it, and the substance itself. The condition of equilibrium will be reached by "contracting those surfaces whose specific energy happens to be large and extending those where it is small." This contraction will result in production of a drop and extension to a spreading film. Turpentine will contract into a drop when it comes in contact with water, as opposed to olive oil, which will instead spread out and form a film on the water's surface. In the context of either of the previously mentioned examples, a pull for equilibrium on a water surface exists as the result of tensions existing in the other two surfaces of contact. Thompson instructs us to imagine a single particle. If a drop is pulled out by another water particle, without finding yet another providing a counter-pull, "it will be drawn upon by three different forces, whose directions lie in the three surfaceplanes and whose magnitudes are proportional to the specific tensions characteristic of the three 'interfacial,' or smoothly coordinating, surfaces."

The chapter then moves from a discussion on the interactions of particles as a function of surface tensions to the forms aggregates of cells tend to take. Thompson elaborates on the tendency not only of cells, "but of any bodies of uniform size and originally circular outline, close-packed in a plane" to adapt the hexagonal pattern, each cell or body being in contact with six others surrounding it "under widely varying circumstances." Such patterns are evidenced in the bee's cell as it is formed to create the honeycomb, a circumstance Thompson elaborates on in much detail.

Chapter 5: On Spicules and Spicular Skeletons

The deposition of inorganic material in the human body "begins by the appearance of small, isolated particles, crystalline or non-crystalline, whose form has little relation or none to the structure of the organism." This deposition then culminates in the formation of spicules, needle-like structures or parts supporting the tissues of certain invertebrates, as well as in the more complex skeletons of the vertebrate animals.

Thompson warns of the complications in studying such forms. In speaking of what he identifies to be "two distinct problems," Thompson states that what form an inorganic material may take involves two scenarios or situations. "The form of a spicule or other skeletal element may depend solely on its chemical nature," or "the inorganic material may be laid down in conformity with the shapes assumed by cells, tissues or organs moulded to the living organism." The author is suggesting, in this case, that points of attachment, or the way bones conform to other tissues, determine their form. The problem between the two scenarios or situations influencing these bony forms arises from the fact that "there may well be intermediate stages in which both phenomena are simultaneously at work, the molecular forces playing their part in conjunction with other forces inherent in the system."

To clarify the problem of the study of such forms, Thompson turns to the problem of studying crystallization in the presence of colloids, or crystals. Such large crystals of salt may be found in a root of rhubarb or the leaf stalk of a begonia. These crystals, extremely numerous in their varieties and form, are "crystalline forms proper to the salt itself, and belong to two systems, cubic and monoclinic." And in either one, "according to the amount of crystallisation, this salt is known to crystallise."

With these problems in mind, Thompson continues with a careful consideration of the forms of various spicules and other skeletal configurations, focusing on the symmetry of crystallization in the sponge as well as the snow crystal. Thompson also considers the complex patterns arising from crystallized forms, as well as the problem of studying skeletal arrangements arising from fluid crystallization.

Chapter 6: The Equiangular Spiral

"A spiral is a curve, which, starting from a point of origin, continually diminishes in curvature as it recedes from that point; or, in other words, whose radius of curvature continually increases," states Thompson. Basically, as the spiral spins outward, it expands outward as well. Thompson sees the presence of spirals everywhere, in the outline of a leaf, in a lock of hair, or in the coil of an elephant's trunk. He adds that, although they express themselves in a mathematically similar fashion, they are fundamentally, from a biological standpoint, different. Some spirals formed by natural phenomena, such as the spiral shape a snake makes in movement, are momentary, the result of "certain muscular forces acting upon a structure of a definite, and normally an essentially different, form." In other words, according to Thompson, these spirals take on more of an attitude or a position than a form, with little or no relation to the phenomenon of growth.

In studying spiral forms, Thompson mentions "several mathematical curves whose form and development may be so conceived, the two most important (1) the equable spiral, or spiral of Archimedes, and (2) the equiangular or logarithmic spiral." The spiral of Archimedes takes a form resembling a rope being coiled in such a manner that each looping of the spiral coil is identical to the one preceding it. A snail shell, in contrast, spirals out, increasing as the shell increases. Each whorl, or circling out, signifies a geometrical progression as the radius increases. Spirals of both plant and shell then are expounded upon in the chapter's remaining pages, in keeping with both mathematical curves.

Chapter 7: The Shapes of Horns and Teeth or Tusks

Mathematical study of the forms that horns take is set aside due to the lack of symmetry of horns. Thompson proceeds from this point to consider the morphology of three types of horns-the rhinoceros horn; the horns of the sheep, goats, and antelope; and the solid bony horns, or "antlers," characteristic of deer.

The rhinoceros horn is "physiologically equivalent to a mass of consolidated hairs." Thompson states that "like ordinary hair, it consists of nonliving or formed material, continually added to by the living tissue at its base." The shape of the horn is elliptical, but some horns may be nearly circular. The horn curves into the form of a logarithmic spiral of a small angle. If the horn occupies a median position on the head, there is no tendency for the horn to twist, and the horn is said to develop into a plane logarithmic spiral. Two median horns are not identical in size, one being smaller than the other and "the rate of growth diminishes as we pass backwards," or move from the first horn "up the rhino's head towards the tail end of the animal." Both horns are essentially the same shape, one (the shorter of the two) with less curvature due to its length.

Thompson describes paired horns, those of a sheep or goat, as being hollow-horned, growing under similar yet sometimes varied conditions from those of the rhinoceros. The horn consists of "a bony core with a covering of skin." The inner layer is supplied with blood vessels, while the outer layer is a fibrous material, "chemically and morphologically akin to a mass of cemented or consolidated hairs, which constitutes the sheath of the horn." A "zone of active growth," or ring at the base of the horn, keeps adding to this sheath, "ring by ring," what Thompson refers to as the "generating curve" of the horn. The two horns, unlike the rhinoceros, are not symmetrical with the animal but are symmetrical with each other, and they form spirals, one being the mirror image of the other. The growth of the horny sheath is described as being periodic rather than continuous (growth in spurts), and this frequency of growth is reflected in the rings of the sheep's horns, which supposedly tell the age of the animal.

"Nail, claw, beak and tooth," states Thompson, all follow the growth pattern of a logarithmic spiral, and the rest of the chapter is dedi cated to these forms as they express themselves morphologically.

Chapter 8: On Form and Mechanical Efficiency

The form bones take is the subject of Thompson's next morphological investigation. Tension and compression are first explained to shape a discussion on bone strength. The author says that "in all structures raised by engineers," there is a need "for strength of two kinds, strength to resist compression or crushing, and strength to resist tension or pulling asunder." Whereas some structures, like a wire rope, realize power in tensile stress (resistance by pulling), others, like a column, are loaded to support a downward pressure. Each has a separate function yet can function effectively, complementing one another as part of a system. Thompson refers to the architecture of a suspension bridge to illustrate this point. In this structure, the ropes and wires of the fabric are subject to tensile strain only, built throughout a series of ropes and wires, while the piers at either end of the bridge support the weight of the entire structure. There is an easilydrawn parallel aptly made to the structure of living organisms:

ligament and membrane, muscle and tendon, run between bone and bone; and the beauty and strength of the mechanical construction lie not in one part or in another, but in the harmonics concatenation which all parts, soft and hard, rigid and flexible, tension bearing and pressure-bearing, make up together.

It is the form the matter adopts that determines its strength, no matter how hollow or solid. The long bone of a bird's wing, for example, is a tubular structure that, although carrying very little weight, is forced to endure "powerful bending moments." Because this bone is a hollow rather than solid bone, it reacts to such force, (i.e., the wind, as it is flying) without snapping, the hollow construction providing some flexibility. It is this hollow construction that creates a stiffness or rigidity necessary to support the bird's wing in flight without snapping. Thin, cylindrical tubes, by the very nature of their shape, also tend not to buckle, as in the joints of a crab's leg, says the author.

Essential to the study of the way bones form to act as supporting structures is an understanding of how stress and compression influence two specific forms. The first situation involves a bending beam. If the stress is applied to a beam, it will be greatest in the middle, and the beam will naturally snap midway, as would a walking stick pressed down against the ground. In reaction to such a strong load, it would be prudent to construct a walking stick or a beam with thick walls in the middle, thinning off gradually at the ends. The resulting structure creates bending moments all along the structure, thus diverting the possibility of what Thompson calls a "danger point," as in the midsection of a walking stick, that would cause the structure to give.

The second point Thompson considers vital to a discussion on form and mechanical efficiency is best explained in the construction of a beam supported by a bracket. The beam attached to a wall by way of a bracket might react a bit differently to an applied load. The point at which the beam is mounted is subject to some pressure, that is, where the lower surface or part of the beam and the wall meet, directed horizontally against the wall. The beam is also subject to pressure or force from an immediate load bearing down upon it. There is an intersection of pressure, called compression lines, crossing as a result of the load, reflecting both the beam's reaction to a specific load and the horizontal load at the base of the beam and bracket. Accordingly, it is tension lines functioning together to carry a load.

Based on the principles of load-bearing and strength, Thompson works throughout the remainder of the chapter to explain the variety in shape of various bones and their structures and how these forms interact to support the structure of an organism.

Chapter 9: On the Theory of Transformations, or the Comparison of Related Forms

Recalling the progression of the text in a sweeping fashion, Thompson recounts his thesis and his mathematical approach to the study of growth and form. He points out that the movement of the text in its description of morphology moves from more common forms of speech to precise mathematical language. The result of this movement is a more desirable definition of morphology, one based on economy, on a few words or symbols "pregnant with meaning."

To Thompson, such strict or rigid language is not limiting but instead opens up myriad possibilities. "The precise definition of an ellipse," he states, "introduces us to all of the ellipses in the world." In other words, the ellipse expresses itself in countless numbers of natural forms. Every natural phenomenon is a composite and every visible action and effect is the result of countless subordi nate actions. In other words, more elementary mathematical principles lead to any number of related conclusions. Though there are many forms that are indescribable by mathematical terms, such as a fish or the vertebrate skull, "the shape of a snail-shell, the twist of a horn, the outline of a leaf, the texture of a bone, the fabric of a skeleton, the stream-lines of fish or bird, the fairy lace-work of an insect's wing," can all be described mathematically.

Although a figure may be left undefined by such principle, the process of comparison, of recognizing in one form a deformation or alteration in the other, does lie within the province of mathematics, states Thompson, and is called the "Method of Coordinates." He defines this method as "a way of translating the form of a curve (as well as the position of a point) into numbers and into words." The study of a statistical curve, for example, is accomplished using the method of coordinates, as is the series of numbers used to plot such a curve. In a related scenario or exercise, the outline of a fish could be plotted in a net of rectangular coordinates and then translated into a table of numbers, as could the outlines of other natural forms. The balance of the chapter is dedicated to such endeavors.

Chapter 10: Epilogue

Summing up the efforts of his work, Thompson reiterates his intentions in writing the work: "I have sought to show the naturalist how a few mathematical concepts and dynamical principles may help and guide him." He adds, "I have tried to show the mathematician a field for his labour-a field which few have entered and no man has explored." He finishes the work by praising the importance of morphology, stating during his argument that "the harmony of the world is made manifest in Form and Number, and the heart and soul and all the poetry of Natural Philosophy are embodied in the concept of mathematical beauty."

Themes

Intellectuals and Intellectualism

Thompson undoubtedly takes great pains to bring his audience along with him in a consideration of the concepts of growth and form. At no time, however, does he suggest the topic is easily simpli- fied. His very mode of explanation is proof positive of the level of intellectual engagement necessary to figure out biological mysteries such as the study of morphology presents. He supports his assertions by quoting classic philosophers and scientists as well as more contemporary intellectuals, references suggesting an engagement of rational, intelligent thought.

On the theory of transformations, or the comparison of related forms, in chapter 9, Thompson draws on the principle of Aristotelian "excess and defect" in a discussion of the comparison of related forms. The reference is timely and reiterates the same ideas present throughout the text. On Aristotle's definition of genus, or class of forms, the author states
he showed that (apart from those superficial characters, such as colour, which he called 'accidents') the essential differences between one 'species' and another are merely differences of proportion, of relative magnitude, or (as he phrased it) of 'excess and defect.'

Another impressive aspect of such references is the endless variety they represent. Such variety demonstrates not only the level of intellectual engagement morphology demands, but it underscores the literal genius behind the work, namely Thompson. Throughout the work, he draws on the wisdom of philosophers Descartes, Goethe, and Hegel, astronomer Galileo, literary giant Herbert Spencer, and physicist Albert Einstein, with a decided authority, indicating Thompson's varied background and great intellect.

Logical and Illogical

Thompson employs a hierarchy in the text to organize his discussion of morphology. The resulting movement of the text is very precise and logical in its construction, successfully demonstrating the author's valid reasoning. Thompson very carefully guides his readers through the discussion. First, he states his thesis, working from a very general argument, namely, that

My sole purpose is to correlate with mathematical statement and physical law certain of the simpler outward phenomena of organic growth and structure or form, while all the while regarding the fabric of the organism, *ex hypothesi,* as a material and mechanical configuration.

The text then moves, chapter by chapter, in the same fashion, Thompson continuing to act as guide, but moving from the specific to a much broader context. The text moves, as stated by the author in chapter 4, from the subject of the single cell to the interaction between two cells to the activities of groups of cells and finally on to the study of the complex tissues to which cells contribute.

Great consideration is also given to the study of an individual topic within the scope of the chapter. Each topic is edified or strengthened by a mathe matical premise or formula. Accordingly, each mathematical formula is followed by an example, an instance in nature that puts the formula into a sharper, more practical perspective for the reader. For further clarity, each topic is also enhanced by the presence of detailed illustrations. Unexplainable phenomena are classified as being a function of the divine, the unexplainable; therefore, the illogical is made logical by default.

Nature and Its Meaning

Central to Thompson's work is the investigation of morphology in relation to nature. Also central to the work is the author's intense admiration for and fascination with natural forms of various kinds. His careful examination and consideration of such forms is apparent in the scope of knowledge that the author draws upon to explain the shape of a honeycomb or the crystals of a snow- flake. Thompson is apt to explain the smallest of physical aspects, taking care to account for growth and form in great detail, such as the form a splash of liquid takes. The appearance of a breaking wave of a splash, an observation based on what the author characterizes as "beautiful experiments on splashes" is described as

the smooth edge becomes notched or sinuous, and the surface near by becomes ribbed or fluted, owing to the internal flow being helped here and hindered there by a viscous shear; then all of a sudden the uneven edge shoots out an array of tiny jets, which break up into the countless droplets which constitute spray.
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Employing such thorough description demonstrates the effort Thompson takes to consider his biological subjects thoughtfully. It is this methodology, a system of great care reflecting a serious consideration of the subject, that the author employs, which seems to support his respect for natural form.

Thompson does indeed demonstrate his love affair with nature in several ways. For example, the text often engages in nature worship, specifically in its references to various experts in various disciplines (i.e., philosophers, scientists, and physicists). It is not uncommon to find references to intellectuals like Pappus the Alexandrine, a Greek mathematician who spoke in admiration of the bee's architectural skills, "that bees were endowed with a certain geometrical forethought." In another instance, he mentions a "beautiful discovery," a specific "Gestaltungskraft," or molecular force.

Most fitting, perhaps, to convey the deep wonder and appreciation Thompson has for nature is found in his comments concerning "many a beautiful protozoan form" difficult to account for mathematically. His reaction to this challenge he thus states: "That Nature keeps some of her secrets longer than others-that she tells the secret of the rainbow and hides that of the northern lights-is a lesson taught me when I was a boy." Nature is described as a great spectacle of mystery, wonder, and awe, personified, named, and, by implication in conjunction with Thompson's gender reference, truly named the mother of all, or the final determinate in the study of morphology.

Style

Allusion

Thompson draws on any number of familiar events, characters, or concepts to illustrate his ideas to make them clearer for the reader. In one particular instance, for example, the author makes reference to Jonathan Swift's *Gulliver's Travels* in his discussion of similitude. The principle of similitude, based on the idea that "in similar figures the surface increases as the square, and the volume as the cube, of the linear dimensions" is compared to an instance in Swift's Lilliput:

His Majesty's Ministers, finding that Gulliver's stature exceeded theirs in the proportion of twelve to one, concluded from the similarity of their bodies that his must contain at least 1728 [or 12 to the third power] of theirs, and must needs be rationed accordingly.

In the footnotes following the passage, Thompson also cites that Gulliver had "a whole Lilliputian hogshead for his half-pint of wine: in the due proportion of 1728 half-pints, or 108 gallons, equal to one pipe or a double-hogshead." Such passages draw on the practical or everyday, and in doing so help the reader make connections between the abstraction of mathematics and real world scenarios, thus providing clarity to otherwise challenging ideas.

Argument

The principal driving Thompson's work is a dramatic departure from traditional zoology because it makes a case for interpreting biological phenomena by way of mathematics and physics. The opening chapter of the work is written in defense of Thompson's method of scientific study.

For example, the author does not refute the idea of final cause, man's consistent pattern for explaining his world, which involves explanation of creation as being a function of purpose or design. Rather, Thompson demonstrates his desire to enhance such study by example. He draws on Aristotle's parable in which "the house is there that men may live in it; but it is also there because the builders have laid one stone upon another." Working from the passage, Thompson points out that "it is a mechanism, or a mechanical construction, that the physicist looks upon the world."

The assertion that traditional consideration of morphology, or growth and form, is enhanced by the introduction of mathematical and mechanical principles is demonstrated in the balance of the text. His defense is furthered by example, whether it be in regard to the hexagonal faces of a snow crystal or when comparing the conformation of a horse's skull to that of a rabbit's.

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Classicism

What makes Thompson's message so powerful is precisely that he chooses to support his ideas by turning to ancient Greek and Roman literature, philosophy, and art. The text is loaded with such references. For example, in a discussion of the equiangular spiral, Thompson credits the earliest investigation, if not the discovery, of the spiral to Archimedes, a famous Greek mathematician and inventor who was known for his work in mechanics and hydrostatics. In speaking of the mathematical definition of form, he also mentions

We are brought by means of it in touch with Galileo's aphorism (as old as Plato, as old as Pythagoras, as old perhaps as the wisdom of the Egyptians), that the book of nature is written in characters of Geometry.

Plato is a well-known Greek philosopher, who, with the help of Socrates and Aristotle, laid the foundations of Western culture. Greek scholar and mathematician Pythagoras was known for making great advances in both mathematics and astronomy.

Image

Literal images are employed often throughout the work. They are concrete and involve little or no extension of the words used to express them; rather, their value is in description. Thompson's images help to clarify the basis of his discussions and also give emphasis to the beauty and wonder of the subjects he is describing. "The large waxen honey cells are nearly spherical, nearly equal in size, and are aggregated into an irregular mass," says Thompson of the bee's honeycomb. He continues to describe their shape, stating that their spherical form is only visible from the outside of the mass of cells, "for inwardly, each cell is flattened into two, three or more flat surfaces, according as the cell adjoins two, three or more other cells." Ultimately, these cells, he adds, when resting on other spheres of similar size, are the three surfaces "united into a pyramid." This description is a "gross imitation of the three-sided pyramidal base of the cell of the beehive."

Historical Context

Introduction

The character of life in 1914, while outwardly chaotic, was driven by what Dr. Alan Axelrod, author of *The Complete Idiot's Guide to 20th Century History,* termed an "inner order, a logic all its own, a myriad of secret alliances that linked the fate of one nation to that of another." It was a world on the verge of explosion.

Noise and Art

Igor Stravinsky's work was an expression of chaos out of logic. Stravinsky was a budding young Russian composer who created scores for the radical ballet *The Rite of Spring* in 1913. The music had a violent, sexual quality and was quite primitive in feeling. The rhythms were intensely erratic, the music discordant. The work was a mirror of a man working from a primitive urge to create a modern, highly complex work in a way that no one had quite experienced. It was a deeper expression, a mirror of this tension of logical inner workings producing an outwardly chaotic sound and feel present in contemporary life. Parisian audiences were moved to tears or to riot-the music was viewed as either a modern triumph or the downfall of Western art and culture.

In New York, a new and different type of art was also raising eyebrows at the International Exhi bition of Modern Art. It featured the works of the antiacademic artists, Paul Cezanne, Henri Matisse, Pablo Picasso, and Marcel Duchamp. The most controversial of the works, "Nude Descending a Staircase," was not true to any conventional form and made no attempt at capturing reality as was traditional to art up to this time. The aim of Duchamp was to capture relative time and motion. His nude was portrayed from various perspectives as well as from different points in time, but simultaneously. The artist himself stated, according to Axel, "I have forced myself to contradict myself in order to avoid conforming to my own taste." The same reviews prevailed-either audiences appreciated the work for its melding of art, physics, and psychology to amplify the relative nature of reality or they hated the work for such a dramatic departure from tradition.

Political Unrest in Europe

In 1914, Germany and Austria had formed a political alliance, and France and Great Britain had formed another. These alliances were defensively formed in a clearly hostile atmosphere that characterized Europe at this time. The pacts amongst nations were vague, and the race for the accumulation of weapons was real. When Austria-Hungary seized Bosnia without Russian approval, Russia criticized the action, as did Britain and France. Germany, on the contrary, supported Austria, deepening the rift amongst countries. The assassinations of Austrian Archduke Francis Ferdinand and his wife

Sophie by rebel Serbs, on June 28, 1914, would be the catalyst for a war occurring only months later.

World War I

Europe was torn apart by the conflict, which involved the participation of thirty-six nations spanning Europe, colonial Asia, as well as Africa. Dr. Alan Axelrod characterizes World War I, claiming

The battle was among the most futile of a war that consisted of a seemingly endless chain of futile battles. Losses from enemy fire, as well as disease and thirst, were staggering, in excess of 200,000, and nothing had been gained by the time the allies were forced to withdraw.

Particularly for the British, the battle at Gallipoli was a tragedy for the British military. Axelrod claims that the lack of ability to plan and mobilize an attack successfully extended the war in addition to causing terrible loss of human life, particularly for the British. Axelrod also fittingly quotes Ber trand Russell, English mathematician and philosopher, in a Letter to the Nation:

And all of this madness, all this rage, all this flaming death of our civilization and our hopes, has been brought about because a set of official gentlemen, living luxurious lives, mostly stupid, and all without imagination or heart, have chosen that it should occur rather than that any one of them suffer under the infinitesimal rebuff to his country's pride.

Before the War

Perhaps the war influenced Thompson's great passion for nature and, by extension, for life, as well as fueled the spirituality threading its way in and out of the text of his work with some frequency. Certainly, earlier in the decade, there were other pioneers who would serve to inspire him with their fantastic, if not revolutionary, discoveries.

Sigmund Freud, a Viennese physician, would also introduce his theories on sexuality, theories that would fundamentally change the approach to the study of human sexuality. In his theories, he expressed the belief that human sexuality was linked to the unconscious mind and was a drive that spanned a lifetime from infancy through childhood and far into adulthood. Although the reaction to Freud was initially one of outrage, he developed a following, his theories leaving a permanent impression on the study of the human psyche.

The theory of relativity was also revolutionary in 1905. Albert Einstein, a German scientist, discovered the theory of relativity, a theory that proposes a universe in which the only absolute is the speed of light and in which matter and energy are ultimately equivalent. He demonstrated that matter and energy are not two separate entities but are, in fact, readily convertible. Because of the theory, the views of theoretical reality changed, inspiring such achievements as the successful harnessing of atomic energy.

Critical Overview

The work of D'Arcy Thompson reveals one of the notable intellectuals in scientific history. His work has inspired much praise from critics of scientific theory. Admirers of the text identify specific attributes that provide the framework for Thompson's brilliance.

To begin with, *On Growth and Form* is considered to be one of the greatest pieces of scientific prose of the twentieth century. Dr. Stephen Jay Gould describes Thompson's prose to be "like a Wagnerian opera: it flows on and on in waves of sumptuous sound, with occasional cadences at climactic moments."

Gould, as others, praises not only Thompson's connection of mathematics to the topic of morphology within the text but the way in which mathematics is expressed. He is quick to point out that although Thompson was well acquainted with mathematical theory, he chose to approach the text as a classical scholar. He states, "This book dwells in the Miraldi angle, the Fibonacci series, the logarithmic spiral and the golden ratio."

In his work, "Doing what Comes Naturally: Morphogenesis and the Limits of the Genetic Code," Martin Kemp believes that insights offered by Thompsonian Morphogenesis point to a largely unexplored potential in the study of art, particularly that of the twentieth century. Kemp bases his claim on two simple assertions, one being "the impact of his writings and illustrations on specific artists." His second claim concerns

the discerning of fundamental qualities of structure and process in nature as shared enterprises of art and science, at a time when a significant number of artists were experimenting with various types of abstraction as revealing basic structures behind natural appearance and when science was increasingly concerned with the mathematics and physics of what could not be seen with the human eye.

Criticism

Critical Essay #1

Kryhoski has previously taught English as a second language overseas and currently works as a freelance writer, specializing in literature. In this essay, Kryhoski considers the influence of classic Greek thought on Thompson's work.

On Growth and Form is an amazing testimony to the power of nature and its impact upon the organism, both organic and inorganic. Many scientists marvel at D'Arcy Thompson's discourse, his consideration of morphology in the light of mathematics, and his use of illustrations. Thompson's contributions as a classicist are perhaps most significant in respect to the overall text of On Growth and Form. Looking back to the work of classical Greek scholars and comparing their work to Thompson's is of paramount importance in understanding the work as a whole. Such a comparison reveals that the very foundation of Thompson's work is based upon classical convention-not surprisingly, as Thompson was very familiar with the classics due to the influence of his father and perhaps time spent working on his own education.

Greek literature is but a reflection of thoughts and ideas at the root of Western civilization. The Greeks were linguistic masters, and they enjoyed the challenge of a conversation, having a deep appreciation for clean, economical language to ex press their ideas. This time in history is also considered a time of great intellectualism, represented by numerous scholars of various disciplines, from theatre to philosophy to science to writing. The concept of "know thyself," or the desire for self-awareness, was intensely Greek; for this reason, the Greeks were also considered to be practical, perceptive individuals. All of these qualities seem to resonate in Thompson's work. Thompson indulges in an intellectualism akin to the Greek tradition. He takes great pains to look at any given topic from various perspectives. All of the topics are also supported by evidence from scholars, scientists, and the like. Thompson, to illuminate a particular point for the reader, draws on the views of these men. A deep consideration of the topic of morphology is apparent in Thompson's use of a vast array of resources. Further, it is apparent that the author respects and defers to the expertise of other scholars to enhance his own areas of weakness:

That I am no skilled mathematician I have had little need to confess. I am advanced in these enquiries no farther than the threshhold; but something of the use and beauty of mathematics I think I am able to understand.

This quote reveals a certain humility in Thompson. As educated a man as he was, as well-rounded a man as he was, he was also open to considering his inadequacies, admitting that perhaps his abilities were not as polished or advanced as he might have liked them to be. Such candor in a text working at such a high-level of intellectual engagement is a surprise, yet this insistence on self-awareness and honest self-assessment does fall within the realm of Greek ideals.

Greek influences abound in the construction of Thompson's text, particularly those of Aristotle to whose authority Thompson refers to support the most fundamental and important premise behind his book, that is, his thesis concerning the relevance of mathematical application to the study of morphology. Thompson, in the introductory chapter of the text, draws on a parable of Aristotle's to further defend the need for employing mathematics in the study of morphology. He explains that, "in Aristotle's parable, the house is there that men may live in it; but it is also there because the builders have laid one stone upon another." The words of Aristotle inspire reverence, and in Thompson's choice of words, he seems to equate his parable with the celestial, or higher life or intelligence. In fact, Aristotle was one of the greatest philosophical minds in the history of the world. During his lifetime, Aristotle studied biology and developed investigative techniques that would become a useful contribution to the study of science. From such ideological roots, Thompson has built his morphological studies.

Comparing "Nichomachean Ethics," considered to be one of Aristotle's most popular and influential works, to Thompson's work reveals the influence of the ancient philosopher's writings on Thompson. Aristotole's discussion in "Ethics" deals primarily with the positive side of life. The work is divided into ten books, the first of which will be compared to Thompson's works. Chapter 1, book 1 opens with the following statement: "Every art and every scientific inquiry, and similarly, every action and purpose, may be said to aim at some good." From this premise forward, the work is organized hierarchically. Each of these actions or purposes is addressed in subsequent chapters of the work. Politics, to which Aristotle assigns great importance, is the focus of chapter 2. The aim of politics is primarily to create optimal conditions for its citizenry. In chapters 3 and 4, Aristotle's methodology is established as he engages in the study of politics and ethics. Here, he contrasts the imprecision of scientific inquiry into the study of politics and ethics with that of the study of mathematics, to demonstrate the uncertainty of such study. In chapter 6, Plato's notion of universal good is introduced to further his discussion. Aristotle believes Plato's concept to be impractical, viewing good as a subject defined rather by needs, circumstance, and the individual. Aristotle then considers the effect of the dead upon the living in chapter 11, and chapter 12 is an inquiry into the nature of virtue.

On Growth and Form is constructed in a similar manner, although, whereas Thompson's volume is divided into ten chapters, Aristotle's is divided into ten books. All of the chapters in *On Growth and Form* relate to one main topic of discussion: the study of growth and form. Like Aristotle's opening, chapter 1 of Thompson's work opens with the following: "for that the criterion of true science lay in relation to mathematics." He also works from this premise in a hierarchical fashion, working from the essence of form to its greater manifestations. Thompson communicates this movement clearly in chapter 4, stating, "we pass from the solitary cell to cells in contact with one another-to what we may call in the first instance 'cell aggregates,' through which we shall be led ultimately to the study of complex tissues." Considering Aristotle's admission in chapters 3 and 4 that the study of politics and ethics, in contrast to the study of mathematics, is rendered imprecise, Thompson has much to share regarding his own experiences as a scientist. In chapter 7, he points out the lack of symmetry as an obstacle to his mode of scientific investigation, stating "let us dispense altogether in this case with mathematics; and be content with a very simple account of the configuration of the horn." Thomp- son is also actively drawing on the theories, discoveries, and observations of countless scholars, but unlike Aristotle in his refutation of Plato, Thompson's use of such references serves to support or assert his agenda. Curiously, too, he supports, like his mentor, the impact of death on the shape and form of skeletal structure. In chapter 5, he speaks on the impact of precipitates in bone formation, stating, "for the actual precipitation takes place, as a rule, not in actively living, but in dead or at least inactive tissue." In other words, deposits of organic matter become evident and influence the forms of bones as they separate from the dead tissues that produce them to cause skeletal changes in form.

In comparison to Thompson's work, however, it is important to note that Aristotle's work is divided into several books that follow book 1, discussed above. It is also important to make note of Aristotle's concluding statements in book 10, in which he says, "It is not enough to know what virtue is, we must strive to have and use it, and try whatever ways we may to become good." Similarly, Thompson has this to share, in conclusion, about his discussion on morphology: "for the harmony of form is made manifest in Form and Number, and the heart and soul and all the poetry of Natural Philosophy are embodied in the concept of mathematical beauty." Aristotle and Thompson, each in his own right, end their theses, solidifying their arguments in clearly identifiable closing statements.

Like Aristotle and other ancient philosophers, Thompson expressed an appreciation for the literature that supports or describes the scientific, the philosophical, surrounding morphology and the drama that played out in the processes of growth and form. His elation and wonder at such developments are evident in a quote Thompson incorporates in his *On Growth and Form* from Milton's *Paradise Lost.* He recounts the quote thus: "He hath measured the waters in the hollow of his hand, and meted out heaven with a span, and comprehended the dust of the earth in a measure."

Source: Laura Kryhoski, Critical Essay on *On Growth and Form,* in *Nonfiction Classics for Students,* The Gale Group, 2002.

Critical Essay #2

Ozersky is a critic, essayist and American cultural historian. In this essay, Ozersky looks at what makes Thompson a true naturalist, and why his gifts and training were so necessary when his book was written.

On Growth and Form, D'arcy Wentworth Thompson's classic 1000 and plus page "essay" is not the final word on natural history. It is not a definitive statement of Darwinism, or even anti-Darwinism. It is not required reading for students of evolution. Thompson did not leave a school of inquiry behind him or found a point of view that other zoologists and naturalists could follow and expand upon. And yet, it continues to be read, both by scientists and non-scientists, all over the world.

But what he did do, and the reason why *On Growth and Form* continues to be read, is to understand nature in a unique way; a way, moreover, which was a departure at the time and has become increasingly rare in the decades since. *On Growth and Form* is not a book likely to be written today by a respected scientist; nor does it seem likely that a scientist would gain much respect from the writing of it. It is not based on experimentation, and does not suggest directions for further experiment. Although written by a learned zoologist, it hardly engages at all with scholarly literature. Instead, it is written in a style rich with classical, literary, and philosophical allusions, which no one writing for either a purely scientific or a general audience would presume to publish. Yet it continues to be republished, and its readers are willing to go the extra step-to look up Thompson's allusions, to stick with his difficult passages, to make allowances they would not make for an ordinary scientist.

The reason is that Thompson is not just a scientist. He is a philosopher, an enthusiast, and an evangelist for nature. What gives a reader pleasure from *On Growth and Form* is its brilliant insight and its beautiful and expansive prose. It is one of the great works of imagination in our language. For those who are interested in such things, it works as an essential corrective to the main line of evolutionary thought.

Perhaps looking at the book in its historical context is the best way to begin to understand and appreciate *On Growth and Form.* Over fifty years had passed since the world of natural science was revolutionized by Charles Darwin's theories about evolution and natural selection. Throughout human history, scientists and philosophers had tried to explain how the world's living creatures, including ourselves, had come into being. Most were ready to credit God as being the first cause; it was the intermediate mechanisms that were so mysterious. Darwin's theories, so ably, soberly, and logically propounded in *The Origin of Species,* provided a natural explanation that essentially solved the problem to the satisfaction of most scientists. According to Darwin, random mutation, spread out over geological time, was the mechanism by which species were formed. Individuals with favorable mutations (a little more speed say, or better vision) would tend to reproduce more often in the long run, thus passing these favorable mutations on to their offspring, who would do so in turn. In this way, new species were developed, many of which derived from a common ancestor. Darwin's natural world was a family tree, with larger and more complex branches extending from the earliest, simplest forms.

Men of Thompson's age, therefore, who belonged to the first generation of evolutionary zoologists, naturally tended to concentrate on the action of environments on living things. The emphasis continued for half a century, during which time the grand vision of Darwinism shrank down to a merely technical scholarship. "British zoology," writes P. D. Medawar in *D'arcy Wenworth Thompson: The Scholar-Naturalist,* "after fifty years, was still almost wholly occupied with problems of phylogeny and comparative anatomy, that is, with the apportioning out of evolutionary principles and the unraveling of relationships of descent." Thompson was an evolutionary zoologist, but this overconcentration on anatomy made him uneasy. Why study adaptations only for what they say about evolution? Why not consider the mechanisms by which these adoptions happen? Like many naturalists since, Thompson appreciated the explanatory power and beauty of Darwinian theory but was impatient with those of his colleagues who settled for a pat understanding of it. Surely there was more to explore? For Thompson, Darwin was the beginning of understanding, not the end.

It was here that Thompson made his great contribution to biology. Like most sciences, biology had begun to be highly professionalized by the late nineteenth century, a fact that helped to account for the airless, insular atmosphere that frustrated Thompson. Thompson belonged to an older tradition, scientists who were learned in the classics, in literature, and other sciences such as mathematics and physics. It was these last fields that Thompson brought to bear on zoology, in *On Growth and Form.*

Thompson is primarily interested in natural forms as they are grow within the matrix of the whole physical world-not just the world of predators and prey. In his second chapter, "On Magnitude," he brings these ideas forward in the most approachable way: how greater size makes whales faster, or why getting wet is so much harder on a fly than it is on a man. As the book develops, he looks more and more closely at the physical laws defining the shape of things. Not every form, Thompson says, has an adaptive benefit; some things look the way they do because of the stuff from which they are made. The spicules of sponges, Thompson says, are a product of crystallization and of adsorption and diffusion. Likewise, his analysis of spiral forms like the chambered nautilus is a *tour-de-force* based almost entirely on classical geometry.

But *On Growth and Form* is more than just a book advancing a particular theory of organic development. If that is all it were, it would be no more than a footnote today. Few scientists since World War II have neglected physical environment as a factor in evolution. What is more interesting in the long run is the organic wholeness of Thompson's approach. Just as Thompson was trained as a mathematician and a classicist as well as a zoologist, his point of view transcends the tunnel-vision of scholarly discourse. Too often, specialists become preoccupied with arcane points of controversy, and develop a kind of technical jargon whose main purpose is to keep the untrained out. Thompson's mind, in contrast, was supremely inclusive. At first, it might not seem so: Stephen Jay Gould notes, in his introduction to the 1994 edition of *On Growth and Form,* that "few people today have his literary and linguistic background;

even fewer will grasp the classical allusions (not to mention the untranslated lines of Greek and Latin) that are not mere adornments but intrinsic parts of the text." Thompson does not put these difficult allusions in as a way of showing off, or (as disgruntled readers today might suggest) of practicing an intellectual elitism. His intellect was naturally discursive, unifying, connecting-he could not comfortably keep to one subject, with one vocabulary. Add to this the fact that educated people of his generation could reasonably have been expected to understand most or all of his allusions, and one sees that far from looking to keep readers out, he was trying to bring them in, using all of his background as a humanist to bridge the gap between science and the world outside science.

Wanting to bridge this gap between science and those outside it was part of his complaint with the comparative anatomists, but it also explains something very central to his method of thinking, and to the achievement of *On Growth and Form.*The book's most famous and influential chapter, "On the Theory of Transformations, or the Comparison of Related Forms," is an eloquent demonstration of the folly of looking narrowly at nature. By placing an even grid over natural forms-a prehistoric fish, a skull, a leaf-and distorting that grid mathematically, Thompson powerfully unlocks one of the inner keys of evolution, showing how all parts of a body change over time. Thompson looks at how the totality of a creature's form changes, where naturalists of his time had been preoccupied with teeth getting sharper, or how a particular quirk of skeletal structure might help an organism survive.

It was Thompson's great gift to look at morphological change holistically.That gift grew naturally out of his wide-ranging mind. It was because he was a classicist and a mathematician and a humanist as well as a zoologist that he was able to see the larger picture and to inspire later students of living forms to do likewise.

No doubt, some of Thompson's conclusions, and many of his arguments, have been weakened or refuted entirely by time. It is generally admitted that he has no modern disciples, strictly speaking, but as Medawar notes,

To many of D'Arcy's contemporaries it must have seemed strange and even perverse that he should have combined a physico-mathematical analysis of Nature with, at all times, a most intense consciousness of its wonder and beauty . . . [but] it is by such diffused and widely pervasive effects as these that we must measure the influence of 'On Growth and Form' upon biological science.

It was as a visionary, a "natural philosopher," and a poet that this nineteenth-century scientist still continues to influence science, even in the twenty- first century.

Source: Josh Ozersky, Critical Essay on *On Growth and Form,* in *Nonfiction Classics for Students,*The Gale Group, 2002.

Critical Essay #3

Partch is a Jungian astrologer, writer, and graphic designer. In this essay, Partch considers Thompson's interdisciplinary approach to the theory of evolution in contrast to Darwin's.

When the Scottish classicist, mathematician, and naturalist D'Arcy Thompson wrote *On Growth and Form* in 1917, Darwin's theory of evolution was not only relatively new, it was at the height of intellectual fashion, certainly within the scientific community if not with the religious community. Thompson's highly original thesis on morphology-the branch of biology that examines the forms and structures of living organisms-dared to question the principle of an ever-upward, genetically directed, ascending spiral toward perfection that Darwin had put forth as the notion of natural selection in his seminal work, *The Origin of Species,* in 1859. Where Darwin draws frequent analogies between Nature and a cow-breeder culling his herd, Thompson sees the physicist's underlying harmony of cause and effect; he sees energy interacting with matter in mathematical terms.

If Thompson's work was regarded as controversial in its own time-because it first of all questioned, and then largely ignored, this prevailing assumption of an inevitable progression toward a supposed ideal-today his work seems nothing less than heretical. Or refreshing, depending on one's point of view. Today, Thompson's audacity is all the more striking, particularly as his challenge to Darwin comes from the scientific, and not the creationist, quarter. Thompson, while not denying the divine mystery as the absolute final cause, also does not deny the phenomenon of natural selection. He simply points out that this process of elimination of the unfit, of unsuccessful forms, need not imply teleology-that is, a purposeful development or progression toward a final end. To dispute Darwin's emphasis on ever-improving adaptation through inherited traits, was then and remains now, quite a radical break with the prevailing thinking about nature.

But are not all the changes over time in organic forms, after all, *improvements* in structure, better suited to meeting challenging changes in the environment? The answer is, actually, no, not necessarily. In fact, while most adjustments in form were at one point in time advantageous to the organism, many of these features have become obsolete. These "leftovers" are simply lingering on past their functional purpose and have not been "cleaned up" after their usefulness has expired. There are also many failures in mutation, many "wrong turns" down blind alleys.

It is Thompson's contention that this philosophical interpretation of progress becomes a dogma. This thought then blinds the naturalist to the more immediate causes for "fortuitous variations" in form: the interplay of physical forces with geometric structures. Thompson maintains that one does not need to look quite so far afield from the core duality of force and form to learn more about changes in form, whether in terms of the growth of an individual organism or part of an organism, or whether one is looking at evolutionary variations within a species over time. Feeding the doctrine of teleology-the assumption of steady movement toward an end or purpose-starves the scientist of the empirical observation of the direct mechanical causes of adaptation and changes in form. The fundamental mechanics of growth and change in form tend to be overlooked. They can be explored, quantified, and described in mathematical detail, furthering the understanding of morphology.

Thompson's Introduction to *On Growth and Form* begins with these words:

Of the chemistry of his day and generation, Kant declared that it was a science, but not Science, for that the criterion of true science lay in its relation to mathematics. . . . A hundred years after Kant, Du Bois Raymond declared that the chemistry of the future must deal with molecular mechanics by the methods and in the strict language of mathematics, as the astronomy of Newton and Laplace dealt with the stars in their courses. . . . [On the mathematical definition of form]: We are brought by means of it in touch with Galileo's aphorism (as old as Plato, as old as Pythagoras, as old perhaps as the wisdom of the Egyptians), that the book of nature is written in characters of Geometry.

Thompson sees the application of physics and mathematics to the field of zoology as no less an occasion for awe in the face of natural phenomena than the prevailing teleological assumptions. He feels his approach enhances an even deeper appreciation of the intricacies of the ultimate mysteries of life. Thompson expresses his love of nature and wonder at its mysteries in such poetic terms that this has been called as much a work of literature as a work of science. It could also be called an extended meditation on the mathematical patterns inherent in nature everywhere, from the inorganic crystalline structures of snowflakes to the spirals in a nautilus shell to the curves of a living and growing ram's horn.

While some may recoil from the "mechanization" of the living body of nature, who can resist the engineer's delight in the design of a bird's wing? But Thompson can hardly be accused of reductionism when he muses on "the shape of a snail-shell, the twist of a horn, the outline of a leaf, the texture of a bone, the fabric of a skeleton, the stream-lines of fish or bird, the fairy lace-work of an insect's wing." These are no less beautiful under closer examination, and he intends no slight when he points out that "no organic forms exist save such as are in conformity with physical and mathematical laws" and demonstrates that all these wonders can be described mathematically. For Thompson, "Numerical precision is the very soul of science."

He elaborates:

To seek, not for ends but for antecedents is the way of the physicist, who finds 'causes' in what he has learned to recognize as fundamental properties, or unchanging laws, of matter and energy. In Aristotle's parable, the house is there that men may live in it; but, the house is also there because the builders have laid one stone upon another. It is as a mechanism, or a mechanical construction, that the physicist looks upon the world; and Democritus, first of physicists and one of the greatest of the Greeks, chose to refer all natural phenomena to mechanism and set the final cause aside.

Throughout *On Growth and Form,* D'Arcy Thompson's unique perspective as a triple scholar is called into play. His fully professional background within each discipline does more than just add to the others-there is a blending between them. They have been "chemically combined," to create a new alloy. His grounding in classics and mathematics assures that he has read (even translated) not only Plato and Aristotle, but Archimedes, Euclid, Pythagoras, et al. He brings the full depth of his decidedly Greek sensibility and insight to bear on his astute observations of nature. Thompson was not only a modern Renaissance man, he was an embodiment of one of his favorite principles, synergy: "The interaction of two or more agents or forces so that their combined effect is greater than the sum of their individual effects." This is exactly the cumulative effect of his arguments. They combine to form a perspective as multifaceted as one of Thompson's beloved dodecahedrons (a 12-sided geometric figure).

Each chapter takes a small question of form and examines it from one angle and then another, and then another, in much the same way that Bach introduces a simple melodic phrase, which is then amplified and extended and interpolated by various instruments. Various points invite reciprocal counterpoints. A certain tension escalates in the call and response. Then there is an explosion, as the individual elements come together and develop their own dance, and a full fugue emerges.

Thompson's overarching theme is that one need not anthropomorphize a celestial engineer working out the immediate advantages of hollowboned birds' wings with a slide rule and protractor. The laws of nature, divinely inspired, do that naturally. The solid-boned birds, whose more rigid, heavier wings weighed them down or which snapped in the wind, were eliminated from the gene pool, allowing the hollow-boned specimens to thrive and multiply. Thin, cylindrical tubes, by the very nature of their shape, tend not to buckle under their own weight or under outside loads or pressures, such as wind. Thompson celebrates the success of this model in a detailed mathematical contemplation of the interplay of forces and stresses in the air pressure working "against" the wing, and the structural resistance and advantages in the actual construction of the wing. He illustrates his points with ancient and recently discovered ratios and formulas in such a way as to suggest that the aerodynamic circumstances themselves, interacting with the developing organism, gave rise to the wing's design. Similarly, the strength of a tree is directly related to the windpressure it must withstand.

Thompson gives an hilarious and informative example of this subtle principle in his examination of honeycombs. There was much impassioned discussion at his time of writing concerning the marvel of the bees' ingenious economy in employing their famous hexagonal shape. There was some debate as to whether it was the bees' own intelligence that devised this architectural plan, or whether it was divine instruction guiding their instincts. But everyone agreed, including the mathematicians, that the hexagonal shape afforded the absolute most effi- cient use of space within the hive, and the most economical use of wax in the construction of the cells. There was much specious comparison of "ideal angles" (110 degrees and 72 degrees), with impossible "measurements" of the bees' roughly hewn angles, but they did come close enough to warrant general amazement.

However, Thompson observes that along the outside edges of the hives, the cells are round, and not hexagonal at all. In other words, when the cells of the hive are not adjacent to other cells, they do not assume the shape of a hexagon. He further observes that as the bees are working, they are not creating flat edges to the sides, but rather, simple rounded out hollows or cylinders. The tubular cell walls only become flat, by default, as neighboring bees scrape down "common" walls to a final degree of thinness, each working to maximize the interior area of his cell, pushing up against the adjacent cells of his neighbors.

Thompson drives his point home with the observation that when soap bubbles, for that matter, are amassed together, their spherical shape tends to distort and collapse into flat edges where the bubbles' walls meet. He concludes his discussion of this subject with the simple fact of geometry that a circle can be surrounded by exactly six circles of similar size; hence, any natural circular or spherical cluster flattens into a hexagonal honeycomb shape, be it soap bubbles or living cells or honeycombs-provided the material with which they are constructed is pliable enough. It is a *necessity* of physical law, geometric, mathematical law, that they assume this shape. In short, honeycomb cells are hexagons because they have to be.

Actually, flat circles become hexagons, but spheres become dodecahedrons, which are solid. One can observe the same "packing" phenomenon in crates of oranges or the compressed, faceted flesh of pomegranate seeds. This phenomenon has far more to do with intrinsic physical dynamics such as surface tension and matter interacting with forces (such as mutual pressure and weight), than with the mysterious motives and causes, immediate or final, behind insect behavior. This is but one example of why it is important for naturalists to take physics and mathematics into account.

This example of crates of oranges and pomegranate seeds is a very clear and simple illustration of what Thompson means when he asserts that the form of an object is a 'diagram of forces.' The object or organism's shape is like a footprint in the sand, tracing where and how various forces have acted, or are acting, upon matter. The organism's own process of growth is one such force. That genetics enters the dialogue between force and matter, such that fetal development anticipates environmental stresses, does not detract from Thompson's argument that force determines form. That is simply nature's prerogative at work to accelerate the process of "adaptation," or, response to a force.

This view also need take nothing whatsoever from one's wonder at the mystery of creation, or the notion of a design or purpose to it. It may not bring one any closer to knowing what that purpose might be, but it certainly doesn't preclude the question. If anything, one is privileged to glimpse the implicate order at an even deeper level of the overall design. This view only enhances the appreciation of Nature's creativity:

The harmony of the world is made manifest in Form and Number, and the heart and soul of all the poetry of Natural Philosophy are embodied in the concept of mathematical beauty.

Thompson is fond of quoting Kant, who says, "it is nature herself, and not the mathematician, who brings mathematics into natural philosophy."

Matter as Diagram of Forces is the introduction of a theme that Thompson builds into a brilliant fugue in his chapter on ratio in logarithmic spirals. What more Greek a concept is there than ratio? And this theme interweaves, warp to woof, with his earlier theme of geometric *necessitas.*

Thompson seems to delight in presenting ratios throughout the text. He begins with the simple. The ratio between the thickness of a stalk of grass to the stress of its own weight is a square; but, its length to its weight? Cube. This he readily correlates to bone mass and body weight in animals. Gradually he builds to one of the most elegant, and prevalent, ratios known to exist throughout nature. Sometimes called, after Euclid, the Divine or Golden Section, it is also known as the Fibonacci series. Expressed as a ratio, it is roughly 3:5. Expressed mathematically it is a recursive sequence: 1, 1, 2, 3, 5, 8, 13, 21; each value is the sum of the previous two.

Expressed geometrically, this ratio takes the shape of the spiral that makes a nautilus shell a nautilus shell. Each chamber within the nautilus shell equals its two predecessors in size. One sees exactly this type of growth throughout not only the nonliving tissues of seashells and animal horns, but with an added corkscrew twist, in the intervals between leaves on a stem; even between the planets in the Milky Way. Wherever growth occurs in this sequential, additive manner it is always in this 3:5 ratio. Wherever this ratio occurs, this spiral occurs. These spirals exist, like the honeycomb hexagons, not because of genetic programming or mutation or instinct, but because of mathematical necessity.

It is perhaps here that one can best see the signature of nature, signed with a flourish.

Source: Marjorie Partch, Critical Essay on *On Growth and Form,* in *Nonfiction Classics for Students,* The Gale Group, 2002.

Topics for Further Study

Examine the world of mathematics as it is expressed in the Fibonacci series, the logarithmic spiral, and the golden ratio. How do these fields of study conform to Thompson's work?

Read Aristotle's "Poetics." Try to find similarities between Thompson's work and Aristotle's. How are their views alike? Provide textual evidence to support your views.

Albert Einstein's discoveries on relativity represent some of the most influential discoveries of the twentieth century in the scientific community. Examine them to determine if and how Thompson was influenced by these discoveries.

Consider the topics of discussion for the classic Greek scholar: philosophy, literature, science, and mathematics. Explain the relationships between any two of these disciplines, as they express themselves in modern life, providing specific examples as support for your argument.

Compare and Contrast

1900s: In 1903, the Wright Brothers embark on the first flights ever in recorded history.

Today: "It's time to say goodbye, station, and good luck, new crew," says the outgoing station commander of the spacecraft Discovery, Russian Astronaut Yury Usachev, as he prepares to return to Earth.

1900s: In 1905, Sigmund Freud coins the term "psychoanalysis," defined as self-examination into one's inner thoughts and feelings.

Today: Internet service providers offer customers the opportunity to discuss their personal problems or field questions to experts in the field of psychology online.

1900s: In 1907, Albert Einstein expresses the relation between matter and energy in the formula e=mc2.

Today: Wolfgang Ketterle earns a Nobel Prize after demonstrating the first "atom laser" by producing a steady stream of drops of identical atoms from a sodium atom condensate.

1900s: In 1913, American geneticist A. H. Sturtevant develops gene mapping.

Today: After English embryologist Ian Wilmut at the Roslin Institute reports that a sheep named Dolly is the first mammal successfully cloned from adult tissue, ethical issues related to genetic engineering gain prominence.

What Do I Read Next?

In *Darwin's Black Box: The Biochemical Challenge to Evolution* (1998), Michael J. Behe makes a strong case on a biochemical level against Charles Darwin's theory of evolution.

Trudi H. Garland's *Fascinating Fibonaccis: Mystery and Magic in Numbers* (1987) is a basic introduction to a Fibonacci series, including an analysis of the numerical sequence and its relation to nature.

In *Life's Other Secret: The New Mathematics of the Living World* (1997), mathematician and award-winning science writer Ian Stewart considers the impact of mathematics as it relates to the origin, structure, and evolution of life.

Philosophy of Science: The Central Issues (1998), by Martin Curd, contains forty-six readings by leading thinkers of the twentieth century who address issues occupying the minds of both philosophers and scientists.

As educated a man as he was, as well-rounded a man as he was, he was also open to considering his inadequacies, admitting that perhaps his abilities were not as polished or advanced as he might have liked them to be."

It was because he was a classicist and a mathematician and a humanist as well as a zoologist that he was able to see the larger picture, and to inspire later students of living forms to do likewise."

The form of an object is a 'diagram of forces.' The object or organism's shape is like a footprint in the sand, tracing where and how various forces have acted, or are acting, upon matter."

Further Study

Clark, W. E. LeGros, and P. B. Medawar, ed., *Essays on Growth and Form,* Clarendon Press, 1945.

Clark's and Medawar's collection of critical essays presents and examines the merits of *On Growth and Form.*

Gould, Stephen Jay, Foreword to *On Growth and Form,* Cambridge University Press, 1961.

Gould offers insights into the nature of Thompson's work.

Thompson, D'Arcy, *A Glossary of Greek Birds,* Clarendon Press, 1936.

This work is the author's study of medieval and modern ornithology, complete with classical references. This book is to be read as a companion to A *Glossary of Greek Fishes.*

—, *A Glossary of Greek Fishes,* Oxford University Press, 1947.

This text by Thompson is a study of fish as they existed in classic Greek literature and in other ancient cultures. This book is to be read as a companion to *A Glossary of Greek Birds.*

Bibliography

Axelrod, Alan, *The Complete Idiot's Guide to 20th Century History,* Alpha Books, 1999.

Clark, W. E. LeGros, and P. B. Medawar, eds., *Essays on Growth and Form,* Clarendon Press, 1945.

"D'arcy Wenworth Thompson," in *Dictionary of National Biography,* Oxford University Press, 1959. pp. 877-79. Gould, Stephen Jay, Foreword to *On Growth and Form,* Cambridge University Press, 1961.

Kemp, Martin, "Doing What Comes Naturally: Morphogenesis and the Limits of Genetic Code," in *Art Journal,* Vol. 55, No. 1, Spring 1996.

Medawar, P. B., "D'arcy Thompson and Growth and Form," in *D'arcy Wenworth Thompson: The Scholar-Naturalist,* Oxford University Press, 1958.

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Project Editor
David Galens

Editorial
Sara Constantakis, Elizabeth A. Cranston, Kristen A. Dorsch, Anne Marie Hacht, Madeline S. Harris, Arlene Johnson, Michelle Kazensky, Ira Mark Milne, Polly Rapp, Pam Revitzer, Mary Ruby, Kathy Sauer, Jennifer Smith, Daniel Toronto, Carol Ullmann

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Product Design
Michelle DiMercurio, Pamela A. E. Galbreath, Michael Logusz

Manufacturing
Stacy Melson

For more information, contact
The Gale Group, Inc
27500 Drake Rd.
Farmington Hills, MI 48334-3535
Or you can visit our Internet site at
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Introduction

Purpose of the Book

The purpose of Nonfiction Classics for Students (NCfS) is to provide readers with a guide to understanding, enjoying, and studying novels by giving them easy access to information about the work. Part of Gale's□For Students□ Literature line, NCfS is specifically designed to meet the curricular needs of high school and undergraduate college students and their teachers, as well as the interests of general readers and researchers considering specific novels. While each volume contains entries on

□classic□ novels frequently studied in classrooms, there are also entries containing hard-to-find information on contemporary novels, including works by multicultural, international, and women novelists.

The information covered in each entry includes an introduction to the novel and the novel's author; a plot summary, to help readers unravel and understand the events in a novel; descriptions of important characters, including explanation of a given character's role in the novel as well as discussion about that character's relationship to other characters in the novel; analysis of important themes in the novel; and an explanation of important literary techniques and movements as they are demonstrated in the novel.

In addition to this material, which helps the readers analyze the novel itself, students are also provided with important information on the literary and historical background informing each work. This includes a historical context essay, a box comparing the time or place the novel was written to modern Western culture, a critical overview essay, and excerpts from critical essays on the novel. A unique feature of NCfS is a specially commissioned critical essay on each novel, targeted toward the student reader.

To further aid the student in studying and enjoying each novel, information on media adaptations is provided, as well as reading suggestions for works of fiction and nonfiction on similar themes and topics. Classroom aids include ideas for research papers and lists of critical sources that provide additional material on the novel.

Selection Criteria

The titles for each volume of NCfS were selected by surveying numerous sources on teaching literature and analyzing course curricula for various school districts. Some of the sources surveyed included: literature anthologies; Reading Lists for College-Bound Students: The Books Most Recommended by America's Top Colleges; textbooks on teaching the novel; a College Board survey of novels commonly studied in high schools; a National Council of Teachers of English (NCTE) survey of novels commonly studied in high schools; the NCTE's Teaching Literature in High School: The Novel;and the Young Adult Library Services Association (YALSA) list of best books for young adults of the past twenty-five years. Input was also solicited from our advisory board, as well as educators from various areas. From these discussions, it was determined that each volume should have a mix of □classic□ novels (those works commonly taught in literature classes) and contemporary novels for which information is often hard to find. Because of the interest in expanding the canon of literature, an emphasis was also placed on including works by international, multicultural, and women authors. Our advisory board members□educational professionals□ helped pare down the list for each volume. If a work was not selected for the present volume, it was often noted as a possibility for a future volume. As always, the editor welcomes suggestions for titles to be included in future volumes.

How Each Entry Is Organized

Each entry, or chapter, in NCfS focuses on one novel. Each entry heading lists the full name of the novel, the author's name, and the date of the novel's publication. The following elements are contained in each entry:

- Introduction: a brief overview of the novel which provides information about its first appearance, its literary standing, any controversies surrounding the work, and major conflicts or themes within the work.
- Author Biography: this section includes basic facts about the author's life, and focuses on events and times in the author's life that inspired the novel in question.
- Plot Summary: a factual description of the major events in the novel. Lengthy summaries are broken down with subheads.
- Characters: an alphabetical listing of major characters in the novel. Each character name is followed by a brief to an extensive description of the character's role in the novel, as well as discussion of the character's actions, relationships, and possible motivation. Characters are listed alphabetically by last name. If a character is unnamed□for instance, the narrator in Invisible Man-the character is listed as □The Narrator□ and alphabetized as □Narrator.□ If a character's first name is the only one given, the name will appear alphabetically by that name. □ Variant names are also included for each character. Thus, the full name □Jean Louise Finch□ would head the listing for the narrator of To Kill a Mockingbird, but listed in a separate cross-reference would be the nickname □Scout Finch.□
- Themes: a thorough overview of how the major topics, themes, and issues are addressed within the novel. Each theme discussed appears in a separate subhead, and is easily accessed through the boldface entries in the Subject/Theme Index.
- Style: this section addresses important style elements of the novel, such as setting, point of view, and narration; important literary devices used, such as imagery, foreshadowing, symbolism; and, if applicable, genres to which the work might have belonged, such as Gothicism or Romanticism. Literary terms are explained within the entry, but can also be found in the Glossary.
- Historical Context: This section outlines the social, political, and cultural climate in which the author lived and the novel was created. This section may include descriptions of related historical events, pertinent aspects of daily life in the culture, and the artistic and literary sensibilities of the time in which the work was written. If the novel is a historical work, information regarding the time in which the novel is set is also included. Each section is broken down with helpful subheads.
- Critical Overview: this section provides background on the critical reputation of the novel, including bannings or any other public controversies surrounding the work. For older works, this section includes a history of how the novel was first received and how perceptions of it may have changed over the years; for more recent novels, direct quotes from early reviews may also be included.
- Criticism: an essay commissioned by NCfS which specifically deals with the novel and is written specifically for the student audience, as well as excerpts from previously published criticism on the work (if available).

- Sources: an alphabetical list of critical material quoted in the entry, with full bibliographical information.
- Further Reading: an alphabetical list of other critical sources which may prove useful for the student. Includes full bibliographical information and a brief annotation.

In addition, each entry contains the following highlighted sections, set apart from the main text as sidebars:

- Media Adaptations: a list of important film and television adaptations of the novel, including source information. The list also includes stage adaptations, audio recordings, musical adaptations, etc.
- Topics for Further Study: a list of potential study questions or research topics dealing with the novel. This section includes questions related to other disciplines the student may be studying, such as American history, world history, science, math, government, business, geography, economics, psychology, etc.
- Compare and Contrast Box: an □at-a-glance□ comparison of the cultural and historical differences between the author's time and culture and late twentieth century/early twenty-first century Western culture. This box includes pertinent parallels between the major scientific, political, and cultural movements of the time or place the novel was written, the time or place the novel was set (if a historical work), and modern Western culture. Works written after 1990 may not have this box.
- What Do I Read Next?: a list of works that might complement the featured novel or serve as a contrast to it. This includes works by the same author and others, works of fiction and nonfiction, and works from various genres, cultures, and eras.

Other Features

NCfS includes □The Informed Dialogue: Interacting with Literature,□ a foreword by Anne Devereaux Jordan, Senior Editor for Teaching and Learning Literature (TALL), and a founder of the Children's Literature Association. This essay provides an enlightening look at how readers interact with literature and how Nonfiction Classics for Students can help teachers show students how to enrich their own reading experiences.

A Cumulative Author/Title Index lists the authors and titles covered in each volume of the NCfS series.

A Cumulative Nationality/Ethnicity Index breaks down the authors and titles covered in each volume of the NCfS series by nationality and ethnicity.

A Subject/Theme Index, specific to each volume, provides easy reference for users who may be studying a particular subject or theme rather than a single work. Significant subjects from events to broad themes are included, and the entries pointing to the specific theme discussions in each entry are indicated in boldface.

Each entry has several illustrations, including photos of the author, stills from film adaptations (if available), maps, and/or photos of key historical events.

Citing Nonfiction Classics for Students

When writing papers, students who quote directly from any volume of Nonfiction Classics for Students may use the following general forms. These examples are based on MLA style; teachers may request that students adhere to a different style, so the following examples may be adapted as needed. When citing text from NCfS that is not attributed to a particular author (i.e., the Themes, Style, Historical Context sections, etc.), the following format should be used in the bibliography section:

□Night.□ Nonfiction Classics for Students. Ed. Marie Rose Napierkowski. Vol. 4. Detroit: Gale, 1998. 234-35.

When quoting the specially commissioned essay from NCfS (usually the first piece under the □Criticism□ subhead), the following format should be used:

Miller, Tyrus. Critical Essay on □Winesburg, Ohio.□ Nonfiction Classics for Students. Ed. Marie Rose Napierkowski. Vol. 4. Detroit: Gale, 1998. 335-39.

When quoting a journal or newspaper essay that is reprinted in a volume of NCfS, the following form may be used:

Malak, Amin. □Margaret Atwood's □The Handmaid's Tale and the Dystopian Tradition,□ Canadian Literature No. 112 (Spring, 1987), 9-16; excerpted and reprinted in Nonfiction Classics for Students, Vol. 4, ed. Marie Rose Napierkowski (Detroit: Gale, 1998), pp. 133-36.

When quoting material reprinted from a book that appears in a volume of NCfS, the following form may be used:

Adams, Timothy Dow. □Richard Wright: □Wearing the Mask,□ in Telling Lies in Modern American Autobiography (University of North Carolina Press, 1990), 69-83; excerpted and reprinted in Novels for Students, Vol. 1, ed. Diane Telgen (Detroit: Gale, 1997), pp. 59-61.

We Welcome Your Suggestions

The editor of Nonfiction Classics for Students welcomes your comments and ideas. Readers who wish to suggest novels to appear in future volumes, or who have other suggestions, are cordially invited to contact the editor. You may contact the editor via email at: ForStudentsEditors@gale.com. Or write to the editor at:

Editor, Nonfiction Classics for Students
Gale Group
27500 Drake Road
Farmington Hills, MI 48331-3535