1.2 NATURE AND BEAUTY

"LIKE UNTO EACH THE FORM,
YET NONE ALIKE; AND SO THE
CHOIR HINTS A SECRET LAW,
A SACRED MYSTERY."

Johann Wolfgang von Goethe,
The Metamorphosis of Plants, 1798

We want to understand what makes teeth beautiful? Then, we must elucidate the nature of organic forms and the natural basis of our perception of the beauty of natural phenomena.

1. Organic form

Tooth shapes are organic forms. Teeth have grown as building blocks of living creatures. This fact that appears all too self-evident to us contains several essential points of views relating to the understanding of dental aesthetics. For this purpose, let us review the development of our understanding of organic form.

The scientific study of organic form originated in the discoveries of the Swiss naturalist *Charles Bonnet* (1720 – 1793). In his investigations of plants, he observed that the arrangements of leaves in 125 plant species can essentially be subdivided into five basic patterns of radial symmetry that provide functional advantages in light absorption and respiration. This went far beyond more than a mere description and depiction, as had previously been common, and established the knowledge that spatial organizational principles of organisms can contribute to our understanding of the regulatory mechanisms of vital processes.

In today's biology, form represents a characteristic that follows from the analysis of an object and reflects its fundamental functional principles. It is not a random projection, but has a set regularity consistent with its object. Form can be verified empirically by measurements. The science of forms and structures studied under the aspect of the processes leading to that attained form is called morphology.

The young J.W. von Goethe (1749 – 1832), already endowed with a fine sense of the beauty of nature, was one of the first to use the term "*morphology*". The lines above were excerpted from his poem "*The Metamorphosis of Plants*" written eight years after his elegy "*An Attempt to Explain the Metamorphosis of Plants*", wherein the German poet and philosophical genius deals with botany after many years of preliminary work and intensive study. In 1817, Goethe started publishing his botanical investigations on the concept he introduced into the science of his day "morphology", a term he coined for the first time in 1796 (according to his diary entries), defined as the science of organic forms, genesis and metamorphosis of organisms. The first published record of the term in 1800 is attributed to the Leipzig anatomist Karl Friedrich Budach, independently of Goethe.

Goethe was one of the first to concern himself with the influence of the environment on plants, acknowledging that form is never something finalized or completed, but rather a moving, metamorphic, transient state. He equated the study of form with the study of metamorphosis. He sought after the primal qualities and primal forms of life. These studies would be able to explain the innate relationships between various sorts that could not be classified by Linnaean taxonomy. Goethe's notion of primal shape embodies an intellectual archetype of pure form. It emerged from his quest for an aesthetic ideal.

Fig. 1: Tooth germs of right upper incisors in various growth phases, from the labial and lingual respectively. The shape is intrinsically determined.

Goethe discovered the visual ideal of a "primal plant" upon which all plants should be based. He did not mean this in an evolutionary sense, but as an archetype that would directly open up the essence of all vegetative life to the beholder. He believed that this plant must exist or, if it did not, it theoretically might because if not all plants were shaped according to a pattern, how would they otherwise be recognized as plants? Goethe's ideal of the primal form is founded on his assumption that if organic form is not the result of a summation of mechanical parts, it must be based on a transcendental principle.

However, Goethe's idealistic understanding of nature was lacking an observational robustness, an understanding for the importance of the relationship of the individual parts to the whole. This is exemplified by his his assumption that the cranial bones would correspond to the subsided and merged vertebrae.

By contrast, back then in 1790, Immanuel Kant (1724 – 1804), another German philosopher, in his *Critique of Judgment* had already postulated that organisms are not planned, but grow. They are purposeful without purpose. He wrote, "In such a product of nature every part not only exists by means of the other parts, but is thought as existing for the sake of the others and the whole, that is as an (organic) instrument. Thus, however, [...] represented only as a purpose that is possible in general; but also its parts are all organs reciprocally producing each other. […] Only a product of such a kind can be called a natural purpose, and this because it is an organized and self-organizing being."

As early as 1769, the French philosopher Denis Diderot (1713 – 1784) compared the human organism with a swarm of bees in a dynamic process of movement, posthumously published in his dialogue in 1830 *D'Alembert's Dream*. Herein, he underscored his analogy with the metaphor that, by somehow fusing the bees together, the cluster could become a single organism. Diderot recognized that the collective properties of vital processes themselves create order when singular components are unified into living oneness.

The form of each organism not only results from the spatial arrangement of its building blocks, but is a property growing from the interplay of simple properties of its elements and the complex organization of their interrelationships. The whole is greater than the mere sum of its parts.

2. "The whole is prior to the parts"

Samuel T. Coleridge, the English romantic poet (1772 – 1834) had a key influence on the understanding of the essence of organic forms. The appreciation and exaltation of beauty are central topics in Romanticism. Characteristically, Coleridge was the poet who introduced the term "aesthetics" into the English language. Coleridge developed his concept of organic form by analyzing Shakespeare's plays. It was his conviction that true art must contain organic and non-mechanical properties. According to Coleridge, a form is mechanic when we impress a predetermined shape on given material that does not necessarily arise from the properties of the material. Contrastingly, organic form is dynamic, vital; it molds itself during its development from within. Nature, as the original artistic genius, is inexhaustible in its capabilities and equally inexhaustible in its forms. Coleridge repeatedly characterized organic forms by 5 properties *(the parenthesis and italics impart the relevance to our field):*

1. The whole is prior to the parts, the parts are derived therefrom. The whole is everything, the parts nothing. *(Face – lower face – masticatory system – dental arch – oral cavity – teeth)*

2. Organic form conveys to a beholder the process of its genesis. "Productive faculty" or growth is the main driving force, the impulse of living creatures and their evolution can be derived from their form. *(e.g. perikymata, Retziu's parallel striae, ridges and fissures)*

3. During its growth, an organism assimilates outside elements into its intrinsic substance. *(e.g. fluorosis spots, tetracycline-induced discoloration)*

4. The final form is determined from within, not like human artifacts from the outside. *(Genetic determination)*

5. The parts of an organic whole cannot be dissevered from one another. *(Teeth – gingiva – pulp – periodontium – alveolar bone – antagonists – adjacent dentition – temporomandibular joints etc.)*

We easily find all these properties reflected in the dentition and teeth as well. Their forms mirror the processes and principles of their individual growth and, beyond that, the general principles of life. When we fabricate dental restorations, this first

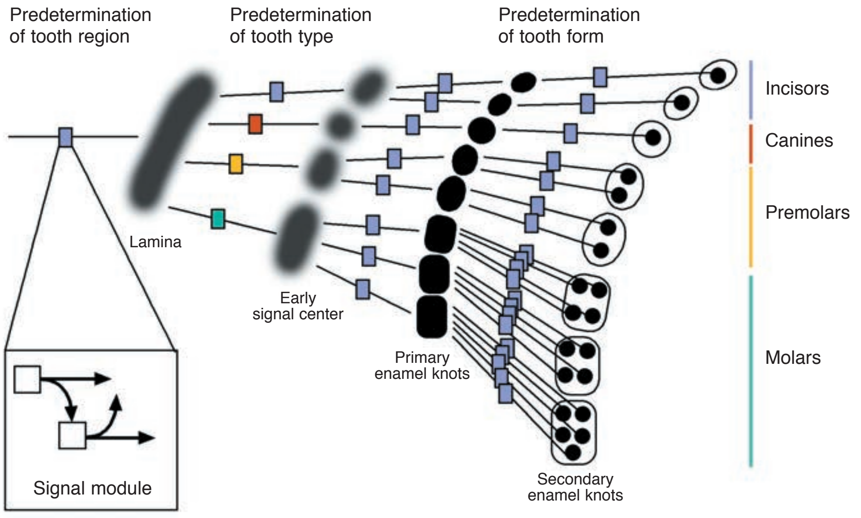

Fig. 2: Iterative signal modules during tooth development in mammals. The first partitioning sets the identity of the tooth type (incisor, canine, premolar, molar) and may be regulated by various signal emissions (different colors in the boxes). The other signal modules determine the number of cusps that may deviate from this scheme in various animals depending on tooth type (e.g. multicuspid incisors in lemurs). According to Jernvall [1], 2000.

point is meaningful. We must not only account for the relations of the individual teeth to their adjacent dentition and antagonists on the plaster model; we must also pay attention to the gingiva, the alveolar ridge, the lips, the tongue, the inner cheek mucosa and the whole face. And do so from both a functional as well as an aesthetic perspective. Natural teeth, as a part of the organic whole, i.e., the oral cavity, are optimally adapted to all these adjacent structures.

Various teeth within a dental arch will exhibit similar contours and traits characterizing their form – all indicating that they derive from a mutual element. This observed homology originally led to the hypothesis that the teeth differentiated from the common whole, called a "developmental module". That form can be used to draw conclusions about the process is nowadays accepted as verified.

Meesenburg et al. [3] demonstrated that the lingual curvature of a maxillary anterior tooth in the sagittal plane can be rediscovered in the cuspal contours of the posterior teeth (Fig. 3-5). The integrative control of tooth development is extraordinary in terms of the fact that the morphology of occlusal surfaces is already predetermined right from the initial stages of tooth development. The teeth develop separately from within the two jaws and the antagonists later occlude perfectly after the tooth eruption.

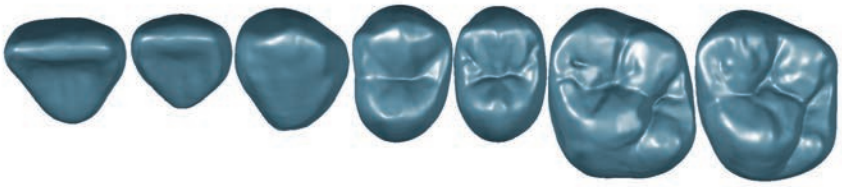

Fig. 3: 3-D scans of natural crowns of teeth #21-#27 in an adolescent arch arranged in a straight row from the occlusal: Contour elements and curvature progression patterns repeat themselves exactly or with slight variational properties on certain teeth. Particularly striking are the mesiobuccal contours on #23-#27. Distolingual contours on #21-#23 appear where the curve flattens towards the anterior due to the increasing incisivation.

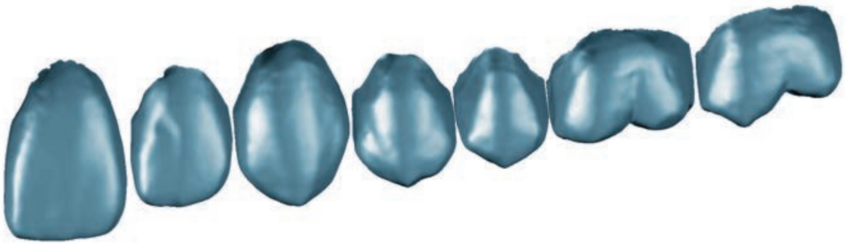

Fig. 4: The same teeth from the vestibular: Although each tooth exhibits its intrinsic anatomical traits, similarities are clearly identifiable across the teeth. Specifically, the cusp angles of #23, #24, #25 and #27 are identical except for a slight tendency to posterior flattening (molarization). (Tooth #26 has been changed by abrasion.)

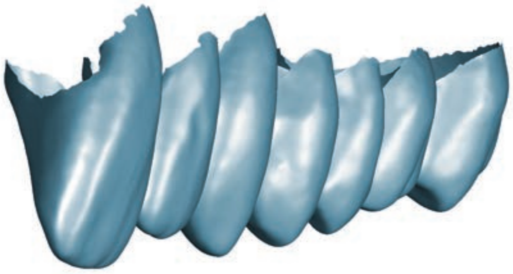

Fig. 5: View from the mesiolateral: The contours running in the cervical-incisal direction are likewise very similar. Due to the individual anatomy of the teeth, the most prominent curvatures of the molars are located more cervically and the incisors are flatter; otherwise, their lines are virtually identical.

Fig. 6: Heterodont dentition of a dog. Heterodontism (anisodont dentition): The jaw contains tooth types with different forms and functions in different parts of the dentition. This is a trait of most mammalian dentition, but can also be found in fish. Homodontism (isodont dentition): All teeth of a jaw are uniformly shaped (mostly a cone, four-sided prism or variously shaped peg). They can, however, vary in size. Characteristic of many fish, amphibians and reptiles.

3. The teeth as constructional elements of the masticatory system

The morphology of individual teeth can be better grasped by observing the whole stomatognathic system in an general context. The full denture, which forms a functional unit, possesses specialized subsections. Whenever teeth are lost by adaptation, certain functions can be assumed by structures not originally intended for that function. Basically, all teeth are very sophisticated and distinctive masticatory tools.

Comparative investigations on various mammalian dental arches have shown that the teeth of heterodont mammals can always be subdivided into four homologous groups according to a basic morphological pattern. Even though their individual detailed shape may vary greatly, not always do all groups have to be present at the same time:

1) Incisors (I: also referred to as dentes incisivi)
2) Canines (C: also referred as dentes canini)
3) Premolars (P: also referred to as dentes praemolares)
4) Molars (M: also referred to as dentes molares)

The individual tooth types always occur in approximately the same section of the jaw. Since all four tooth shapes can be found in human dentition, it can be regarded as highly specialized. The highly specialized tooth types of mammalian dentition enable it to functionally adapt to different nutritional conditions. This has led to a unique diversity among vertebrates.

It is generally assumed that the originally hypothetical completely or maximally dentulous mammalian jaw has the following dental formula:

I 3 C 1 P 4 M 3 (x 4 = 44)

In most mammals, the number of teeth became reduced. The dental formula in humans is:

I 2 C 1 P 2 M 3 (x 4 = 32)

This is equivalent to a regression of one third lateral incisor (as occurring in dogs for example) and two premolars.

One main characteristic of mammalian dentition is how it differs from the dentition of other vertebrates by virtue of the exact form-fit of the occlusal surfaces of its two dental arches with each other, especially in the molar area. The overwhelming majority of mammals erupt two generations of teeth, the first dentition and then the permanent dentition (diphyodontism). In the permanent dentition, which is not renewed, the structure of each tooth already exhibits a unique congruency with its antagonistic occlusal surfaces. The high precision of occlusion is associated with very effective food processing and dictates a clear functional classification with in the jaw.

Comparisons of various mammalian dental arches prove that dental morphology can provide information about the eating habits and the ecological habitat of the animal. Jaws of herbivore, carnivores, insectivores and piscivores each exhibit intrinsically characteristic traits [4]. Specializations like those in rodents or tusk-bearing animals are testimony to the amazing ability of the life to adapt forms and structures to certain circumstances. It also becomes clear that these changes are also always associated with skeletal transformations of the entire supporting structures (Fig. 7). Functions

Fig. 7: Skull of a muskrat.

create structures and structures, in turn, dictate the functions. Parafunctional influences can impact the form of the overall structure. Morphometric investigations on human skulls of three North American Indian tribes (Aleutian Islanders, Arikara Indians and Illinois Bluff Indians) subject to varying habitual levels of ingestive and paramasticatory processing by the incisors showed markedly identifiable differences in their skeletal basis. Their skulls and jawbones have adapted plastically or evolutionarily to the different stressor [5].

Fig. 8: Fully dentulous mandible of an adolescent.

Relationships between the tooth shape of the incisors and nutrition are identifiable in apes for example. Their broad shovel-shaped incisors indicate that they tend to eat more soft foods (e.g. fruits), whereas their narrow incisors point to a diet rich in fibers (e.g. bark, bamboo, leaves). In humans, the connection between the emergence of shovel-shaped incisors ("shoveling") and increased masticatory forces is considered highly probable [6]. Humans are omnivores who eat both animal and plant foods. The structure of human dentition is generally patterned for omnivorous eating and is thus not characterized by any distinctive morphology. In humans, a connection is also seen between the effects of evolutionary brain development over the course of humanization and the formation of the current form of the masticatory organs, having been used as a tool for verbal, but also non-verbal communication [7].

The form of our teeth is an expression of a multi-layer network of form-function complexes, enabled by the teeth as organs integrated into the masticatory system. In this context, a number of secondary, at first glance, not obvious functions, play a role, like the tactile feel of the teeth or self-protective mechanisms (e.g. mesial drift, oral and vestibular crown contours to protect the gingiva, physiological mobility etc.).

Hence, it can be exemplified how orientation of the dental crowns and roots in the jawbone reveal the direction of forces they are required to absorb. The roots in the upper jaw are inclined towards each other and direct the masticatory forces into the

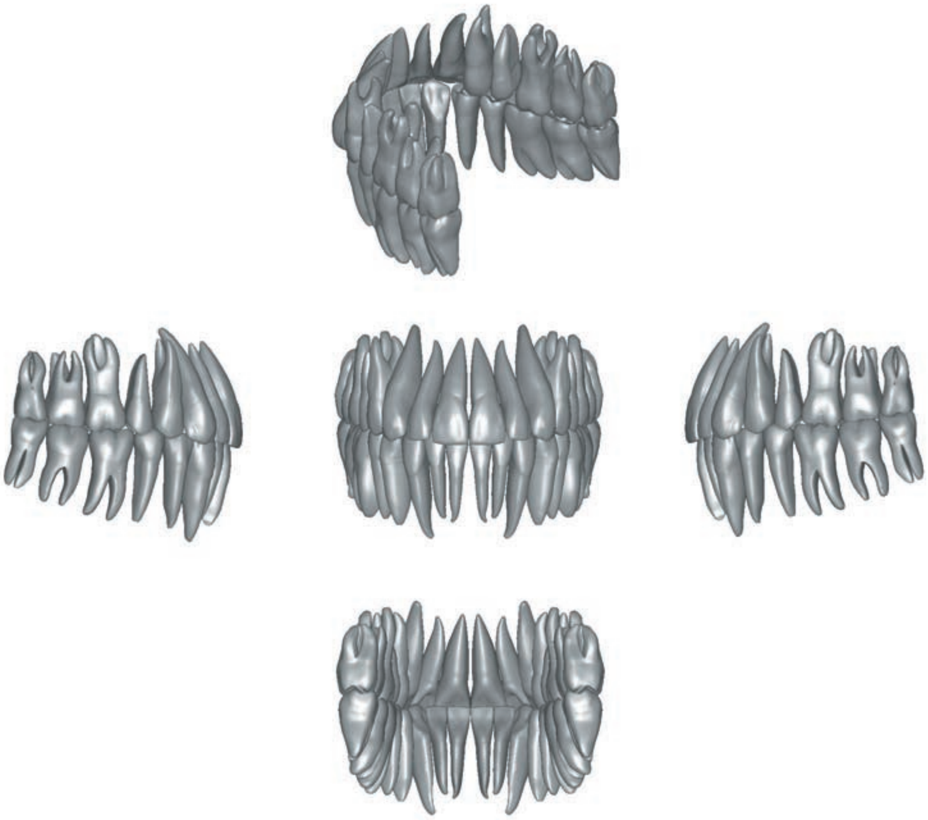

Fig. 9: Form and positional relationship of all permanent teeth

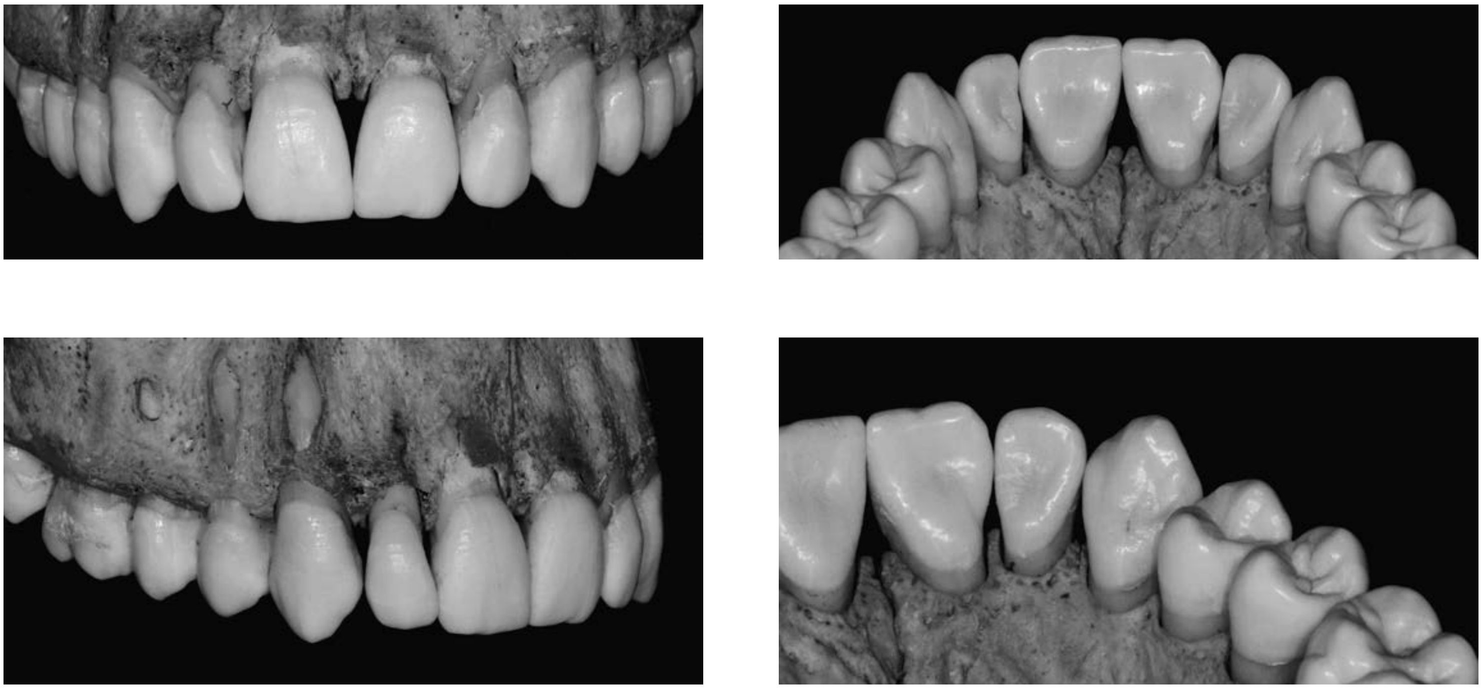

Fig. 10: Skeletonized fully preserved dentition of a 19-year-old male.

vault of the maxillary bone. During eccentric loading, the buccal roots of the molars also channel forces into the zygomatic bone. The canines – subject to the strongest lateral stresses – also have the longest roots whereas those teeth absorbing the strongest occlusal stresses and strain are multi-rooted. The roots of the individual premolars exhibit a compensatory curve to the distal.

Given the fact that teeth cannot fulfill their occlusal function unless in connection with jaw movements, their form is closely matched to the form and functional patterns of the temporomandibular joints and with our central nervous system. Additional examples of functionally adapted tooth morphology include the occlusal surface profile with functional free spaces, spherical proximal contacts, the 3-dimensional sphericity of the occlusal plane, the emergence profiles of the oral and vestibular tooth surfaces, tooth innervation incorporating pulp cavity and the entire periodontal complex. This list could go on and on. Obviously, the forms of the teeth – in isolation and in their entirety – are inseparable from all their functions and requirements, available spatial conditions as well as from evolutionary and developmental preconditions.

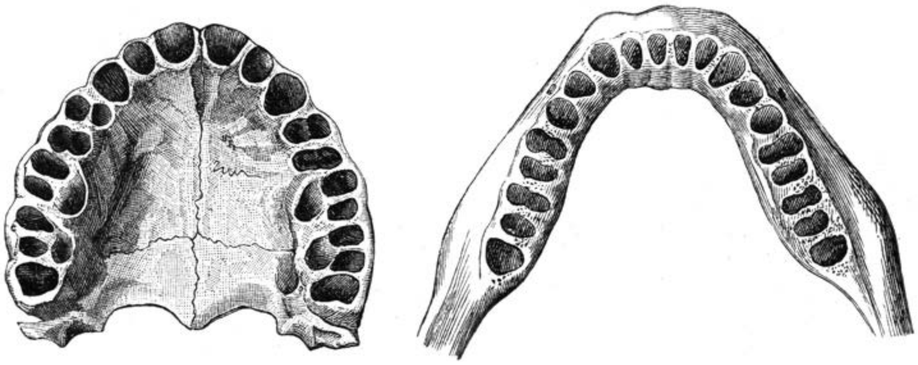

Fig. 11: The form of the teeth is inseparably connected to the form of the supporting and adjacent structures. Alveoli of the upper and lower jaw. From Mühlreiter [8] 1928.

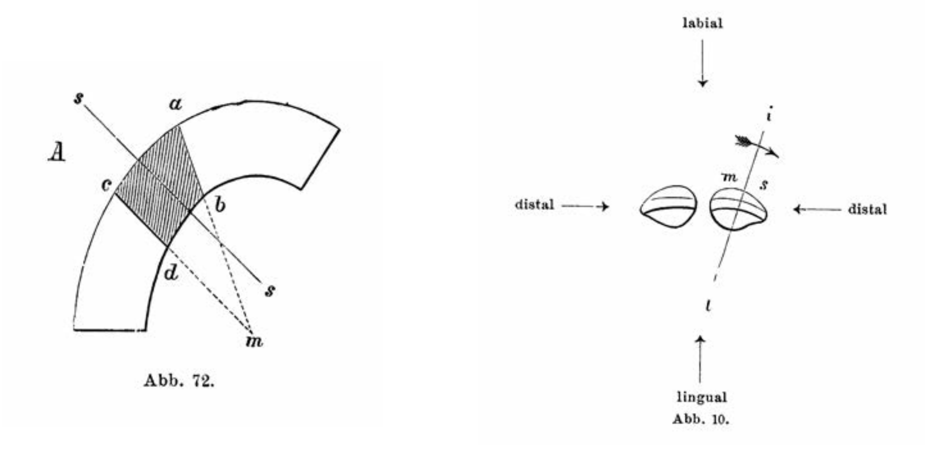

Fig. 12: This arrangement into a non-circular arch results in an asymmetry of the individual elements. This was attributed by Mühlreiter to the characteristic curvature trait he was the first to describe. From Mühlreiter [8] 1928.

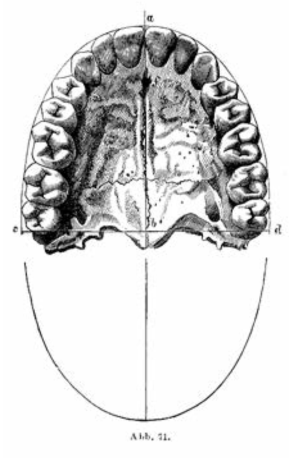

Fig. 13: The maxillary arch. From Mühlreiter [8] 1928. The teeth draw an elliptical arch.

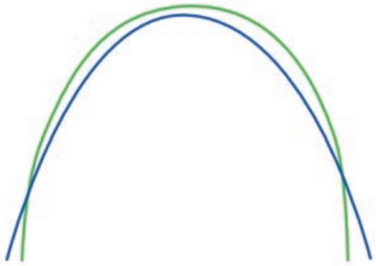

Fig. 14: The form and size variants of the jaws: Mandible blue, maxilla green. In the entire anterior region up to the area of the first molars, the alveolar process of the upper versus the lower jaw moves out so far that the upper crowns trace a wider arch than the lower, even in the vertical position. The premolars stand perpendicular to the occlusion plane. Behind this, the parabolic branches of the mandibular arch run always farther apart, whereas the elliptical maxillary jaw narrows slightly.

Due to the difference in the size and form of the mandible and maxilla, the lower molars are slightly inclined to the lingual and the upper molars slightly to the buccal. This inclination increases dorsally.

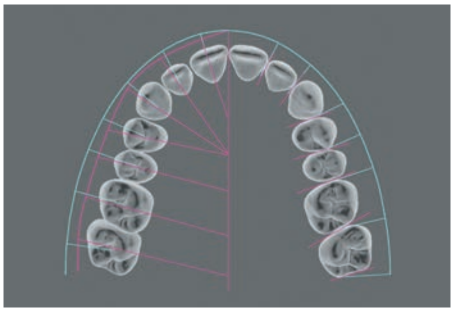

Fig. 15: The dental crowns do not form the perfect segments of an elliptical arch: Neither do the oro-vestibular axes of the crowns nor the tangents of the proximal surfaces agree exactly with the perpendicular lines on the arch. Most of the time, the vestibular surfaces do not form a perfect ellipsis, which is even much less the case orally. The 2nd premolars usually exhibit a reverse buccal flexion characteristic. Geometric constructions can merely be an aid and reflect natural reality only approximately.

(3-D scan of a natural maxillary arch)

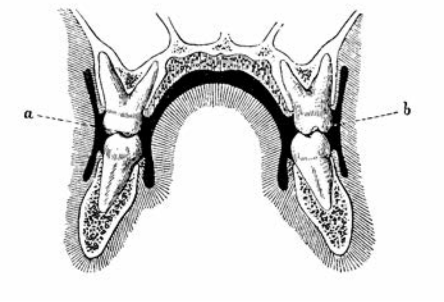

Fig. 16: Relation of dental arches to cheeks and tongue. From Mühlreiter [8] 1928. By virtue of an overbite of the shearing cusps, the cheeks and tongue are protected against bites. In the frontal segment, the relations to the lips play a very significant functional role.

Fig. 17: Living nature is capable of bringing forth infinite diversity while continuing to preserve similarity.

4. Variation and individuality: Unity in diversity – diversity over simplicity

In the forms of nature, there are no identical repetitions on certain planes. Individuality is one of the key strategies of evolution. This individuality can be found in all natural forms. Nevertheless, for us humans it is sometimes more and sometimes less obvious. Whereas certain creatures like ants or sparrows generally appear all the same to us, our ability to distinguish human faces from one another is honed to a fine art. How much our perception of individuality depends on honing our senses is evidenced therein that most Caucasians find that Asian faces look much more like each other than Caucasian faces do to them. Likewise, an experienced shepherd recognizes every sheep in his herd by its face, whereas, for most of us, all sheep appear to look the same. In the same way, anyone concerned intensively with tooth shapes learns to grasp their individuality of form.

Our intuition tells us that this extraordinary diversity is the truly monumental achievement of evolution resulting from selection and adaptation. Interestingly, several aspects indicate that things actually behave in exactly the opposite way, and that the inexhaustible diversity of many biological incarnations derives from relatively simple control mechanisms.

S. Wolfram [9] showed that the simplest programs and rules, when repeatedly applied in succession, can lead to completely irregular patterns and a high degree of complexity. The apparent complexity of biological systems suggests that the underlying rules must be of an ultra-highly complex nature. The common assumption is that biology has used astonishing means to find intelligent ways to fulfill highly sophisticated tasks. Consider the artistry of the patterns in the shells of some mollusks and snails. According to Wolfram, the true reason for these patterns lies elsewhere.

Wolfram's discovery of cellular automata shows that extremely simple rules and control mechanisms can sometimes lead to immense complexity and diversity (Fig. 18). Shapes of plant leaves or other plant parts, insect wings, camouflage schemes and pigmentary patterns of various animals and many other forms in nature can be recalculated using the same or similar mathematical methods.

Several reasons indicate that such simple rules apply to biology. Firstly, this diversity existed very early on in evolution. Fossils exhibit a wealth of forms and structures that are unparalleled in today's realm. Secondly, it is not advantageous for functioning natural selection whenever it is too complicated or too many completely different rules have to be changed. Great diversity exists in dimensions where it affects the survival of individual organisms the least. According to this postulation, when evolution determinately intervenes it achieves a simplification of the species, like we humans accomplish through planning and construction. This simplification is what we are able to perceive as a construction plan because it is equivalent to our approach to specific problems.

The expression of the paradoxical synchrony of order and freedom intrinsic to life visible for us is the unity in the diversity of patterns and forms in organic nature.

By observing a juxtapositioning of these kinds of natural forms, the tension existing between the typical construction plans and individual variation becomes crystal clear. This is no different with teeth. Indeed, this book will particularly attempt to highlight this aspect of the relationship between norm and individuality.

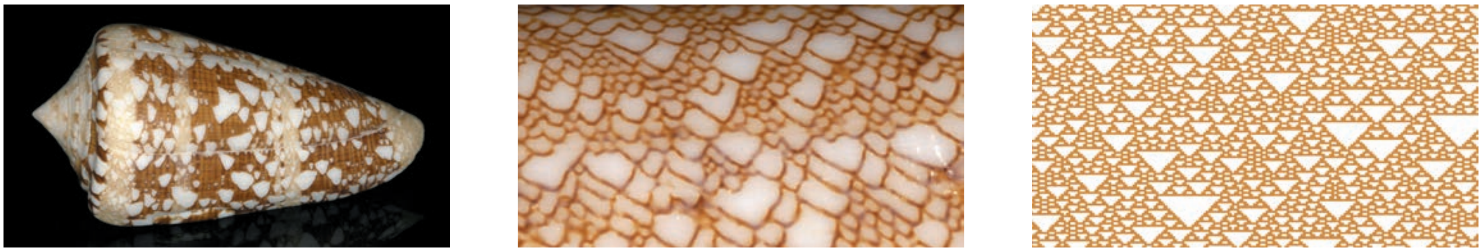

Fig. 18: Typical pigmentary patterns of seashells. During growth, the mollusks build up their shells in a lamellar fashion. The patterns mirror two-dimensional "cellular automata". These are patterns that emerge by repeating the same simple mathematical rule applied lamella by lamella. By this method, the lower pattern is built from top to bottom, starting with a random distribution of yellow and white pixels in the first lamellar layer. In simple terms, the underlying rule (rule 126) states that the next pixel located under a pixel in the next line specifies that it is white when the pixel above and its two neighbors are all three the same (i.e. either yellow or white). In all other cases, a yellow pixel is produced. There is a total of 256 such cellular automata that lead to the most variously regular, irregular or combined patterns. According to Wolfram 2002 [9].